GOTHIC 8.1 BENCHMARK TO THAI FACILITY EXPERIMENT WITH STEAM-HELIUM STRATIFICATION

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ABSTRACT

The ThAI (Thermal hydraulics, Aerosols and Iodine) facility, located in Eschborn, Germany, is a 60 m^3 steel test vessel designed to simulate operational and accident conditions in a nuclear containment structure. The ThAI facility provides experimental data used for validation of thermal hydraulic codes. The test performed at this facility has been modeled using the [1]GOTHIC 8.1(QA) software package for the purpose of validating both the physical models and modeling techniques.

The test analyzed is from Step 2 of the ISP-47 test performed at the ThAI facility. This test consisted of three injection ports for steam and helium to enter the vessel asymmetrically. The asymmetry along with the compartmented geometry of the facility provide a complex coupling of physics that would be present in an accident transient inside of the containment of a typical light water reactor. Key considerations of this analysis are the stratification of the steam and helium, condensation deposition, and the flow patterns within the vessel.

KEYWORDS
GOTHIC, ThAI, Stratification, Helium, Condensation

1. INTRODUCTION

The objective of this work was to validate the GOTHIC software package as well as the modeling techniques to capture the complex physics occurring in the ISP-47 experiment performed at the ThAI facility. GOTHIC is a multi-physics general thermal hydraulic software package that solves the conservation equations for mass, momentum, and energy for multi-component, multi-phase flow in lumped and/or multi-dimensional geometries [1]. To better qualify GOTHIC for complex accident scenarios within a containment building, the accident scenarios within the ThAI facility have been modeled and compared with experimental data.

The ThAI facility consists of a large steel vessel in which accident conditions within containment can be simulated. The ThAI experiment analyzed for this paper is International Standard Problem 47 (ISP-47). It is characterized by an outer vessel surrounding an inner cylinder with multiple steam and helium injections. The injections are dispersed vertically within the vessel to create large temperature gradients as well as stratification of steam and helium. Helium was used as an injection gas to simulate the hydrogen that can be generated during severe accident scenarios.

[1]GOTHIC ™ is maintained and developed by the Numerical Applications Division of Zachry Nuclear Engineering, Inc. for the Electric Power Research Institute (EPRI)

2. FACILITY DESCRIPTION

The ThAI facility for ISP-47 consists of the 60 m^3 vessel surrounded by an oil filled cooling jacket. The inside of the vessel is characterized by a lower sump region at the bottom, an inner cylinder with condensate trays in the middle, and an upper plenum at the top. The facility is shown below in Figure 1.

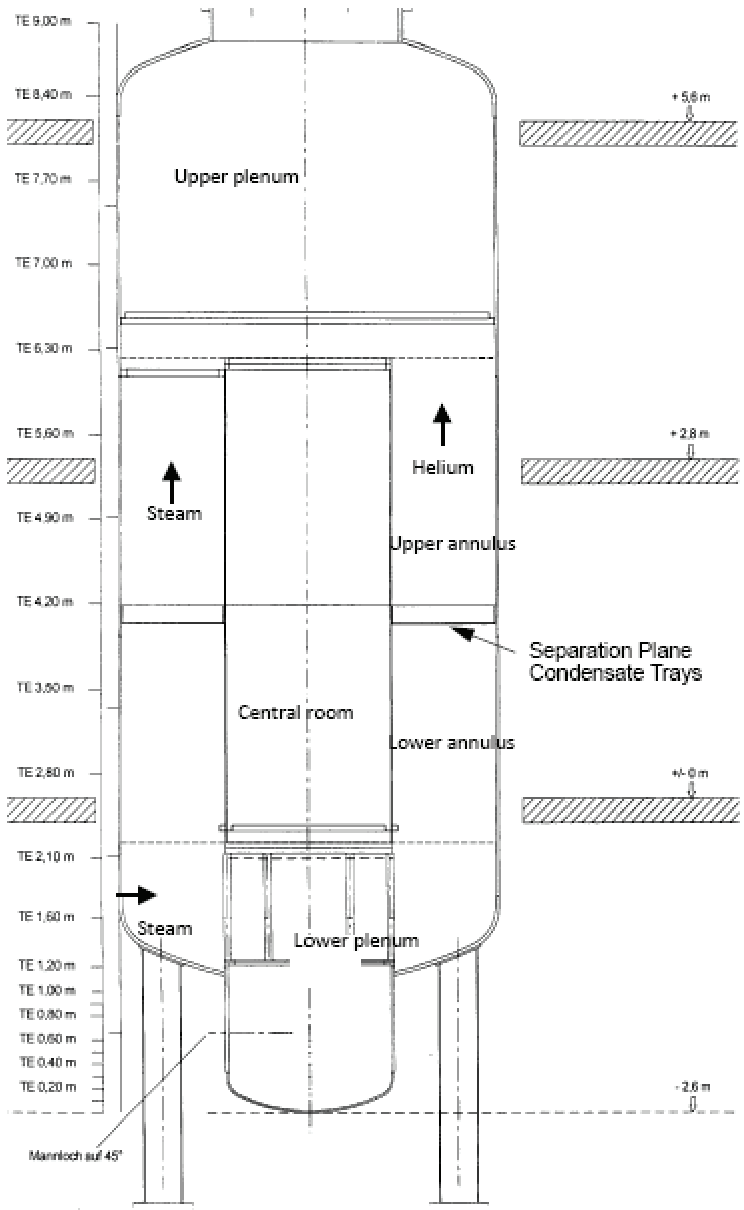

Figure 1. ISP-47 Experimental Facility [2].

The facility has a design limit of 14 bars at 180 C, covering the range of temperature and pressure that would be expected to occur in containment during most accident situations.

3. TEST DESCRIPTION

The vessel has three injection points for the steam and helium to enter the vessel. The two upper injection points are oriented vertically upward while the lower injection point enters horizontally towards the center of the vessel. The test consists of four phases. During the first phase helium is injected into the upper annulus. This occurs from time 0 until 2700 seconds. Phase two, the upper steam injection into the upper annulus, occurs from time 2700 seconds until 4700 seconds. The third phase consists of the lower steam injection into the lower plenum. It occurs from time 4700 seconds until 5700 seconds. The final phase consists of no injections. The injection rates and injections locations are shown below in Figure 2. All injections are located on the bisecting plane connecting angles 135° and 315°.

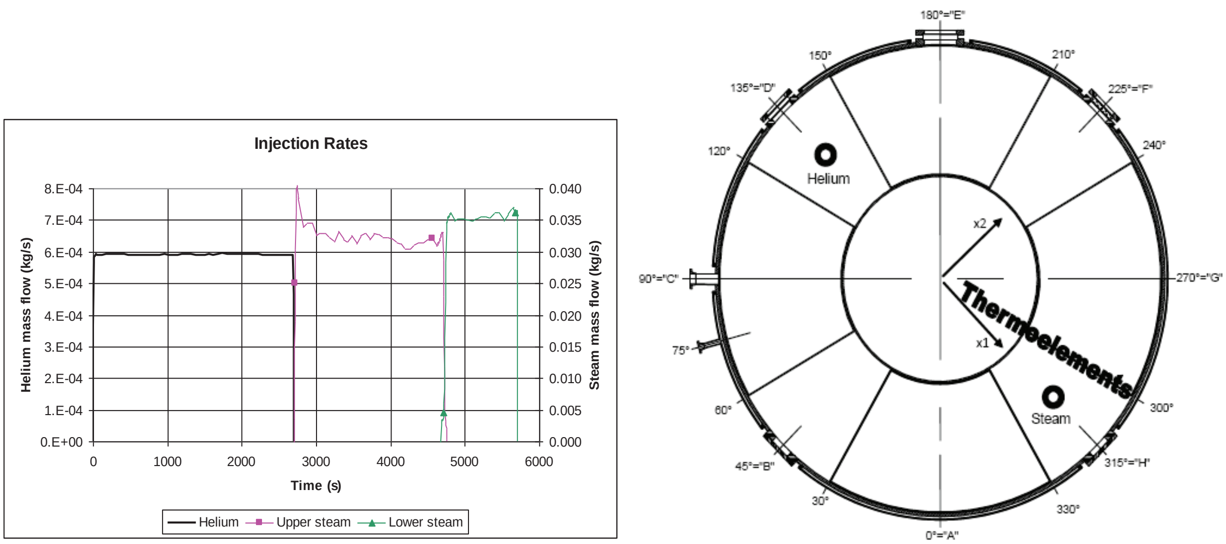

Figure 2. ISP-47 Experimental Injection Rates and locations[3].

The steam injections are saturated or even slightly superheated (depending on the pressure). Saturation enthalpy was recommended for modeling by the experimenters. This allows for GOTHIC to calculate the percentage of flow that is liquid or vapor. The temperature of the helium injection was imported from the available data. The vessel is initially at 22 C (air and structures) and has a pressure of 1.013 bar at 60% relative humidity [3].

4. GOTHIC MODEL DESCRIPTION

The GOTHIC model representing the ThAI facility is shown below in Figure 3. The facility is split up into three subdivided control volumes. Volume 3s represents the outer vessel including the upper and lower heads. Volume 2s represents the inner cylinder. Volume 1s represents the sump. These volumes are subdivided using Cartesian coordinates. This was necessary because GOTHIC only allows for subdivisions in Cartesian coordinates. All volumes are initially three dimensionally rectangular. Blockages which form the facility surfaces are used to more accurately model the facility. A blockage was inserted in the vessel volume where the inner cylinder is located. 3D Connecters were used to connect the open ends of the inner cylinder to the outer vessel. Volumes 4 through 7 represent the condensate trays that collect the condensate from the outer cylinder wall and the inner cylinder inside and outside walls.

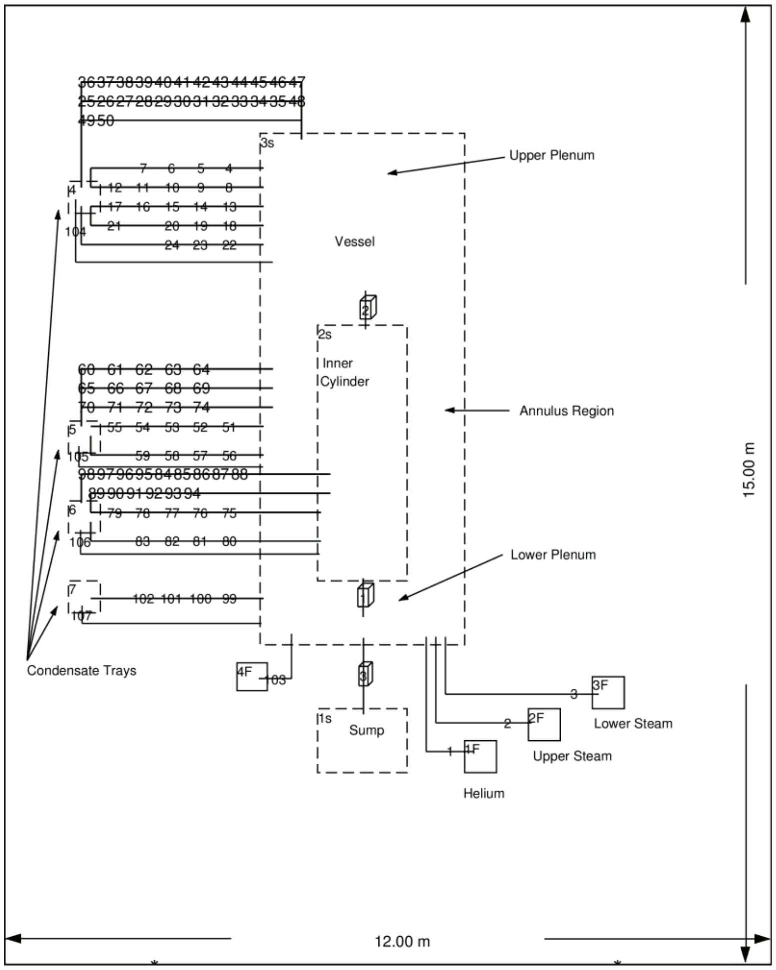

Figure 3. GOTHIC System Model for ISP-47 ThAI Experiment

The facility was modeled using half-symmetry along the 135°-315° axis. This was possible due to the orientation of the injections. The x-axis is defined by the 135°-315° axis. The maximum y-coordinate is representative of the radius of the vessel. Grid lines were chosen to represent any defining features such as the bottom and top of the inner cylinder as well as locations for the injections. Grid lines were added amidst these defining features to further resolve the solution space. The grid spacing is nominally 15 cm in the z-direction and 12 cm in the x and y directions. Closer spacing was used in regions around the injection points as indicated in Figure 4. This allows for GOTHIC to better resolve the jet plume from the injections. The vessel contains 26 nodes in the x-direction, 15 in the y-direction, and 64 in the z-direction. Including cells from the sump, condensate trays, and the inner cylinder, the total cells being modeled is 28,582, including those that are completely obstructed by blockages. The grid lines for the vessel and inner cylinders are shown in Figure 4 and Figure 5.

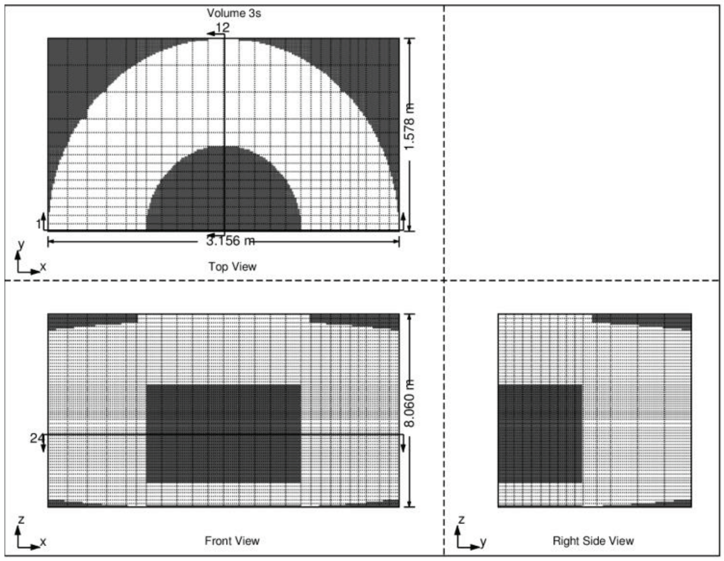

Figure 4. Subdivided Volume Noding for the ISP-47 ThAI Vessel.

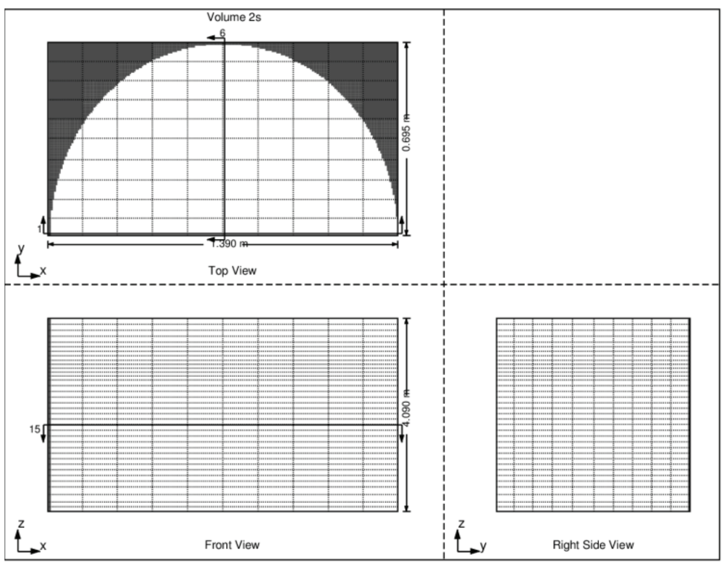

Figure 5. Subdivided Volume Noding for the ISP-47 ThAI Inner Cylinder.

Boundary conditions 1F, 2F, and 3F represent the three different injections relevant to this test. Boundary condition 4F is used to input steam during the helium injection. The steam is injected at 0.16 g/s. The steam is used as a tracer for the Laser Doppler Anemometer (LDA) in the experiment. The quality of the steam that enters with the helium injection is unknown. For steam to be created it must enter at or above the saturation temperature inside the vessel (otherwise it would be liquid). It is reasonable to assume that the steam enters at the saturation temperature.

Features such as the lower and upper heads, the cylindrical wall, and lid area are all modeled by blockages that define these portions of the grid. The structures thermal properties are modeled by using thermal conductors. Thermal conductors represent all of the structures except for the support pieces of the inner cylinder. All conduction is modeled as one-dimensional. All of the external conductors that model the oil filled cooling jackets include 12 cm of mineral insulation as is stated in the test facility description [3].

Many sensitivity studies were performed in an attempt to improve the agreement between the GOTHIC results and the experimental data. Major sensitivity studies performed included grid line spacing, heat transfer options, and injection enthalpy. By varying these inputs (and others) the current GOTHIC model was created. The average run time of this model took between 3 and 5 days to complete.

5. RESULTS

The test results for ISP-47 are from reference [3]. The experimental results are represented by dots in the figures while the lines are the results from the GOTHIC model. Results in GOTHIC were based on locations where experimental data was reported. The graph title line at the top of the graph indicates the measurement station identified in the test description [3].

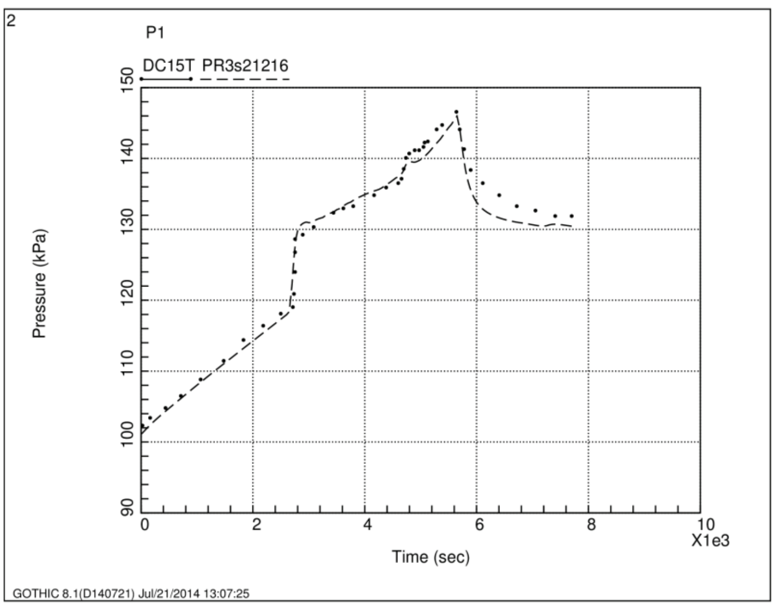

Figure 6. ThAI Vessel Pressure.

Figure 6 shows the pressure response in the vessel. Except for the small departure during the final cool down phase and some inconsistencies during the lower steam injection phase, the GOTHIC results are in good agreement with the data. Figures 7 through 12 are the temperature results.

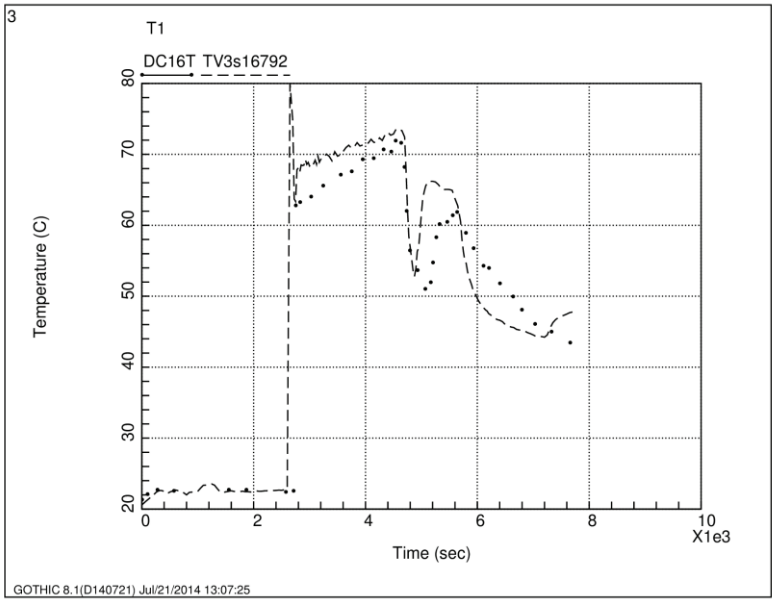

Figure 7. Temperature Above Upper Steam Injection.

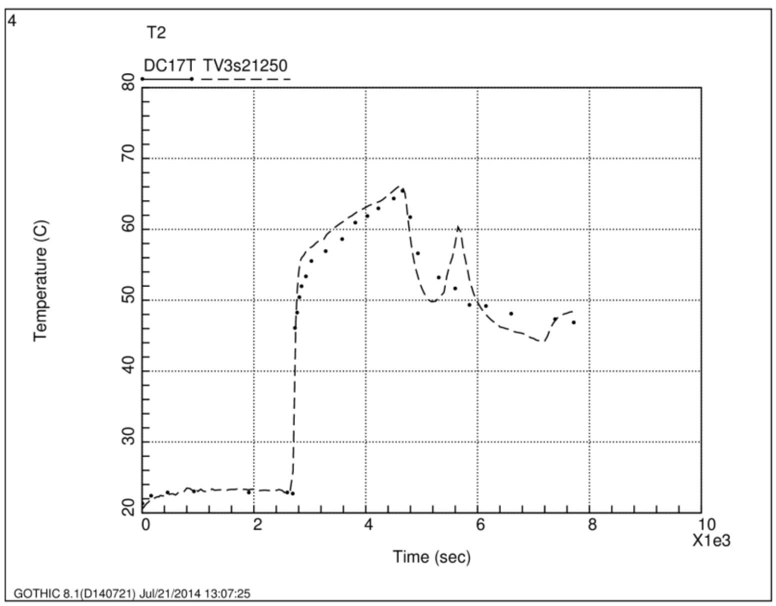

Figure 8. Temperature in Upper Plenum.

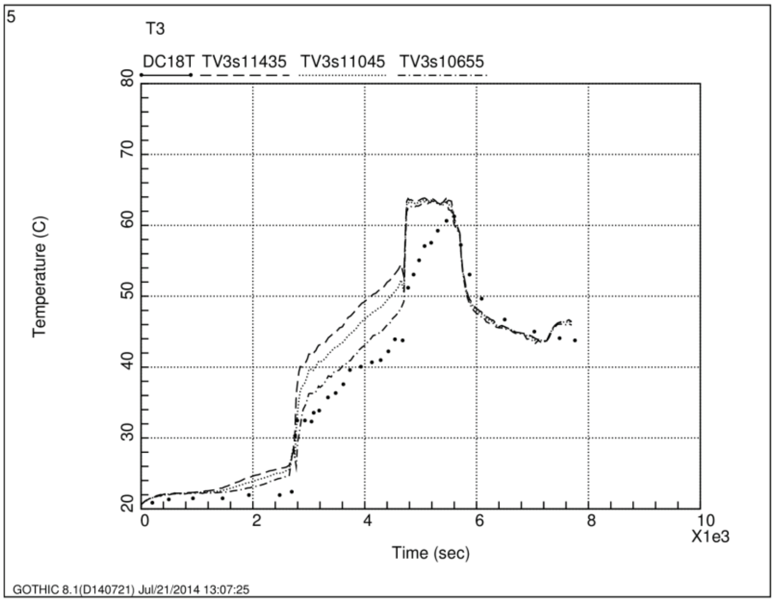

Figure 9. Temperature in Upper Annulus.

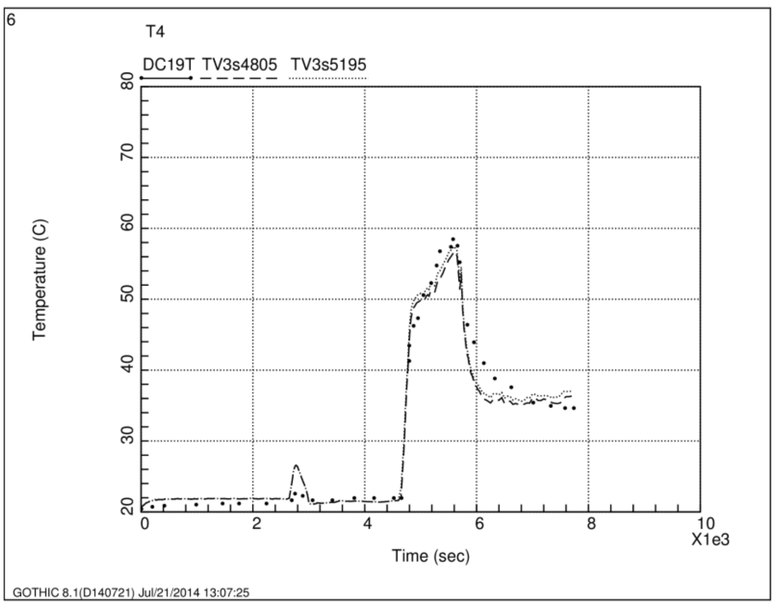

Figure 10. Temperature in Lower Annulus.

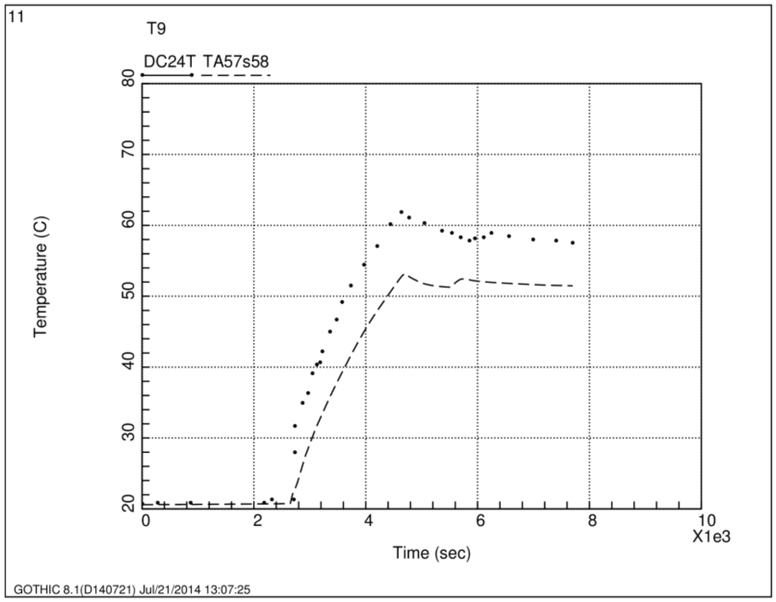

Figure 11. Surface Temperature of Upper Vessel Wall.

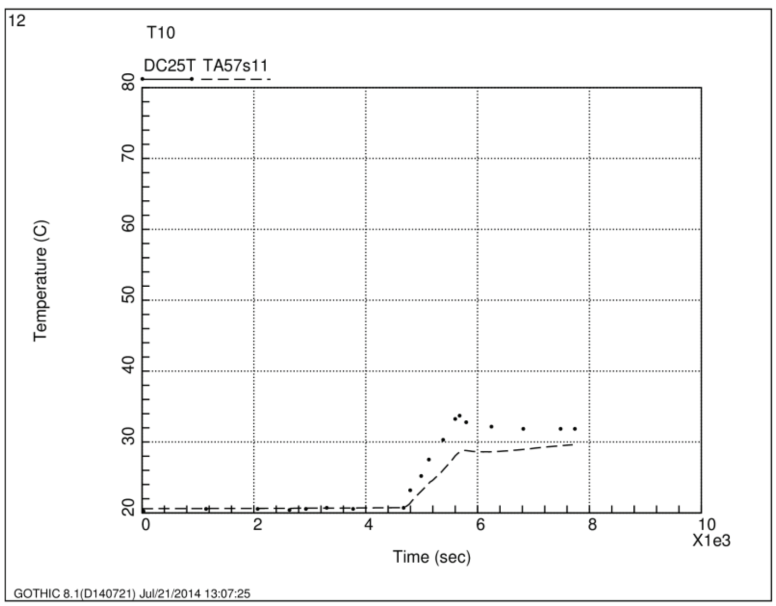

Figure 12. Surface Temperature of Lower Vessel Wall.

Figure 7 through Figure 12 show the various vapor and wall temperatures in the ThAI facility and the corresponding GOTHIC results. In general, the GOTHIC predicted temperatures replicated the trends observed in the experimental data. Some minor deviation in the predicted and measured magnitude exists. In some cases this deviation can be attributed to the data measurement being taken in a region with very large temperature gradients. In those cases, multiple data curves from GOTHIC were plotted. For example, Figure 9 shows the temperature just below the injection point for the upper steam injection. The specified measurement elevation is at the grid line between two cells. Even though the vertical grid spacing in this region is less than 10 cm, it is difficult to resolve the fine details in these steep gradients. Nonetheless, the results show that GOTHIC is able to establish and maintain the observed stratification, although the exact elevation may be shifted slightly. Also to be noted about this graph is the spike in temperature that occurs around 4700 seconds. This is the time the lower steam injection occurs. Discrepancies between GOTHIC and experimental results are related to sensitivity of the system to the lower steam injection. This injection is oriented horizontally inward. The amount of heat that travels to the inner cylinder compared to the amount of heat rising up the annulus region can cause the results to change drastically during this period. Sensitivity studies in the flow split show that helium concentration and temperature in the upper annulus and upper plenum can change drastically with minimal changes to the flow split.

Figure 11 and Figure 12 are the upper and lower vessel exterior wall temperatures, respectively. The upper and lower wall temperature GOTHIC curves are lower than the experimental data. One possible reason for this is the lack of information about the ambient air temperature in the experimental facility outside of the vessel. An estimated heat transfer coefficient was input for the vessel wall to the room. It is possible that more information about this interface could improve the GOTHIC results of this test. Many attempts at resolving this by changing heat transfer options within GOTHIC. The final version of this model utilized the Diffusion Layer Model with Film roughening and heat transfer between the wall and film (DLM-F).

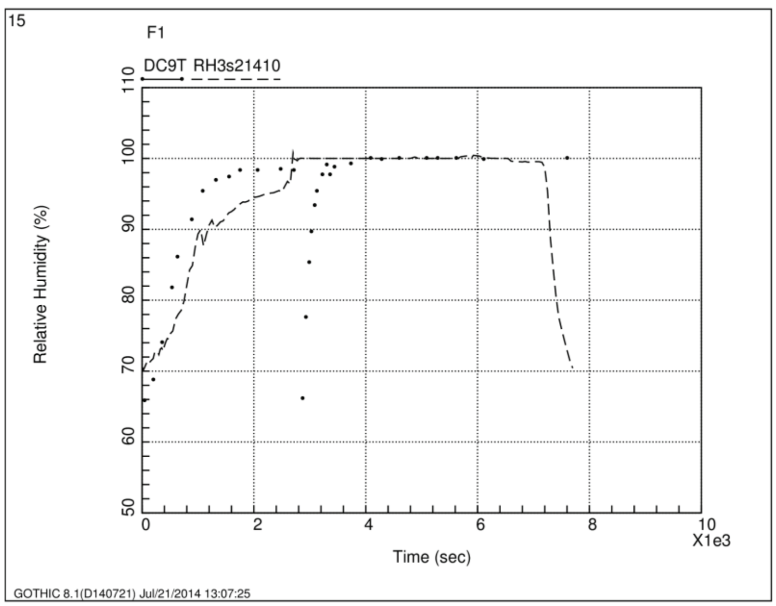

Figure 13. Relative Humidity in Upper Plenum.

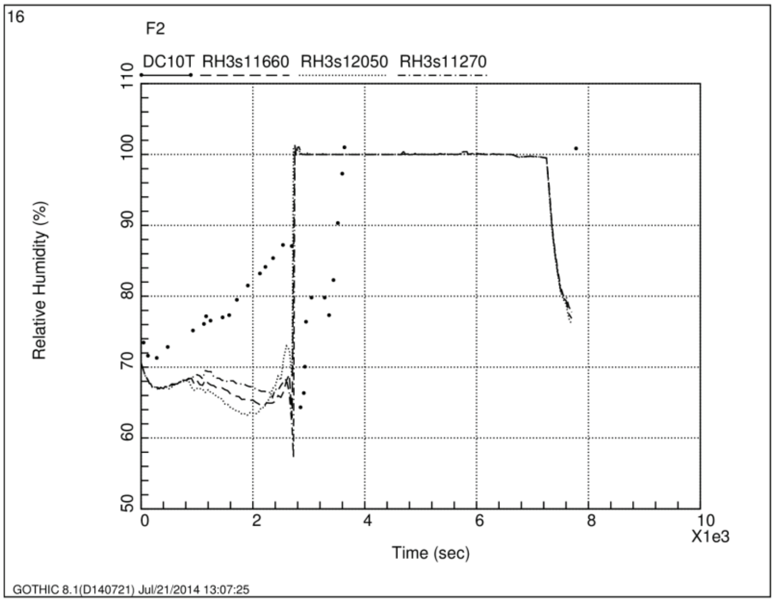

Figure 14. Relative Humidity in Upper Annulus.

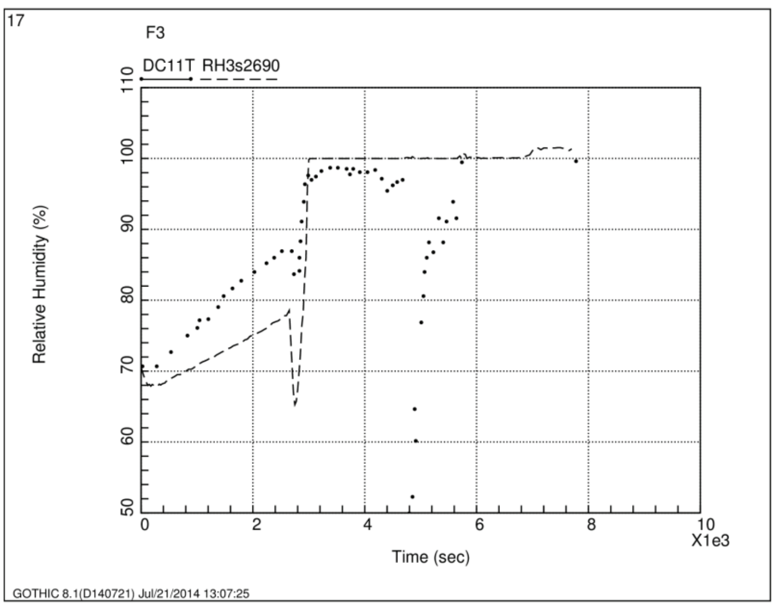

Figure 15. Relative Humidity in Lower Plenum.

Figure 13 through 15 are the humidity results. All three figures show values lower than the experimental data during the first phase. This may be related to the small steam injection during the helium injection. This steam is added to provide particles in the vapor phase to allow tracking with the LDA. The steam condenses in the mixture as a fine mist and travels with the vapor phase. The droplets tend to fall and vaporize when they encounter hot surfaces lower in the vessel. This effect was apparently simulated in the upper plenum at the opposite side of the vessel from the injection tube. However, on the side of the vessel with the tube, GOTHIC did not predict significant drop settling to cause the noted humidity increase. The drop in the relative humidity data at different times throughout the transient (and in various locations) is not understood at this time.

Some of the tracer steam from the helium injection will likely condense on the injection nozzle, possibly resulting in larger drops forming on the piping and falling to the lower elevations. This effect is not included in the GOTHIC model and is one possible explanation for the increase in humidity below the nozzle.

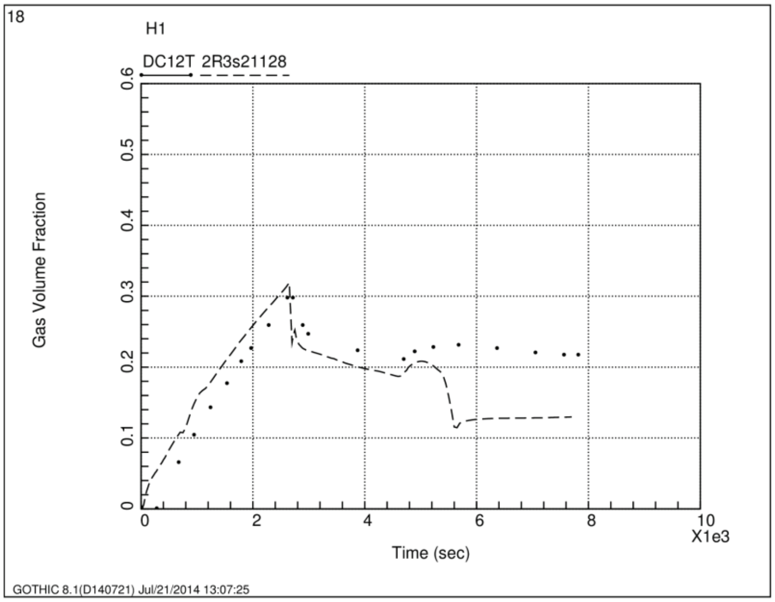

Figure 16. Helium Concentration in Upper Plenum.

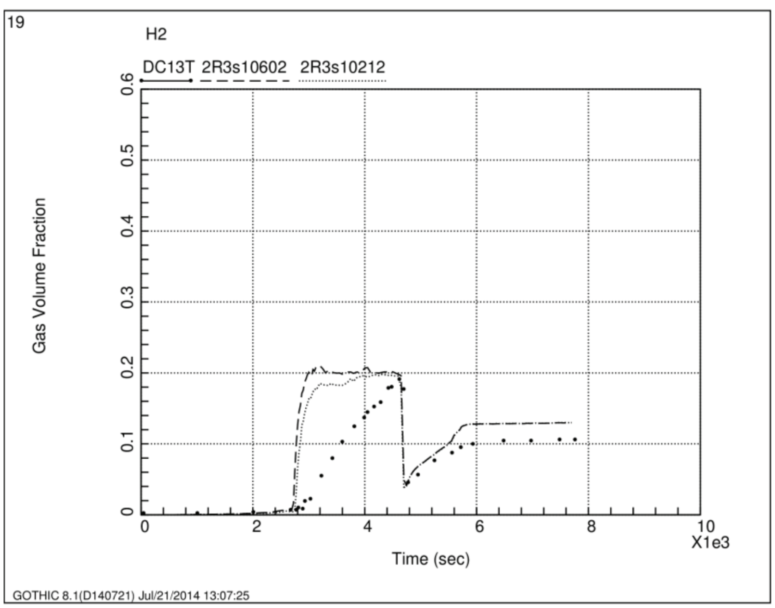

Figure 17. Helium Concentration in Upper Annulus.

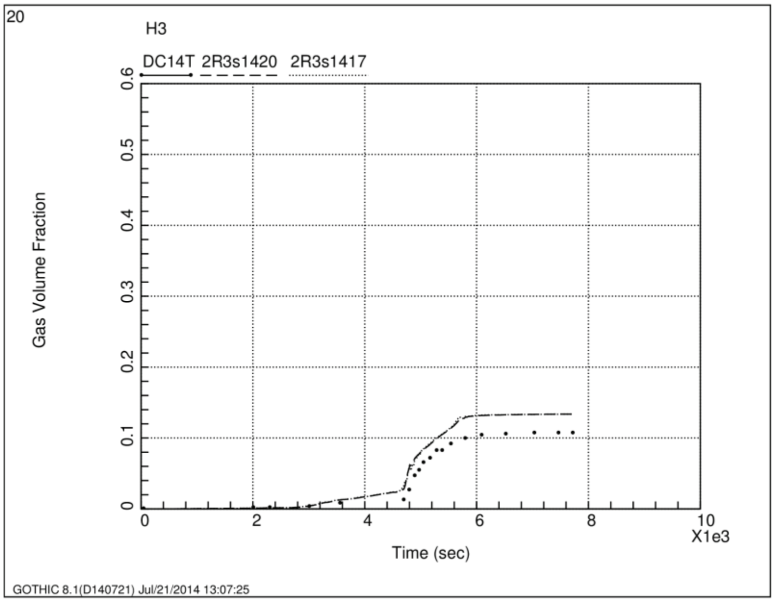

Figure 18. Helium Concentration in Lower Plenum.

The helium concentration in the upper plenum is high at the end of the helium injection in Phase 1. It decreases somewhat during the upper steam injection but the overall vessel atmosphere is still strongly stratified with high helium concentration in the upper dome. The test data in Figure 16 indicates that this stratification persists during the lower steam injection. The GOTHIC results for the helium concentration in the dome are in good agreement for the first half of the lower steam injection. At that time (between 3000 and 4000 seconds), GOTHIC predicts that the stratification is broken up by the plume of hot steam rising up from the lower part of the vessel. The helium concentration in the upper annulus region and lower plenum (compared to the upper plenum) follow the experimental data much closer during the later portion of the transient.

6. CONCLUSIONS

The GOTHIC computer code was used to model the ISP-47 experiment performed at the ThAI facility run by Becker Technologies in Eschborn, Germany. In general, the agreement between the experimental results and GOTHIC results were good with some slight discrepancies in temperature, humidity, and helium volume fraction. The complex geometry of the experiment coupled with the location and timing of the injections causes complex flow fields that are difficult to model. The flow from the lower steam injection gradually rises through the vessel. This steam rises through the inner or outer annulus. The percentage of this flow split seems to be a key factor in resolving the solution.

Several attempts were made to resolve this issue, including grid refinement in the upper plenum and around the lower steam jet and a reduction in the injection enthalpy. These changes did not substantially improve this behavior in the model. The disruption of the stratification layer is also the likely cause of the small under prediction of the system pressure during the final phase of the test. The splitting of the jet/plume from the lower steam injection between the inner cylinder and the annulus could also significantly affect the disruption of the stratification. If more of the steam rises through the inner cylinder, the entire steam plume will spread out more thereby reducing the disturbance of the stratification. The grid around the lower steam jet was refined in the model presented here but it may be possible that even more refinement is needed in this area. For now, it is unclear if the discrepancy is due to a modeling deficiency in GOTHIC, inadequate noding or an unknown feature of the test facility or test operation that is not included in the model. It is known however that the model is highly sensitive to the flow patterns during the lower steam injection.

In conclusion, GOTHIC predictions have reasonable agreement with the ISP-47 experimental results at the ThAI facility. The GOTHIC model captured the stratification of steam and helium accurately on a macro level throughout the experiment. Results could be improved by performing additional iterations on the lower injection steam enthalpy, gridline density, and heat loss to the environment.

ACKNOWLEDGMENTS

This project is being supported by Electric Power Research Institute (EPRI).

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