CONTAINMENT ANALYSIS OF

FUKUSHIMA DAIICHI UNIT 1 POWER STATION USING GOTHIC

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ABSTRACT

This paper is a part of Fukushima Technical Evaluation Project [1, 2 and 3] which investigates various aspects of the Fukushima Daiichi event using the GOTHIC[1] code [4]. The project was founded by Electric Power Research Institute (EPRI) and intended to support and augment analysis of the event using the MAAP5 computer code [5]. The analysis takes advantage of the capability of GOTHIC to model certain aspects of the system geometry and behavior in more detail than typically considered in containment performance analysis. GOTHIC is a general purpose thermal hydraulics code that is used extensively in the nuclear industry for system design support, licensing support and safety analysis. It has the capability to model 3-dimensional flow behavior including the effects of turbulence, diffusion and buoyancy [4]. This allows GOTHIC to be used in cases where mixing effects and stratification are important.

The analysis presented here considers the events at Fukushima Daiichi Unit 1 (1F1) following the tsunami and leading up to the time of the hydrogen detonation in the 1F1 Reactor Building. The 1F1 MAAP5 Baseline Scenario [5] is used to define the steam, hydrogen and carbon-monoxide source terms from the primary system and the core concrete interaction. The model incorporates three dimensional modeling of the drywell (DW), wetwell (WW) and connecting vent system that can predict the 3-dimensional flow patterns and the temperature and gas distributions. The model also includes leakage to the surrounding reactor building and the wetwell vent to the stack.

The 3D containment model includes models for the heat transfer from the steam and gas in the drywell vent system to the torus room, wetwell gas space and pool. Inclusion of vent heat transfer had a significant impact on the overall containment response for the 1F1 scenario, particularly during the steam and hydrogen release from the primary system following the postulated failure of reactor vessel. Condensation in the vent system reduced transfer of noncondensing gases to the wetwell resulting in lower containment pressure and higher gas concentrations in the drywell.

KEYWORDS

GOTHIC, Fukushima Daiichi Unit 1, Containment Analysis, Vent Heat Transfer, Gas Mixing

1. INTRODUCTION

A typical Mark I containment consists of vent pipes that are open one end to the drywell and the other into the wetwell pool. When the pressure increases in drywell, the steam and gas mixture can transfer from drywell to wetwell through vent pipes and exchange heat from the vent pipe walls to the torus room and wetwell gas space. The objective of this task is to investigate the impact on the calculated containment behavior when multidimensional effects and vent heat transfer details are included in the analysis. The investigation began with construction of a multidimensional GOTHIC model that includes

[1] GOTHIC incorporates technology developed for the electric power industry under the sponsorship of EPRI, the Electric Power Research Institute

subdivided volumes for the wetwell, drywell and vent system. The detailed model was then reduced to a lumped model that is comparable to the MAAP5 model. The lumped model relies on mass and energy source terms calculated by MAAP5 for the steam, H_2 and CO released to the drywell, and the heat flux from the Reactor Pressure Vessel (RPV) to the drywell. With some minor adjustments to the MAAP5 source terms results comparable to those from MAAP5 were obtained.

It is important to recognize that the objective is this analysis is to determine the sensitivity of results to different modeling assumptions within the GOTHIC modeling capabilities. There was no intention in comparing GOTHIC results to MAAP5 results for predictive capabilities. The comparisons with the MAAP5 results are included only to show that the assumed scenario is in reasonable agreement with the MAAP5 analysis for the 1F1 event and establishes the GOTHIC baseline model for the sensitivity studies.

Using the GOTHIC lumped model as a baseline for comparison; the effects of multidimensional behavior in the drywell and vent heat transfer were investigated with the subdivided model. The analysis presented here takes advantage of the capability of GOTHIC to model certain aspects of the system geometry and behavior in more detail than typically considered in traditional containment analysis.

As a result of the seismic event, a tsunami inundated the station (41 minutes after the earth quake). Following the arrival of the tsunami and flooding of the 1F1 turbine building, a Station Blackout (SBO) started 55 minutes from the time of the earthquake with a loss of all the alternating current (ac) power and direct current (dc) power circuits. Because power was not restored to the 1F1 control, core cooling was lost for a significant period of time [1]. According to MAAP5 baseline scenario [5], the following assumptions are made in GOTHIC baseline analysis:

1. No RPV seal leakage is assumed to occur.
2. Steam leak (around 1 hour in to the event) and H_2 leak (around 4 hours into the event) through the in-core instrument structures are assumed to occur (Figure 2 (a), (b)).
3. RPV depressurization through Safety Relief Valves (SRV) starts around 6 hours into the event
4. RPV lower head failure occurs around 9 hours into the event (Figure 2 (c), (d)).
5. Leakage from the Pressure Containment Vessel (PCV) occurs through the drywell head gasket. Drywell head lifting starts around 12 hours into the event, with an assumed leakage area of about 10 cm^2 (1.55 in^2).
6. Venting of the Suppression Chamber (SC) to the environment is assumed to occur around 24 hours into the event and continues until drywell pressure falls to ~ 520 kPa (75 psia).

The MAAP5 calculated drywell pressure is shown in Figure 1 with the recorded pressure. The calculated progression of core damage results in earlier containment pressurization than indicated by the measured pressure but, overall, the containment response is closely matched [5]. It must be recognized that there are many unknowns and uncertainties in this analysis and the good agreement with the recorded data is achieved by adjusting the unknown inputs within reasonable limits. Figure 2 (a), (b), (c) and (d) show the MAAP5 total gas (Steam, H_2, and CO) and heat release from RPV to drywell predictions respectively [5]. These predictions are used as inputs to model the RPV response in the GOTHIC models.

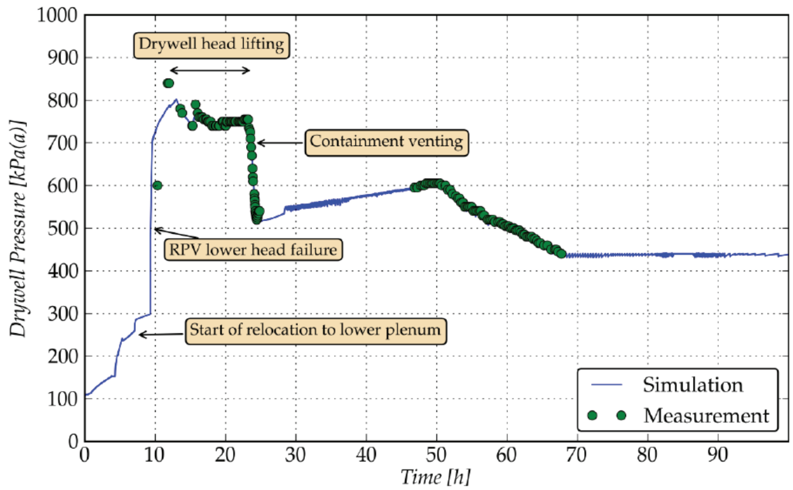


Figure 1: 1F1 MAAP5 Baseline Scenario—Simulated Drywell Pressure Transient [5]

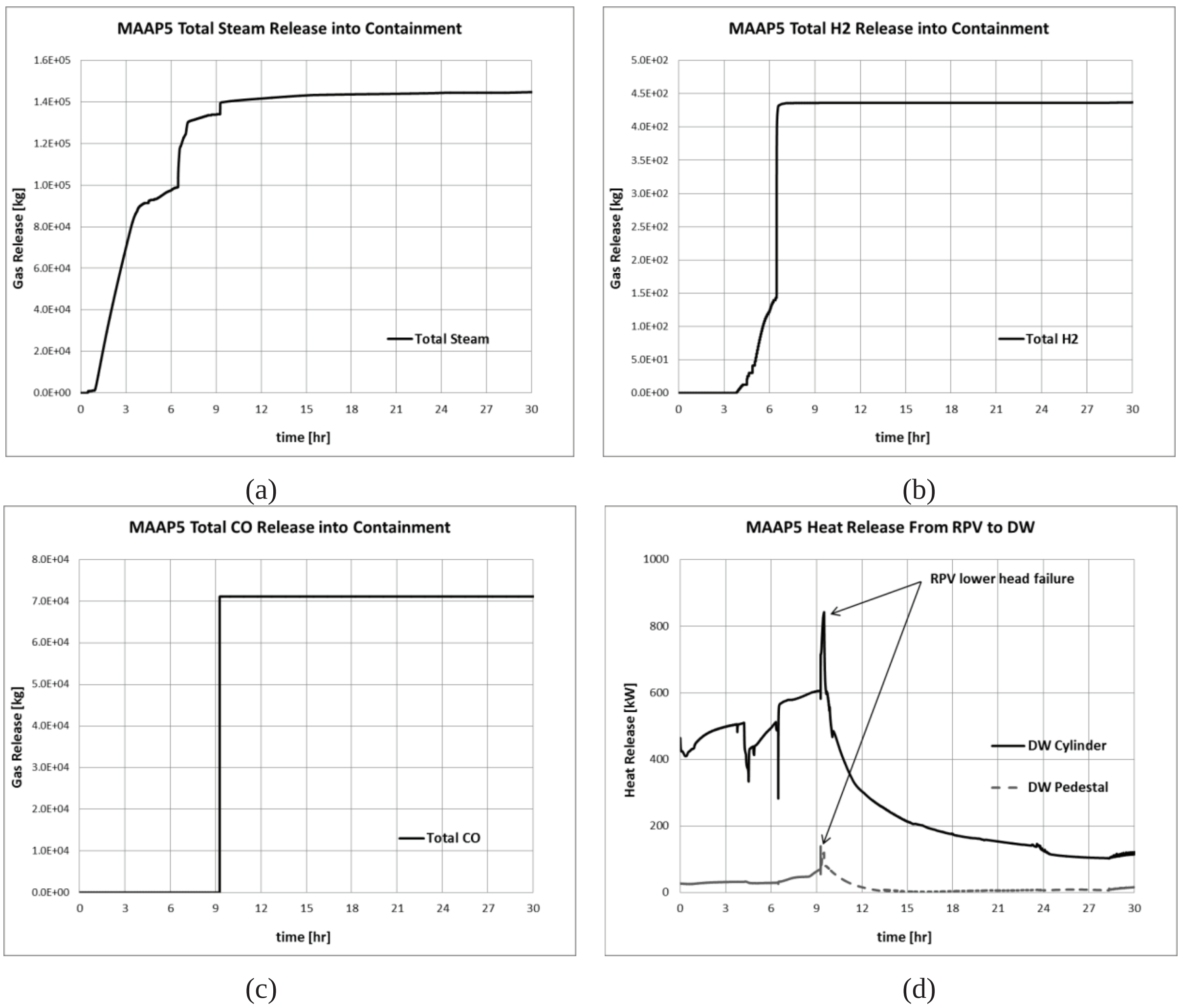


Figure 2: 1F1 MAAP5 Baseline Scenario, Total Gas Release (Steam (a), H_2 (b), CO (c)) and Heat Release (d) from RPV [5]

2. GOTHIC BWR CONTAINMENT MODEL

GOTHIC Version 8.1 [4] was used to model the 1F1 containment system. The multidimensional model for the containment is described below. The containment model is designed to address drywell mixing and the heat transfer between the drywell vent system and the wetwell during the postulated 1F1 scenario. The scope is limited to the containment response and does not include prediction of the fuel or RPV response. The MAAP5 1F1 baseline simulation of the event is used to provide input to the GOTHIC model for to the steam, H_2 and CO release and heat transfer from the RPV to the containment (Figure 2). A graphical representation of the GOTHIC model is shown in Figure 3 with pertinent information for the GOTHIC volumes shown in Table 1.

In order to reduce the runtime of the multidimensional simulation, a 1/8 sector of the total containment geometry is modeled using an assumed 3D axisymmetric treatment of a generic Mark 1 containment geometry. The geometric parameters of the model are consistent with the Unit 1 measurements [1]. Other unknown parameters, such as the SRV T-quencher geometry, are estimated from the Monticello plant Mark I design [6].

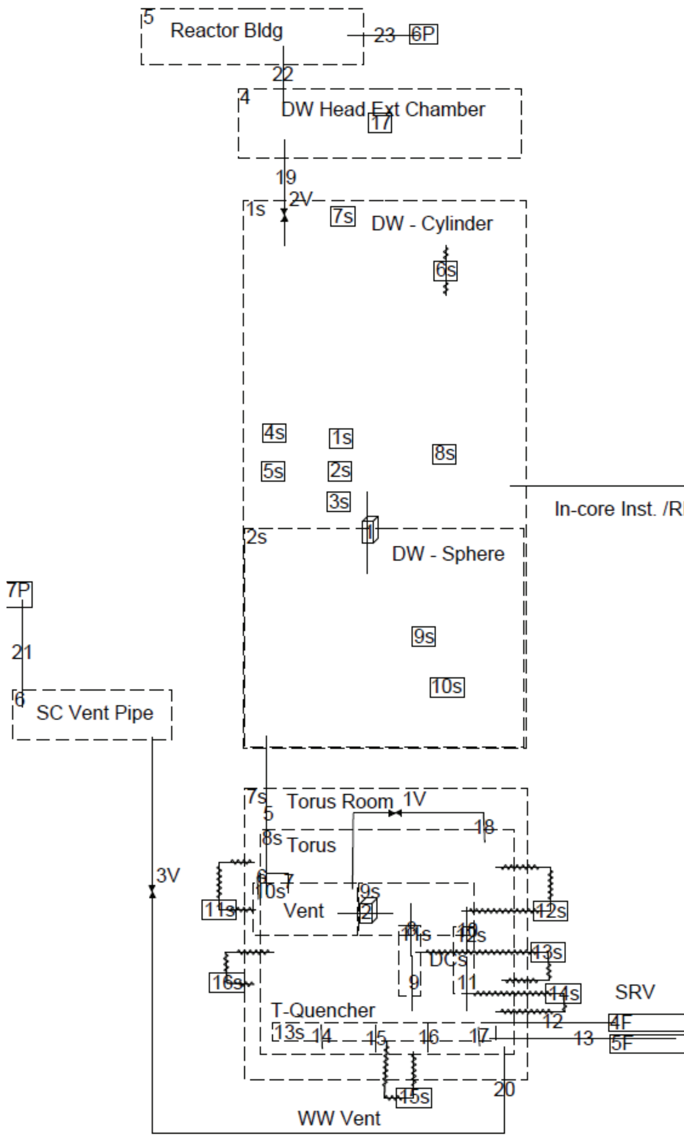


Figure 3: 1F1 Containment Noding Diagram

Table 1: Unit 1 Volume Data

Volume 1	DW Inner Cylinder
Volume 2	DW Outer Sphere
Volume 3	RPV Leak Mix Volume
Volume 4	DW Head Exit Chamber
Volume 5	Reactor Building
Volume 6	Suppression Chamber Vent Pipe
Volume 7	Torus Room
Volume 8	Torus Tube
Volume 9	Vent inside Torus Tube
Volume 10	Vent Inside Torus Room
Volume 11	Inner Downcomers
Volume 12	Outer Downcomers
Volume 13	T-quencher

2.1 Drywell Model Description

A subdivided drywell model was constructed for a 3D representation of the cylindrical and lower spherical portions of the drywell including the RPV, bioshield wall, and major flow paths for natural circulation that exist within the drywell. The important aspects of the drywell model are listed as follows:

1. The drywell model is divided into a central cylindrical volume (Volume 1s), representing the interior cylindrical volume from the drywell top to bottom (including the pedestal region), and a volume representing the outer spherical portion of the lower drywell (Volume 2s). These two volumes are subdivided with sufficient detail to model the natural circulation paths within the drywell. The inner and outer drywell volumes are connected via a 3-D flow connector, allowing unrestricted flow between the inner and outer portions of the lower spherical portion of the drywell.
2. As shown in Figure 4, blockages represent the RPV and Main Steam piping within the DW as well as the bioshield wall supporting and surrounding the lower RPV. The approximate 8 inch gap between the RPV and the bioshield wall may create a potential chimney effect as the hot vessel heats the surrounding air that would enhance mixing in the drywell by buoyancy driven flow. However, in some Mark I containment designs, there is a skirt at the bottom of the bioshield annulus that effectively blocks flow into the annulus from below. Annulus details were not available for 1F1. As shown in Figure 4, the annular opening is assumed to be blocked by a thin plate from the pedestal region. Therefore, the annulus is open to the drywell at the top, but not at the bottom. This assumption will tend to reduce the drywell mixing by natural convection.

3. Shell conductors 1, 2 and 3 are assigned to RPV blockages, providing a heat source for the upper DW cylindrical region, lower DW spherical region and bottom pedestal region, respectively. For the GOTHIC lumped model analysis, the MAAP5 baseline simulation heat flux results (Figure 2 (d)) were used to specify the heat flux on the RPV side of the conductor. In the subdivided model analysis, however, the local RPV heat flux varies as the DW gas temperature changes in each region. Thus, the uniform heat flux assumption is not appropriate in subdivided models. Instead, the conductor surface temperatures that were obtained from the lumped model were specified as input for the RPV side of the conductors in the 3D model.

4. The convective heat transfer from the main steam lines and recirculation lines to the drywell is modeled using conductors 4 and 5 located at appropriate positions within the drywell. The heat sources are modeled with multi-region conductors including an interior metal wall, estimated air gap (5.08 cm (2 in)) and an insulation layer. In the lumped model, an estimated constant 287 C (550 F) internal temperature is used as boundary condition for conductors 4 and 5. In the subdivided model, the internal temperature of the RPV side of the conductor 1 is used as a boundary condition for conductors 4 and 5.

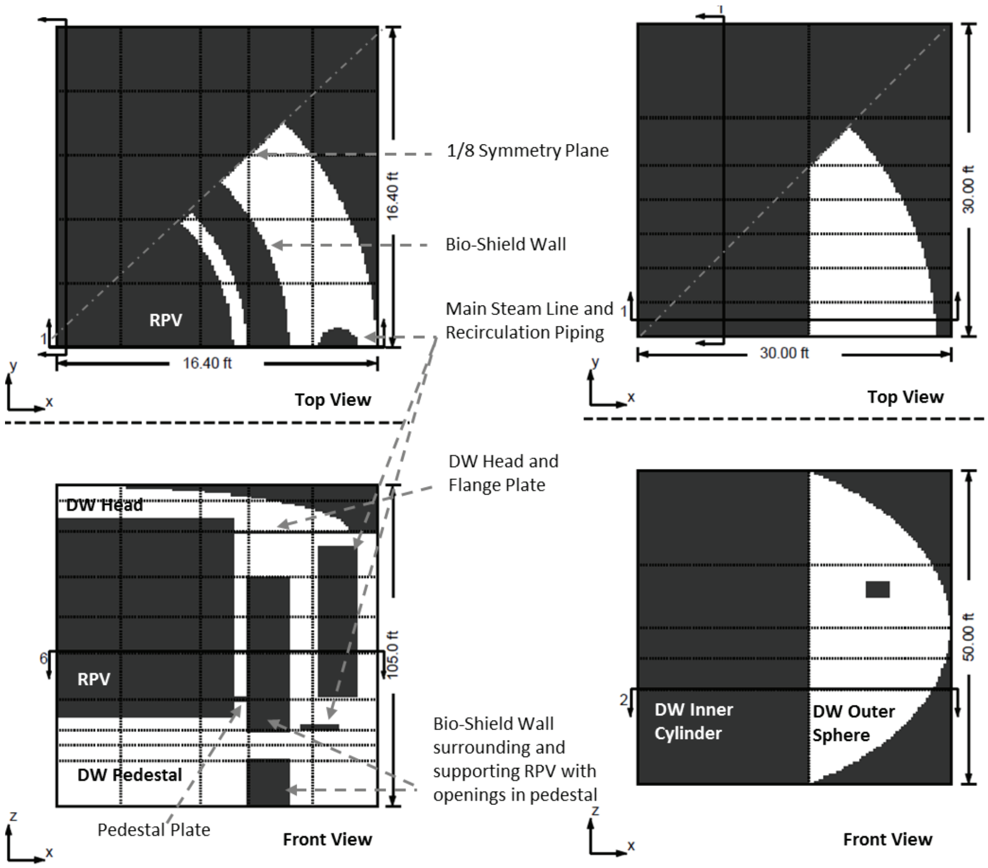
5. The drywell metal liner for the cylindrical and spherical regions is modeled by conductors 8 and 9, respectively. It is assumed that the material for the metal liner includes a 5.08 cm (2 in) air gap between the steel and the structural concrete that is several feet thick. Convective heat loss to the ambient air is assumed for the outside surface of this conductor.

6. Boundary conditions (1F, 2F and 3F) and flow paths (1, 2, 3 and 4) are included to simulate the postulated sources for steam, H_2 and CO to the drywell. In the MAAP5 analysis, the early release is from an assumed leak through the in-core instrument structures (4 hours into the event). The later sources follow the RPV lower head failure (9 hours into the event) (Figure 2 (c), (d)). It is assumed that for all of these sources that the release occurs inside the RPV support pedestal.

7. Valved flow path (19) is included to simulate the postulated leak from the drywell flange to the Refueling Pool Compartment in the Reactor Building when the DW head lifting starts (12 hours into the event).

8. In the subdivided model, the DW head region above the RPV is modeled as shown in Figure 4. The cylindrical region is separated from the head region with a thin flange plate. The heat transfer through the flange plate is modeled with external conductor 6. There is a 0.9 m (3 ft) diameter open manway in the plate. This opening is assumed as the only flow passageway from the cylindrical region to the upper head region. The opening is assumed to be located in the modeled 1/8 sector of the drywell. Therefore, the opening size, relative to the modeled dome region is overly large and the calculated mixing between the dome region and the lower drywell may not be as much as indicated in the GOTHIC analysis.

9. The drywell dome metal liner is modeled by thermal conductor 7, including a 1.5 m (58.5 in) air gap between steel and concrete layers. The surface-to-surface radiation across the air layer is included in the GOTHIC model.



(a) (b)

Figure 4: 1F1 Inner DW Cylinder Volume 1s (a) and Outer DW Sphere Volume 2s (b)

2.2 Wetwell Model Description

The wetwell model consists of seven individual subdivided volumes that are connected to each other with 3D connecters and flow paths. To calculate the steam condensation inside the vent and its potential impacts on steam and noncondensable gas flow into the suppression pool, each system is modeled individually in detail as described below:

1. The Torus model is divided into two main sections; the Torus Room (Volume 7s) which represents the concrete and air space surrounding the vent and torus, and the Torus Tube (Volume 8s). A graphical representation of the Torus and Torus Room is shown in Figure 5 (a) and (b) respectively. The average vertical grid spacing both in the suppression pool is 0.33 m (1.1 ft) and gas space above the pool surface is 1.25 m (4.1 ft). The grid spacing across the torus minor diameter is 1.25 m (4.1 ft). It should be noted that the grid spacing inside the torus is fine enough to investigate the vent and downcomer heat transfer effect but it is too coarse to accurately predict the stratification inside the suppression pool.

2. The vent system is modeled with two subdivided volumes; one inside the Torus Tube (Volume 9s) and one inside the Torus Room (Volume10s). Flow paths from the outer spherical portion of the drywell model represent the main vent lines from the drywell to the Vent Ring Header pipe that resides in the wetwell gas space and distributes the steam/gas/liquid flow from the drywell around the circumference of the suppression pool during a LOCA. The Torus Room Vent and Torus Tube Vent volumes are connected via 3-D flow connectors.

3. There are 40 inner downcomers and 40 outer downcomers in the 1F1 DW system [1]. Based on the 1/8 axisymmetric modelling approach, 5 downcomers are modeled by each of Volumes Volume 11s and 12s for the inner and outer downcomers, respectively.
4. Volume 13s represents the T-quenchers near the bottom of the pool. The Monticello Nuclear Plant [6] was used for the geometric parameters.
5. Shell conductors (11, 12, 13, 14 and 15) are assigned to the blockages inside each subdivided volume to model the heat transfer across the vent system to the torus room, torus air space and pressure suppression pool.
6. Flow path 18 and the associated valve model the vacuum breaker (VB) line from the wetwell into the drywell via the drywell vent header.
7. Flow path 20 and associated valve models the manual wetwell venting operation performed at about 24 hours into the event at 1F1.

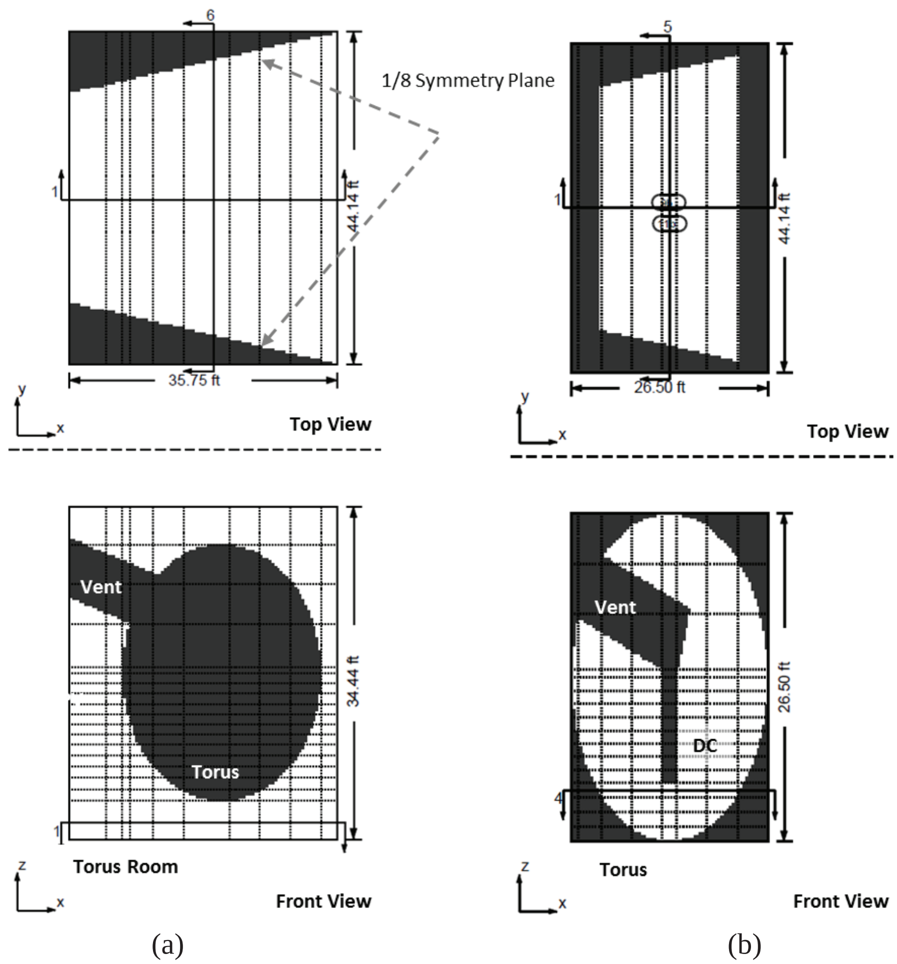


Figure 5: 1F1 Torus Room Volume 7s (a) and Torus Volume 8s (b)

3. GOTHIC BASELINE MODEL RESULTS

The following discussion compares the GOTHIC lumped model results against the results from the MAAP5 1F1 baseline scenario analysis. Then, the relative effects of drywell mixing and vent heat transfer are investigated by comparing the subdivided model results with the lumped GOTHIC model results.

3.1 1F1 Lumped GOTHIC Model without Vent Heat Transfer

Before investigating the multidimensional and vent heat transfer effects, a lumped GOTHIC model was created for the containment that is comparable to the MAAP5 model. This lumped model serves as a baseline for investigating multidimensional and vents heat transfer effects.

The 1F1 Lumped GOTHIC model was generated from the detailed subdivided model nodalization (Figure 3). Each subdivided volume was reverted to a lumped volume, preserving the net free volume. The vent system heat transfer was deactivated. Similar to the MAAP5 nodalization, the DW head and DW upper cylindrical regions are represented by Volume 1, and DW pedestal and DW lower spherical regions are represented by Volume 2. By doing so, the MAAP5 calculated heat fluxes (Figure 2 (d)) from the RPV could be used as boundary conditions in the lumped GOTHIC model.

In order to achieve agreement between the MAAP5 and GOTHIC lumped model results, especially during RPV lower head failure, some adjustments to the specified release rates from the MAAP5 analysis were made. The flow rate functions are defined based on MAAP5 total amount of steam and noncondensable gas predictions. The total steam release during vessel breach was tuned (about 10% more than MAAP5) to match the containment pressure response. In Figure 6, the DW and WW pressure response calculated by GOTHIC is compared to the MAAP5 results. The agreement between these two models provides reasonable confidence that the major components of the GOTHIC 1F1 containment model as well as the basic elements of the accident scenarios are appropriately addressed in the GOTHIC lumped model.

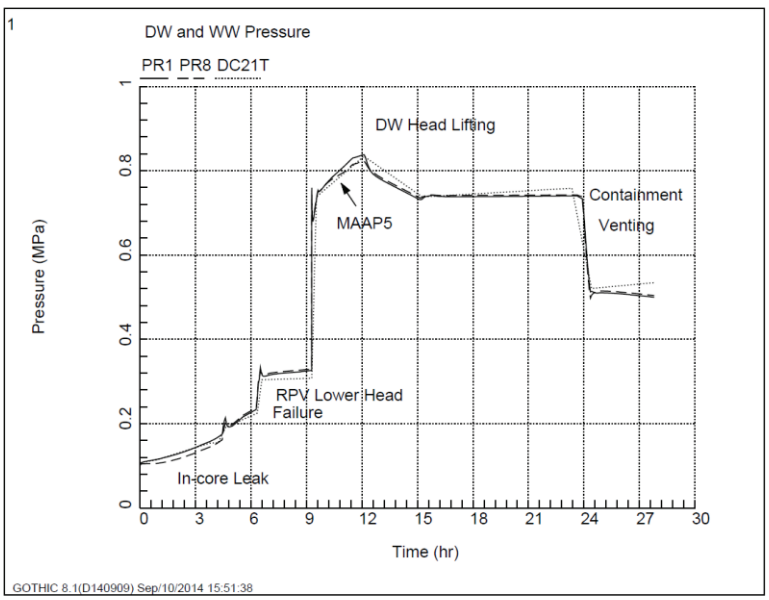


Figure 6: GOTHIC Lumped Model, Containment Pressure

3.2 1F1 Subdivided 3D GOTHIC Model with/without Vent Heat Transfer

The subdivided GOTHIC model was used to investigate the localized gas concentrations, the temperature distribution and the containment pressure response. This model and scenario are identical to the 3D model described in Section 3.1 except that the heat transfer between the drywell vent system and the wetwell gas space is included. Figure 7 shows the subdivided GOTHIC containment pressure response in DW and compares it with the subdivided model without the vent heat transfer. The pressure predictions agree until the RPV lower head failure at about 9 hours into the event. After the vessel breach, the inclusion of vent heat transfer results in lower containment pressure.

Compared to the lumped model, a larger pressure spike is calculated by the 3D drywell model during the vessel breach. This is due to the very rapid release of steam into lower DW resulting in a clearing of the DW to WW vents and gas flow into the WW. The 3D model includes the effects of the details of the inertia of the water in the vent system and the WW pool swell caused by the incoming gas. The pool swell increases the WW gas space pressure and the DW pressure is correspondingly higher due to the inertia of the water in the vent. Although the vent water inertia can be modeled by close attention to the user specified inertia lengths for the flow connections, there was no attempt to do so in the lumped model. Also, the lumped model cannot capture the pool swell effects. The calculated pressure spike in the 3D model is likely to be more consistent with the actual behavior.

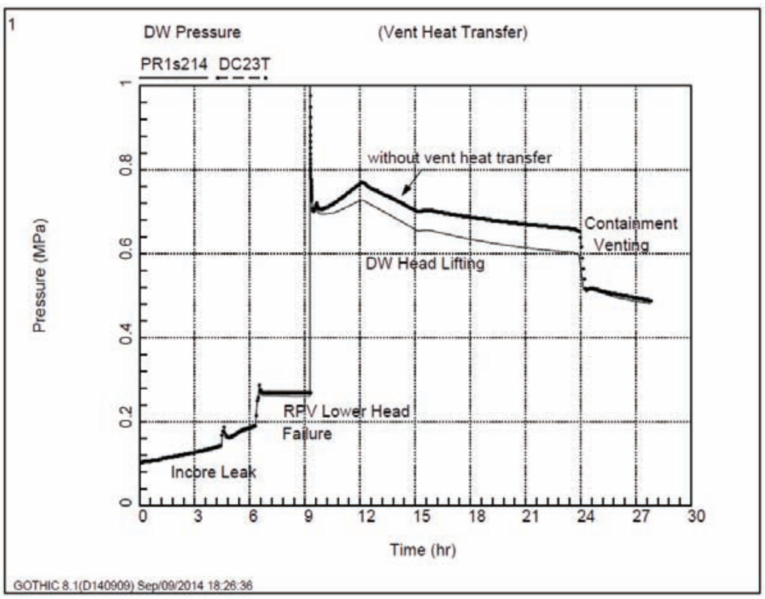
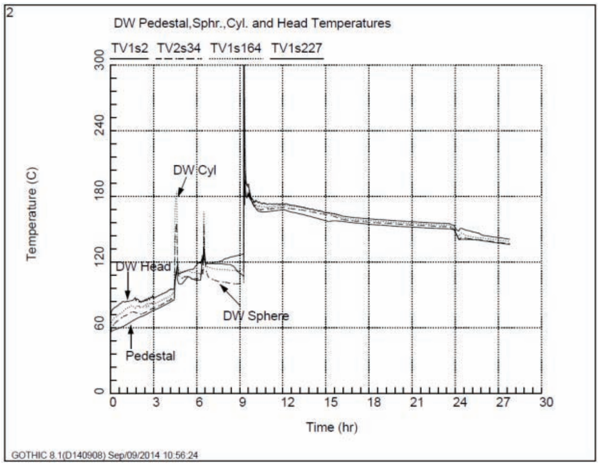


Figure 7: 3D Model, DW Pressure with/without Vent Heat Transfer (VHT)

Figure 8 shows the DW temperatures at different elevations without the vent heat transfer. The DW is generally well-mixed (thermally) with some modest variation during the initial heat up. Between 6-9 hours, the DW sphere region temperature is low due to the increase in gas flow from WW through VB (Figure 9). Before the RPV lower head failure occurs around 9 hours, the averaged DW temperature difference between pedestal and head regions was around 11 C (20 F).

Comparing Figure 10 to Figure 8, the heat transfer across the vent does not have a significant impact on DW temperature. However, as shown in Figure 11, vent heat transfer does result in increased WW gas space temperature. Even though, the WW gas temperature has a direct relationship to the containment pressure response, the temperature increase effect was more than offset by a reduction in gas transfer to the WW as described below.



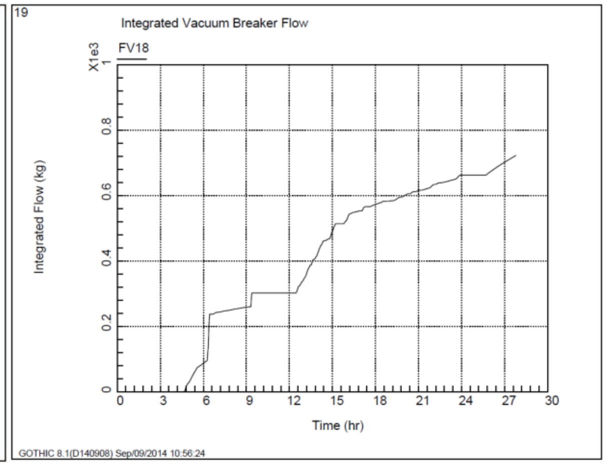
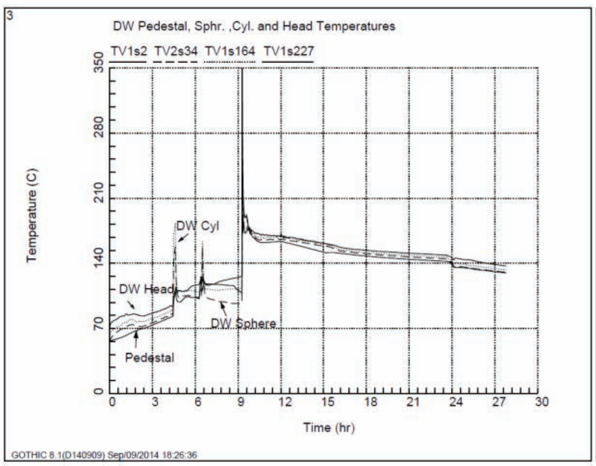


Figure 8: DW Temperature without VHT

Figure 9: Integrated VB Flow without VHT



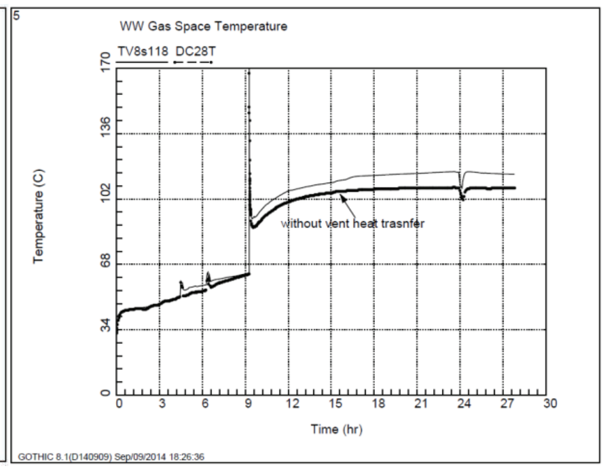
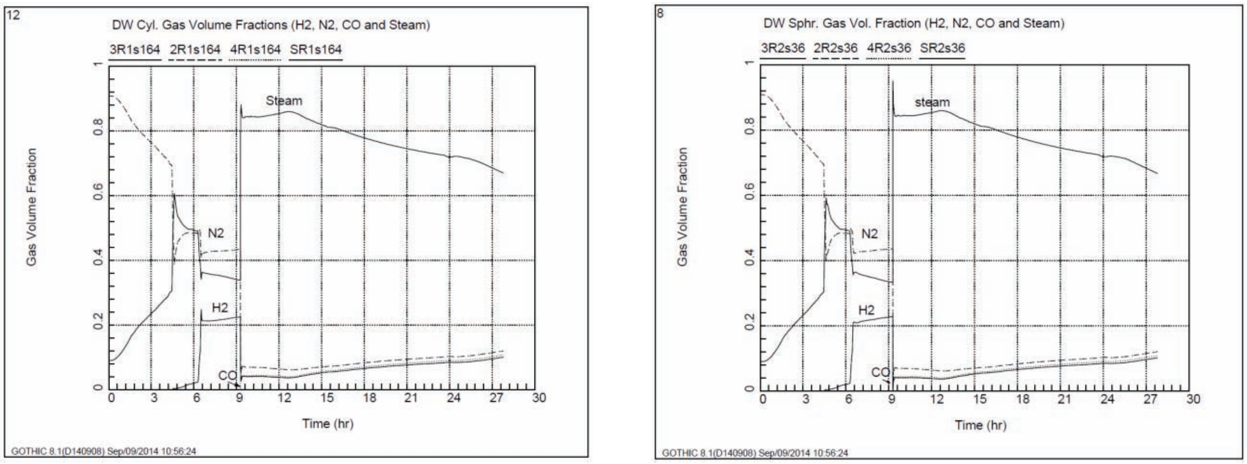


Figure 10: DW Temperature with VHT

Figure 11: WW Gas Temperature with/out VHT

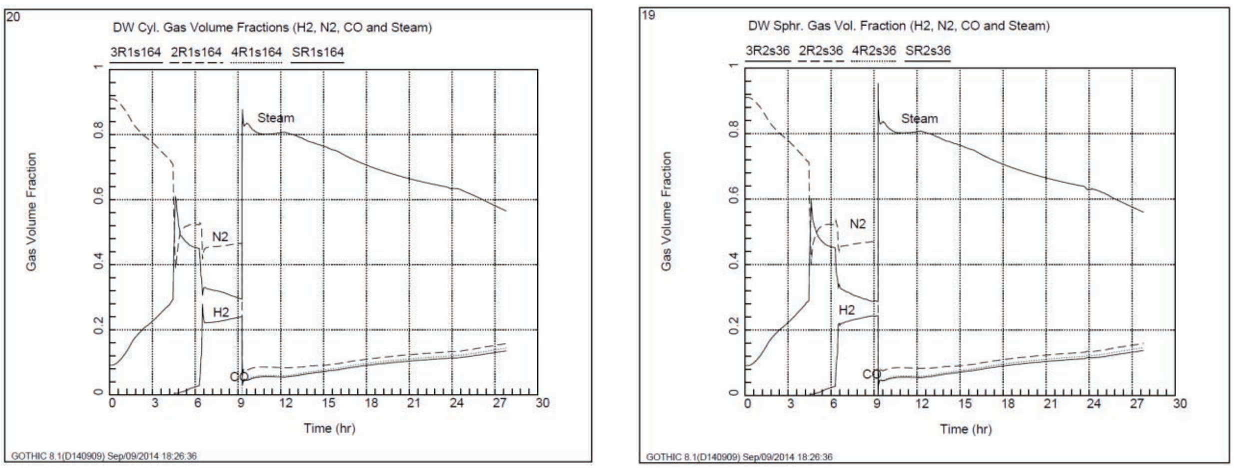
Figure 12, Figure 13 present the steam and noncondensable gas distribution within the DW cylindrical region and spherical region, without and with vent heat transfer, respectively. In both cases, the gas concentrations in the DW are generally uniform with lower steam and H_2 concentrations and higher in N_2 before the RPV failure. After the vessel breach (t= 9 hours), however, vent heat transfer does result in a decrease in the steam concentration inside the DW.

Figure 14 shows that the calculated gas concentrations in WW gas space are similar in the two cases. However, even though both models give similar gas concentration in WW the lower pressure in the case with vent heat transfer indicates less gas transfer from the DW to the WW. Figure 15 (a) shows that the total amount of gas transferred from DW into WW through the vent system is reduced when vent heat transfer is included. In addition, Figure 15 (b) shows a continuous liquid flow through the vent, indicative of the condensation that occurs in the vent.



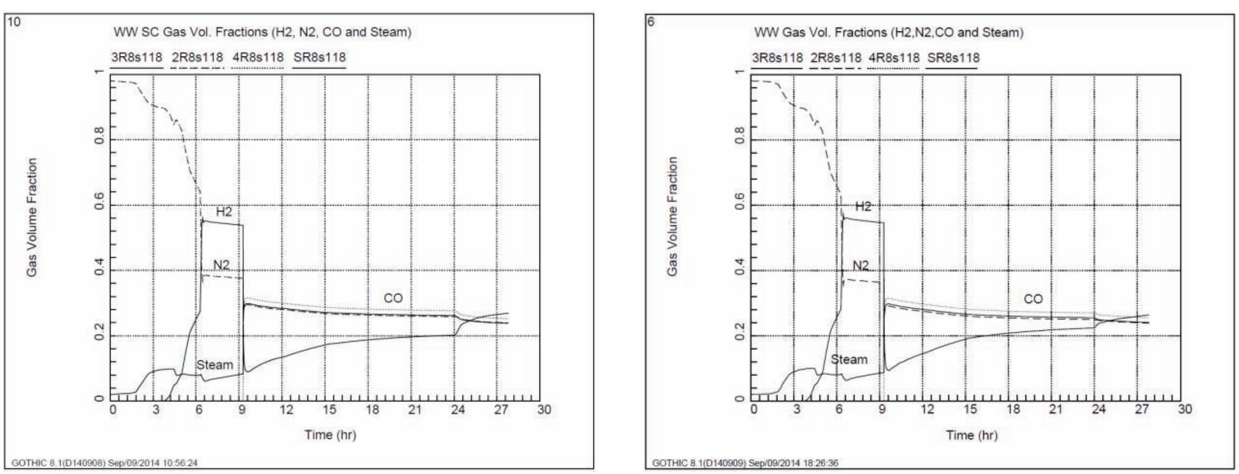
(a) (b)

Figure 12: DW Cylinderical Region Gas Vol. Fractions without VHT (a) and DW Spherical Region Gas Vol. Fractions without VHT (b)



(a) (b)

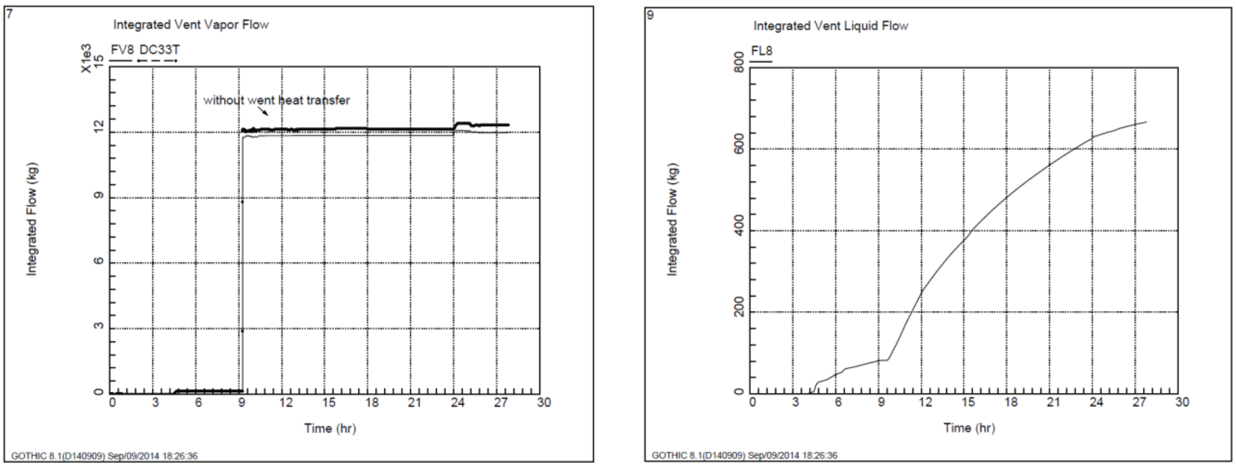
Figure 13: DW Cylinderical Region Gas Vol. Fractions with VHT (a) and DW Spherical Region Gas Vol. Fractions with VHT (b)



(a) (b)

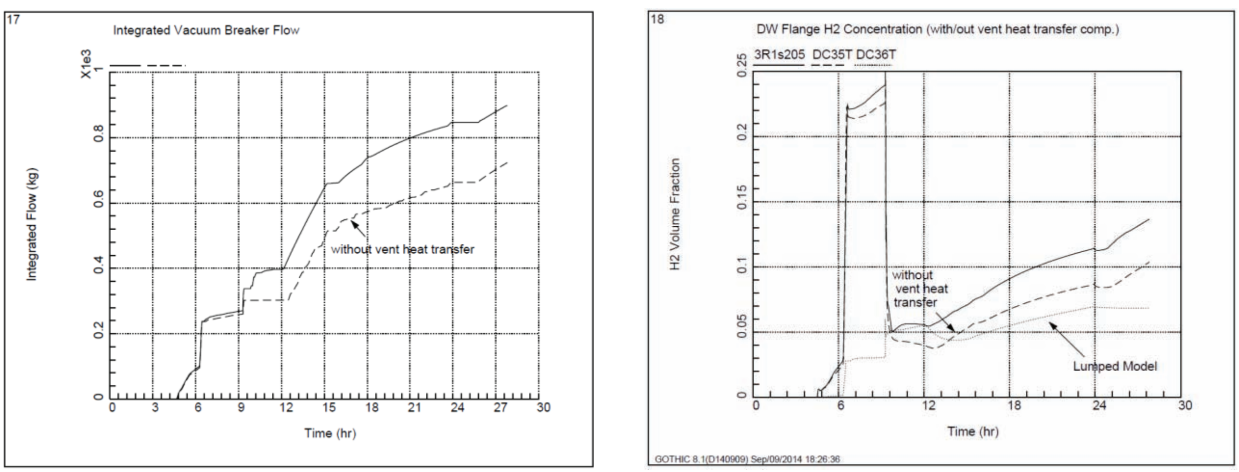
Figure 14: WW Gas Volume Fractions without VHT (a) and with VHT (b)

The steam condensation in the vent system reduces the amount of noncondensing gases that are transferred to the WW through the vents. As observed in Figure 7, the vent heat transfer and condensation results in lower containment pressure. Since the mass and energy to the WW via the SRVs is unchanged in these two cases, there is an increase in the flow from the WW to the DW via the vacuum breakers as shown in Figure 16(a). The increased backflow from the WW to the DW and the reduced gas transfer to the WW via the vents results in higher hydrogen concentration in the DW when the vent heat transfer is included as shown in Figure 16(b). This would be an important factor in assessing the potential for drywell head leakage to lead to the 1F1 hydrogen explosion in the Reactor Building.



(a) (b)

Figure 15: Integrated Vent Vapor Flow with and without VHT (a) and Integrated Vent Liquid Flow with VHT (b)



(a) (b)

Figure 16: Integrated Vacuum Breaker Flow with and without VHT (a) and H_2 Concentration at DW Flange with and without VHT (b)

4. CONCLUSIONS

The effects of multidimensional modelling and vent heat transfer on the 1F1 event simulation through the WW venting have been investigated. The model incorporates a subdivided drywell model that can predict the 3-dimensional flow pattern, temperature and gas distribution within the drywell. To capture the major coupling effects of other system components, the model also includes the drywell vent system, wetwell with the suppression pool, leakage to the surrounding reactor building and the wetwell vent to the stack.

The 1F1 MAAP5 Baseline Scenario [5] is used to define the steam, hydrogen and carbon-monoxide source terms from the primary system and the core concrete interaction. It must be recognized that there are many unknowns and uncertainties in this analysis and the good agreement with the recorded data is achieved by adjusting the unknown inputs within reasonable limits.

The postulated scenario, with the mass and energy sources low in the drywell, results in a fairly well-mixed drywell, although there are still some variations in the temperature and gas concentrations that influence the containment pressurization and the hydrogen release to the reactor building.

The containment system model was modified to consider heat transfer from the steam and gas in the drywell vent system to the wetwell and torus room. It is clear that for the given scenario, any amount of condensation in the vent system would reduce the amount of steam flow into the WW and consequently reduce the amount of noncondensing gas transferred to the WW. The GOTHIC capability to predict the steam condensation in the presence of noncondensing gases is well established [7]. The inclusion of vent heat transfer had a significant impact on the overall containment response for the 1F1 scenario, particularly during RPV lower head failure and the subsequent steam flow from the vessel to the drywell. In spite of the increase in wetwell gas temperature, the vent heat transfer model predicted continued condensation of the steam in the vent system and a smaller amount of noncondensable gas transfer to the wetwell compared to the model without the vent heat transfer. The net result was a reduction in the containment pressure.

ACKNOWLEDGMENTS

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