

MELCOR and GOTHIC Analyses of a Large Dry Pressurized Water Reactor Containment to Support Resolution of GSI-191

B. Beeny^a, R. Vaghetto^a, K. Vierow^a, Y.A. Hassan^a

^a *Texas A&M University, Department of Nuclear Engineering, 3133 TAMU, College Station, TX 77843, United States*

Abstract

The thermal-hydraulic response of large dry pressurized water reactor (PWR) containments under loss-of-coolant accident (LOCA) conditions - particularly with respect to containment pressure and sump pool temperature - is crucial for risk informed decision making about GSI-191. Texas A&M University (TAMU) has developed models with several computer codes including MELCOR and GOTHIC.

MELCOR is a best-estimate thermal-hydraulics and severe accident code created and actively maintained by Sandia National Laboratories (SNL) for the Nuclear Regulatory Commission (NRC). GOTHIC is a thermal-hydraulics software package meant for design, licensing, and safety calculations for, among other systems, nuclear power plant containments. It was developed and is maintained by Numerical Applications Inc. (NAI) for the Electronic Power Research Institute (EPRI).

The overarching goal of analyses presented here is to produce a best-estimate time profile of sump pool temperature under double-end guillotine break (DEGB) accident conditions. Sump pool temperature has direct implications for sump pool chemistry, residual heat removal in the recirculation phase of a LOCA, and pressure drop across sump screens. For a best estimate of sump pool temperature response, the physics of pipe break effluent flashing, steam condensation and film drainage, and engineered safety features (fan coolers, sprays) must be modeled with good fidelity subject to code constraints. In this paper, aspects of the modeling strategies for MELCOR and GOTHIC are discussed and best estimates of containment thermal-hydraulic response are presented. Particularly for sump pool temperature, code predictions agree at certain transient times and significantly disagree at other times. Further exploration of observed differences via sensitivity calculations is the subject of a separate paper. However, possible explanations for said differences are hypothesized with due consideration given to code mechanics.

Keywords: MELCOR, GOTHIC, LOCA, containment, sump

1. Introduction

Computational and experimental activities are currently focusing on the resolution of Generic Safety Issue (GSI) 191. System codes have been extensively used to perform thermal-hydraulic calculation of the reactor and containment response under specific accident scenarios to support the ongoing research. A set of computations performed with MELCOR and GOTHIC have been selected and presented in this paper. Using both codes, models of a typical large dry PWR containment were developed. These models were used to predict the containment thermal-hydraulic response under postulated DEGB conditions with particular emphasis on obtaining a time profile of the sump pool temperature. Because sump pool temperature has an impact on sump pool chemistry, residual heat removal during recirculation cooling, and sump screen pressure drop, information about the sump pool temperature response is vital to industry decision-making for GSI-191.

To have confidence in the accuracy of MELCOR or GOTHIC sump pool temperature predictions, certain thermal-hydraulic phenomena and in-containment equipment must be modeled with good fidelity. The system must also be nodalized in sufficient detail so as to capture the important physics. Essentially, the code modeling strategy must be tailored to the end goal of the analysis. In subsequent discussions on modeling strategy, the aspects of containment nodalization, flow path and thermal surface specification, pipe break effluent flashing, and engineered safety features (fan coolers, sprays) will all be addressed in turn. The “best-estimate” prediction of containment thermal-hydraulic response from both codes will be presented. Hypotheses about any observed differences between MELCOR and GOTHIC predictions will be put forth. These hypotheses will be explored in greater depth as the subject of a separate paper [1]. Without experimental data for benchmarking, the code-to-code comparison can offer no insight as to which code better depicts reality. Only the differences in code predictions and their potential causes can be identified. Thus no conclusions of the present analysis contend that one code is preferable to the other, especially since user-imposed modeling constraints often result in under-utilization of full code capabilities. Rather, the conclusions of the present analysis serve to motivate more in-depth studies that include an experimental benchmark.

2. MELCOR Code Mechanics and Modeling Strategy

Created by SNL for the NRC, MELCOR was originally conceived as a flexible, fast-running probabilistic risk assessment tool that has since evolved into a best-estimate, systems-level severe accident analysis code for light water reactors [2]. MELCOR is capable of tracking severe accident progression up to source term generation. It can be employed in alternate capacities to study various thermal hydraulic, heat transfer, and aerosol transport phenomena. This is due in large part to MELCOR’s lumped parameter control volume/flow path modeling approach that is quite general and adaptable.

In MELCOR terminology, a control volume (CV) is an entity that contains hydrodynamic material (water, steam, noncondensable gases) with geometry specified by a volume/altitude table. Therefore, CVs in the MELCOR model represent physical volume associated with containment compartments. Initial thermodynamic conditions are part of CV input. A flow path (FP) allows for relocation of hydrodynamic material between CVs, so each FP physically represents an inter-compartment passageway in the MELCOR model. A heat structure (HS) is a thermal surface that can interact with hydrodynamic material in adjacent CVs via heat and mass transfer. Each HS physically represents a structure such as a wall, floor, pipe, etc. that may be heated, cooled or may act as a condensing surface that accumulates a condensate film. An engineered safety feature (ESF) in the present context refers to either fan coolers or containment sprays. Both have specialized models in MELCOR and both are utilized in the containment model with “best-estimate” conditions and set-points. Ancillary code elements allow for description of material properties, control logic, problem run-time characteristics, etc.

To begin, geometry data for containment compartments, inter-compartment passages, and major thermal surfaces was collected for a typical large, dry containment. This information was used to build the several CVs, FPs, and HSs comprising the MELCOR containment model. Nominal operating conditions suggested initial conditions while operating procedures and equipment technical specifications dictated control logic.

The MELCOR containment model CV/FL nodalization is shown in Figure 1. Containment HSs are excluded as their sheer number would render the diagram unreadable. The boxed numbers correspond to a given compartment CV. The cavity CV comprises the volume directly below the reactor vessel. The lower compartment includes the steam generator and pressurizer compartments plus volume below the vessel but outside the cavity. The upper compartment consists of volume above the operating deck up to the dome. The annular compartment sits below the operating deck but outside the lower compartment. The annular compartment is the physical location of the containment sump which is represented by the

lowest portion of the annular compartment volume/altitude table. To round out the description of each CV, initial thermodynamic conditions including pressure, atmosphere temperature, atmosphere noncondensable gas composition, and relative humidity (water vapor partial pressure in the atmosphere) are specified. No pools (consisting of liquid water) initially exist in any CVs.

There are several FPs as indicated by the double-headed arrows in Figure 1 and as described in Table I. In some cases multiple arrows are used for the same FP, indicating multiple passages between the same two CVs are lumped into one FP. Each FP requires geometric input like flow area, inertial length, and open fraction. Each FP also has one or more “piping segments” that span its length and account for friction/losses through segment parameters like flow area, friction length, and hydraulic diameter.

The several HSs of the containment model are described in Table II. Input parameters for any given HS describe surface geometry, structure material, structural thickness, shape, orientation, CV coupling, and surface boundary conditions. Concrete comprises HS1 through HS12, while stainless steel comprises miscellaneous structures HS13 through HS35. Additionally, HSs may be grouped into film tracking networks so as to model condensate drainage down a sequence of structures.

The ESFs described in Table III are indicated by spray and fan cooler symbols in Figure 1. A single spray header is assigned to a source CV (the upper compartment in this case) and is given a droplet volume flow rate, droplet temperature, and droplet size (in this case a mono-disperse droplet diameter distribution). Droplets fall through the source compartment and are then either collected in a sump CV pool (the upper compartment in this case) or are allowed to fall through the atmosphere of lower CVs (lower and annular compartments in this case). Differential equations formulated under certain assumptions are integrated over the spray fall height to predict droplet heat and mass transfer. Several identical fan coolers are assigned suction and discharge CVs (upper compartment and lower compartment in this case). Hot, humid steam/air is drawn in from the suction CV atmosphere while cool, dry air is sent out to the discharge CV. To characterize the heat transfer and wetness removal within the fan cooler(s) between suction and discharge, characteristics like volumetric steam/air flow, secondary side heat exchanger water temperature and flow rate, and rated cooler capacity are specified.

To model containment response under LOCA conditions, a representative time profile of DEGB effluent mass and energy is taken from a separate RELAP5-3D calculation. Break effluents are sourced into the lower compartment CV as high pressure, subcooled water. To capture effects of rapid pressure reduction, the MELCOR flashing model apportions the break effluents among water vapor (steam), fog (droplets persisting in the steam/air atmosphere), and liquid water according to thermodynamic considerations of stagnation and equilibration. Plots of break mass flow rate and enthalpy are included in Figure 2 and Figure 3, respectively, including insets for the initial thirty seconds of primary loop blowdown to containment.

Once the high-pressure break effluents are partitioned upon flashing as previously described, the hydrodynamic material is free to travel throughout the containment as predicted by the governing equations. Steam evolved from the break is free to move between compartments, condense on HS surfaces, condense by action of spray droplets, or be removed by action of fan coolers. Water emanating from the break accumulates in the lower compartment pool and can move to other CVs provided pool liquid levels are within FP junction opening height limits. Eventually, excess water relocates to the annular compartment and hence to the containment sump.

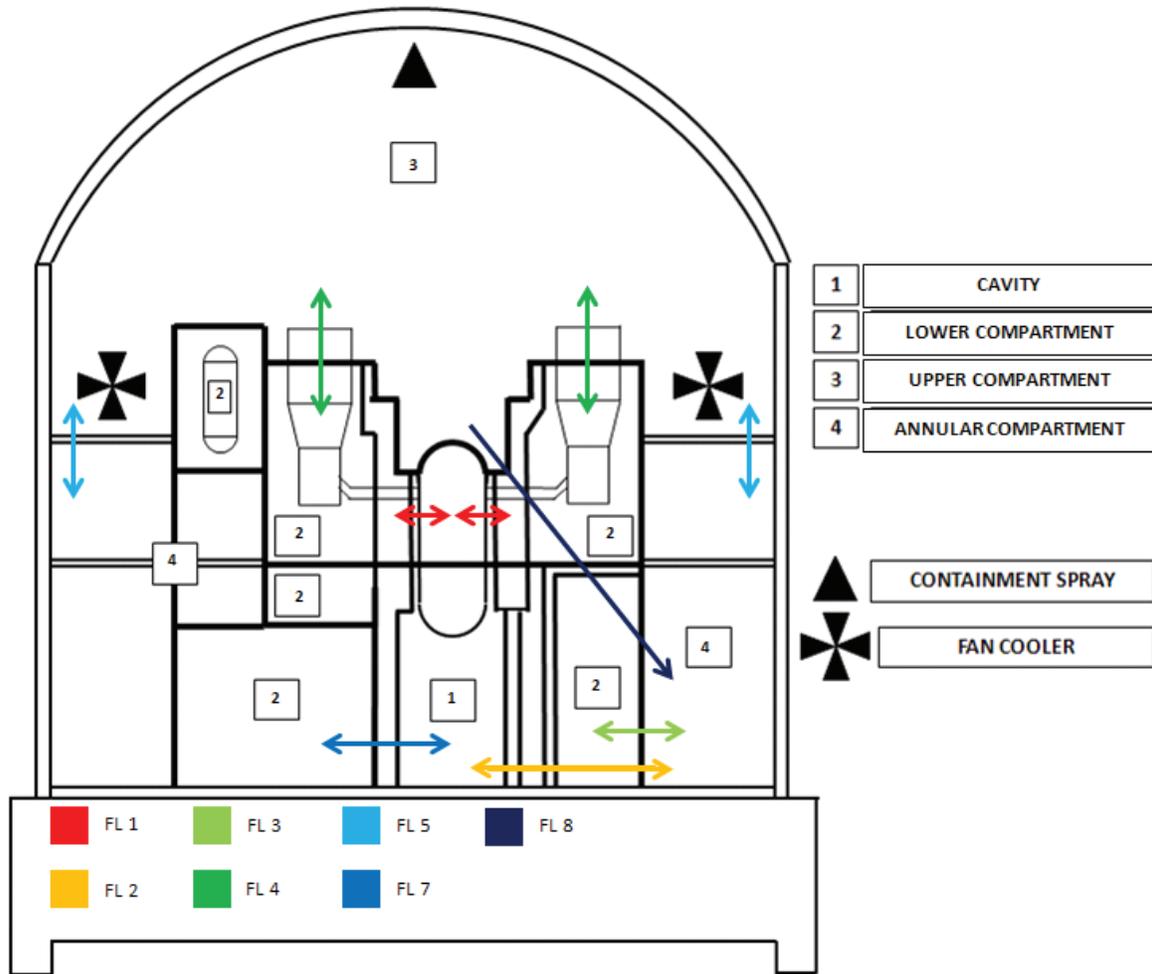


Figure 1. MELCOR containment CV/FL nodalization

The MELCOR model as described above permits simulation of a DEGB LOCA from the initial break opening through the blowdown stage and out beyond the so-called sump switchover time. At the point of sump switchover, safety injection of coolant from the refueling water storage tank (RWST) to the primary loop (via cold legs) ceases and the system is realigned for recirculation from the containment sump. At the same time, spray pump suction is realigned from the RWST to the containment sump. These effects are accounted for in both the MELCOR model and the RELAP5-3D model from which the DEGB break source was borrowed. For a DEGB, a problem time of 5000 seconds is sufficient to observe the major factors affecting containment pressure and sump pool temperature response. Hence a 5000 second calculation demonstrates MELCOR containment modeling capabilities and establishes an adequate basis for comparison to other analysis tools, e.g. GOTHIC. Note that other MELCOR calculations of other LOCA transients (various break size) were run out to far longer problem times (e.g. 30 days), but such analyses are beyond the scope of the present study.

Table I. Description of flow paths illustrated in Figure 1

FP #	FP From CV	FP To CV	FP Description
1	Cavity	Lower Compartment	In/around vessel annulus
2	Cavity	Ann. Compartment	Tunnel passageway
3	Lower Compartment	Ann. Compartment	Bioshield wall passageway(s)
4	Lower Compartment	Upper Compartment	Steam generator compartment roof
5	Ann. Compartment	Upper Compartment	Operating deck passageway(s)
6	-	-	Placeholder, not used in analysis
7	Cavity	Lower Compartment	Vent duct/doorway
8	Upper Compartment	Ann. Compartment	Refueling canal drain(s)

Table II. Description of heat structures in the MELCOR containment model

HS #	HS Interfacing CV(s)	HS Description
1	Cavity	Cavity Wall
2	Cavity, Lower Compartment	Lower Compartment Wall
3	Lower Compartment	Lower Compartment Floor
4	Lower, Annular Compartment	Lower/Annular Compartment Wall
5	Annular Compartment	Annular Compartment Outer Wall
6	Upper Compartment	Upper Compartment Outer Wall
7	Lower/Upper Compartment	Upper Compartment Interior Wall
8	Lower/Upper Compartment	Operating Deck Structure
9	Cavity	Cavity Floor
10	Annular Compartment	Annular Compartment Floor
11	Upper/Annular Compartment	Operating Deck Structure
12	Cavity/Annular Compartment	Cavity/Annular Compartment Wall
13-35	Various	Miscellaneous Steel Structure (piping, equipment, etc.)

Table III. Description of engineered safety features illustrated in Figure 1

ESF #	ESF Interfacing CV(s)	ESF Description
SPR 1	Upper/Lower/Annular Compartment	Spray droplets injected at: top of upper compartment surviving fraction split between: lower/annular compartment and upper compartment pool
FCL 1	Upper/Lower Compartment	Warm, humid steam/air drawn in from: upper compartment Cool, dry air blown out to: lower compartment
FCL 2-8	Upper/Lower Compartment	Same as FCL 1

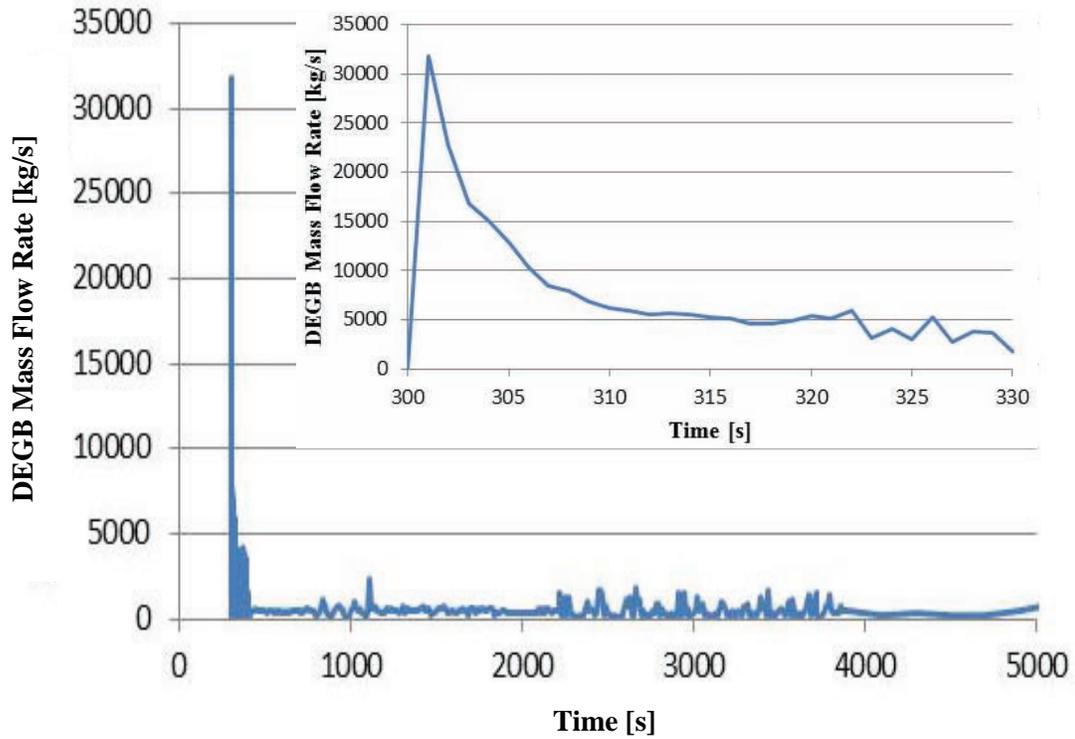


Figure 2. DEGB effluent mass flow rate sourced into lower compartment

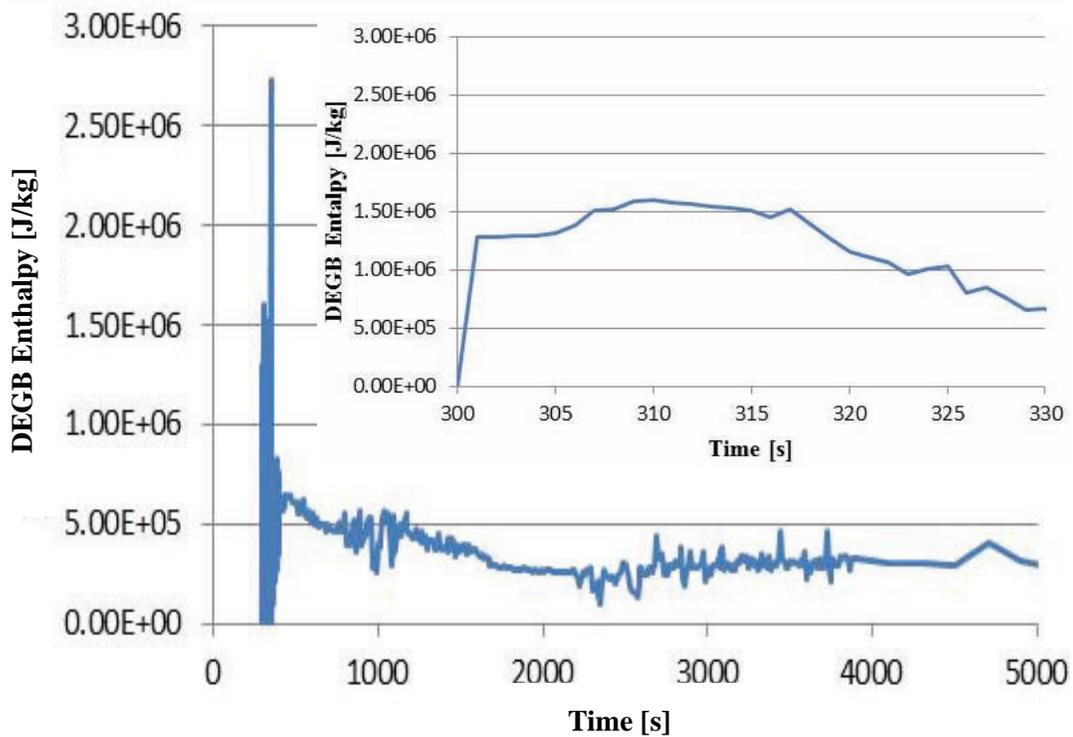


Figure 3. DEGB effluent enthalpy sourced into lower compartment

3. GOTHIC Code Mechanics and Modeling Strategy

GOTHIC is a thermal-hydraulics software package meant for design, licensing, and safety calculations of, among other systems, nuclear power plant containments [3]. It was developed and is maintained by Numerical Applications Inc. for the Electronic Power Research Institute.

In GOTHIC terminology, a control volume is an entity that contains hydrodynamic material (water, steam, noncondensable gases) with geometry specified by a volume/altitude table. There is really no distinction between GOTHIC and MELCOR when it comes to specifying CV volumes/altitudes apart from the definition of reference elevation. CVs in the GOTHIC model represent physical volume associated with containment compartments. Initial thermodynamic conditions are part of CV input. Unlike MELCOR, GOTHIC is not limited to a lumped-parameter modeling approach but for purposes of this study lumped-parameter CVs were used exclusively. A flow path allows for relocation of hydrodynamic material between CVs, so each FP physically represents an inter-compartment passageway in the GOTHIC model. There is essentially no difference between MELCOR and GOTHIC for an FP between lumped-parameter CVs. A thermal conductor (TC) is a thermal surface that can interact with hydrodynamic material in adjacent CVs via heat and mass transfer. There are several different types of TC available in GOTHIC, but the internal-type, two-sided TCs are used exclusively in the present study. They are analogous to a MELCOR HS. Each TC physically represents a structure such as a wall, floor, pipe, etc. that may be heated, cooled or may act as a condensing surface. GOTHIC ESFs include fan coolers and containment sprays. There are special code provisions for each kind of ESF in GOTHIC and choices made for present modeling purposes are described below. Note that, due to the selected modeling strategy, the full faculties of GOTHIC with respect to control volume and fan cooler modeling are not fully leveraged. This is an artifact of user-imposed modeling constraints and in no way reflects poorly on GOTHIC and its complement of phenomenological models. Similar to the MELCOR containment model, the GOTHIC calculations use ESFs with “best-estimate” conditions and set-points. Ancillary code elements allow for description of material properties, control logic, problem run-time characteristics, etc.

To begin, geometry data for containment compartments, inter-compartment passages, and major thermal surfaces were taken from the same set of data used for the MELCOR model. This information was used to build the CVs, FPs, and TCs comprising the GOTHIC model. Nominal operating conditions suggested initial conditions while operating procedures and equipment technical specifications dictated control logic. There are no noteworthy differences between MELCOR and GOTHIC with respect to initial conditions and transient control logic.

The GOTHIC containment model as it appears in the graphic user interface (GUI) is included in Figure 2. The dashed yellow lines represent CV boundaries, the green solid lines represent FPs, the red squares denote TCs, the light blue squares represent fluid boundary conditions (FBC), and the small white icons indicate features like the spray nozzle and the fan coolers. Each element is assigned a number or number/letter combination for accounting purposes. The CV numbers (yellow boxes with red writing) in Figure 2 correspond to those of Figure 1. The FP numbers (green boxes with red writing) and TC numbers (red boxes with yellow writing) in GOTHIC do not exactly correspond to those of MELCOR, but all the same flow passages and thermal surfaces are modeled. The cavity, lower compartment, upper compartment, and annular compartment CVs are situated exactly as in the MELCOR model. Initial CV conditions for GOTHIC match those of MELCOR. The position of any given TC or FP component in Figure 2 does not indicate spatial location but conveys a CV-TC/FP relationship.

There are several FPs as indicated by green lines in Figure 2 and as described in Table IV. FP pairs 1 and 2, 3 and 4, and 5 and 6 each actually represent upper and lower halves of the same physical flow passage. This modeling approach follows recommendations from the GOTHIC manuals. The FPs

numbered 11 and 12 are not physical flow passages but rather represent connections between FBCs and CVs. It is through such FPs that the break mass/energy and the spray droplets enter the simulation. FP 13 physically represents a flow passage on which the fan coolers reside. This FP is necessary because a “volumetric fan” component was chosen to represent fan coolers as discussed below. Each FP numbered 1 to 10 requires geometric input like flow area, inertial length, friction length, and open fraction.

Table IV. Description of flow paths illustrated in Figure 2

FP #	FP From CV	FP To CV	FP Description
1	Cavity	Low Compartment	Top half, in/around vessel annulus
2	Cavity	Low Compartment	Low half, in/around vessel annulus
3	Cavity	Ann. Compartment	Top half, tunnel passageway
4	Cavity	Ann. Compartment	Low half, tunnel passageway
5	Low Compartment	Ann. Compartment	Top half, bioshield wall passage
6	Low Compartment	Ann. Compartment	Low half, bioshield wall passage
7	Low Compartment	Upper Compartment	Steam generator comp. open roof
8	Ann. Compartment	Upper Compartment	Operating deck passageway(s)
9	Cavity	Low Compartment	Vent duct/doorway
10	Upp Compartment	Ann. Compartment	Refueling canal drain(s)
11	Upp Compartment	-	Spray FP b/t domain and FBC
12	Low Compartment	-	Break FP b/t domain and FBC
13	Upp Compartment	Low Compartment	Residence of volumetric fan

The several TCs of the GOTHIC containment model are detailed in Table V. Input parameters for any given TC describe surface geometry, structure material, structural thickness, shape, orientation, CV coupling, and surface boundary conditions. Either concrete or stainless steel, both with material properties identical to those of MELCOR, comprises any given TC. The same thermal surfaces appearing in the MELCOR model are present in the GOTHIC model, but for convenience some thermal surfaces in GOTHIC are divided into 2 TCs (one per side).

The GOTHIC model ESFs are described in Table VI. A single spray nozzle component, 1N, is assigned to FP 11 between FBC 1F and the upper compartment CV. FBC 1F specifies the spray water source mass flow rate and temperature while nozzle 1N essentially converts water into droplets of a mono-disperse size distribution (as in MELCOR). Once droplets enter the upper compartment CV, their behavior and transport is entirely subject to the solution of droplet field equations. Droplets can interact with steam (heat and mass transfer), travel through FPs, etc. Note the contrast with this approach and that of MELCOR as described in the previous section. Several identical fan coolers are lumped into one volumetric fan component, 1Q, which resides on FP 13 between the upper compartment and lower compartment CVs. Steam/air mixture is drawn into FP 13, processed by the volumetric fan, and discharged as dry, cool air. To characterize the heat transfer and wetness removal of the volumetric fan, a look-up table describing fan cooler heat removal rate as a function of upper compartment CV saturation temperature was used. This table is based on plant data for fan cooler performance. Note the contrast with MELCOR as described in the previous section. In this instance GOTHIC is under-utilized as a consequence of the selected modeling strategy since much more detailed phenomenological models are available, e.g. the specialized heat exchanger component intended for fan coolers.

To model containment response under LOCA conditions, a time profile of DEGB effluent mass and energy identical to that of the MELCOR model is programmed with forcing functions and table functions. Flashing effects due to stagnation and equilibration are accounted for in GOTHIC.

Table V. Description of thermal conductors in the GOTHIC containment model

TC #	TC Interfacing CV(s)	TC Description
1	Cavity	Cavity wall
2	Lower Compartment	Lower compartment floor
3	Ann. Compartment	Outer wall
4	Upper Compartment	Outer wall
5	Cavity	Cavity floor
6	Ann. Compartment	Ann. Compartment floor
7-29	Various	Miscellaneous steel structure
30	Lower Compartment	Left face, LC/UC wall
31	Upper Compartment	Right face, LC/UC wall
32	Lower Compartment	Bottom, operating deck
33	Ann. Compartment	Top, operating deck
34	Ann. Compartment	Right face, cav/AC wall
35	Cavity	Left face, cav/AC wall
36	Cavity	Left face, LC/cav wall
37	Lower Compartment	Right face, LC/cav wall
38	Upper Compartment	Top, operating deck
39	Ann. Compartment	Bottom, operating deck
40	Upper Compartment	Top, operating deck
41	Lower Compartment	Bottom, operating deck

Once the high-pressure break effluents enter the simulation, the hydrodynamic material is free to travel throughout the containment as predicted by the governing equations. The vapor (steam/air) evolved from the break is free to move across FPs, to condense on TC surfaces, to interact with the droplet field, or to be removed by the volumetric fan. Water emanating from the break accumulates in the lower compartment pool initially and can subsequently move to other CVs provided pool liquid levels reach FP bottom elevations. Eventually, excess water relocates to the annular compartment and hence to the containment sump.

The GOTHIC model as described above permits simulation of a DEGB LOCA from the initial break opening through the blowdown stage and out beyond the so-called sump switchover time. A 5000 second calculation demonstrates GOTHIC containment modeling capabilities and establishes a basis for comparison to MELCOR.

Table VI. Description of engineered safety features illustrated in Figure 2

ESF	ESF Interfacing Components	ESF Description
1N	Upp Comp CV,FBC 1F,FP 11	Spray droplet flow, temperature governed by FBC FP 11 carries water through 1N, to Upp. Comp. CV Nozzle 1N produces monodisperse spray droplets
1Q	Upp/Low Comp CV, FP 13	Hot, humid steam/air in from Upp. Comp. CV Volumetric fan 1Q removes heat/H ₂ O using Q(T _{sat}) Cool, dry air flows to the Low. Comp. CV

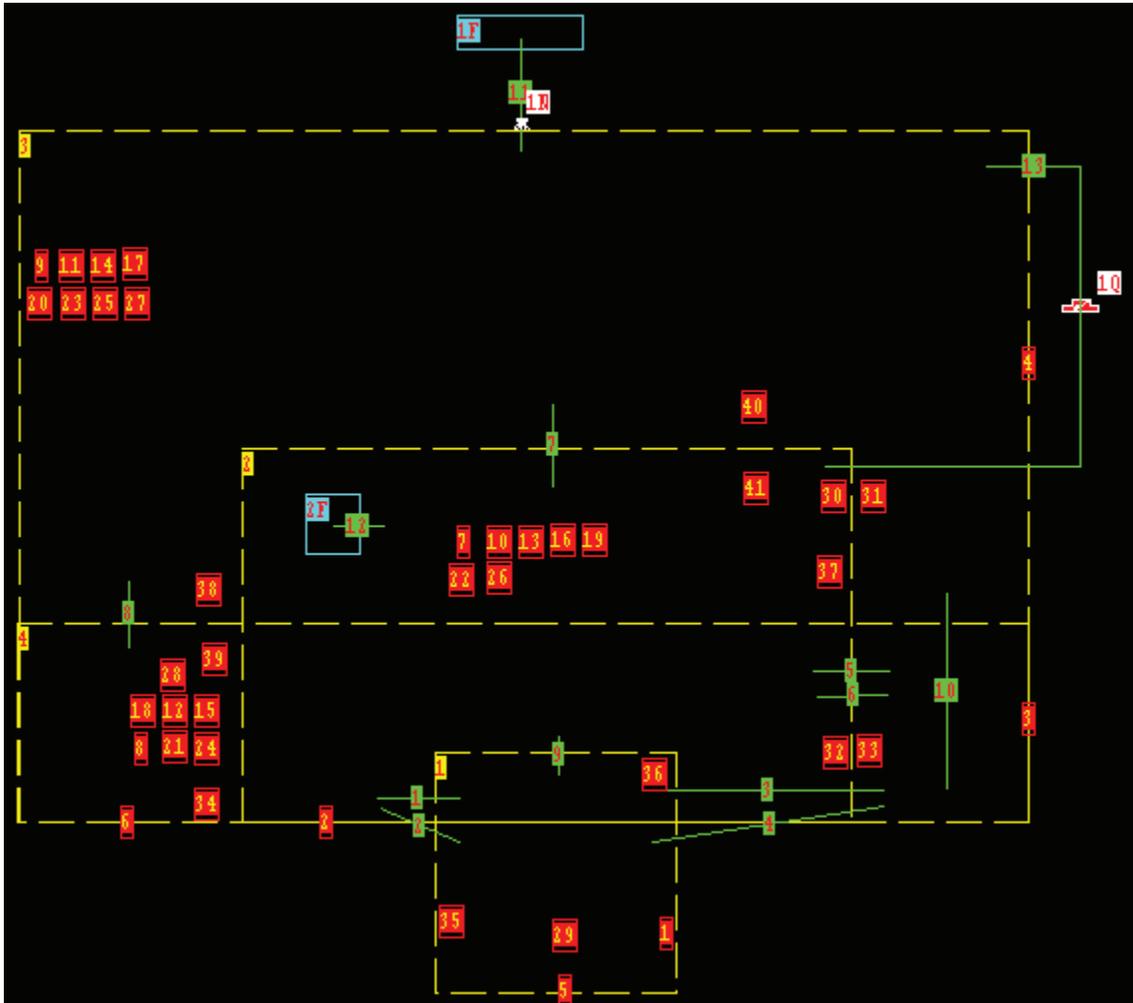


Figure 2. GOTHIC GUI containment model nodalization

4. Results

Both the MELCOR and GOTHIC models were used to predict containment thermal hydraulic response to a LOCA. Realistic (not overly conservative) values of initial thermodynamic conditions, DEGB boundary conditions, and engineered safety feature characteristics lead to best estimates of containment pressure and sump pool temperature throughout the transient. Note a 300 s time period precedes the DEGB to ensure steady-state, equilibrium conditions are established prior to the transient.

Figure 3 and Figure 4 shows MELCOR and GOTHIC calculations for two important metrics of containment response, namely pressure and sump pool temperature. To facilitate a MELCOR-to-GOTHIC results comparison, user input for the code models was configured to agree as much as possible. Thus, the obvious dissimilarities between MELCOR and GOTHIC predictions point almost exclusively to phenomenological modeling differences between the two codes. No “accepted” time-profiles of pressure or sump pool temperature exist for benchmarking, so the focus here is confined to identification and explanation of code disagreements.

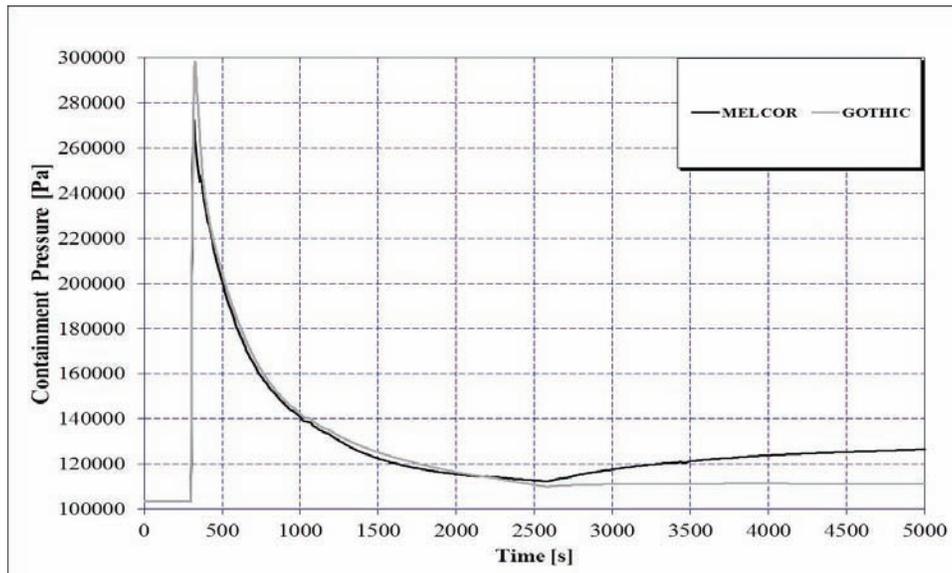


Figure 3. Containment model predicted pressure response, MELCOR vs. GOTHIC

With respect to the pressure curves of Figure 3, both the magnitude and timing of the blowdown pressure peaks disagree somewhat. Thereafter, both codes predict similar pressure suppressions as condensation, sprays, and fan coolers remove energy from the containment atmosphere. Beyond sump switchover, which occurs at problem time 2580.8 s, the pressure profiles again diverge and the transient terminates with a pressure differential. Relevant features of Figure 3 are summarized in Table VII below.

With respect to the sump pool temperature curves of Figure 4, there is some disagreement in terms of magnitude and timing of the initial peak. Shortly after liquid water first enters the sump, the pool cools under the influence of several factors such as condensate drainage/runoff, pool-to-structure heat transfer, spray water collection, refueling canal drainage, etc. The rate of cooling as predicted by MELCOR differs markedly from that of GOTHIC. Between the temperature peak and sump switchover, MELCOR predicts a sharp initial drop followed by a nearly linear decrease. Over the same time period, GOTHIC predicts a less severe initial drop followed by a steeper linear decrease. At sump switchover, curve slope changes occur and by the end of the transient both curves converge to just below 340 K within half a degree of each other. Relevant features of Figure 4 are summarized in Table VIII.

Prior to theorizing about code disagreements, it is helpful to associate certain features of Table VII and Table VIII with in-containment physical phenomena. In the first 40 s after break opening, the most impactful factors are:

- Break source and flashing treatment
- Pressure suppression via condensing surfaces
- Water/structure (e.g. floors and walls) heat transfer, pool/atmosphere heat transfer

- Water influx to the sump pool from various sources (FPs, condensate run-off)

Due to their pressure set-points and time delays, sprays and fan coolers do not actuate until about 50 s and 42s after the DEGB, respectively. During the first 40 s, pressure and sump temperature both peak, turn over, and begin to decrease. Any code disagreements in peak value and timing likely stem from the aforementioned phenomena.

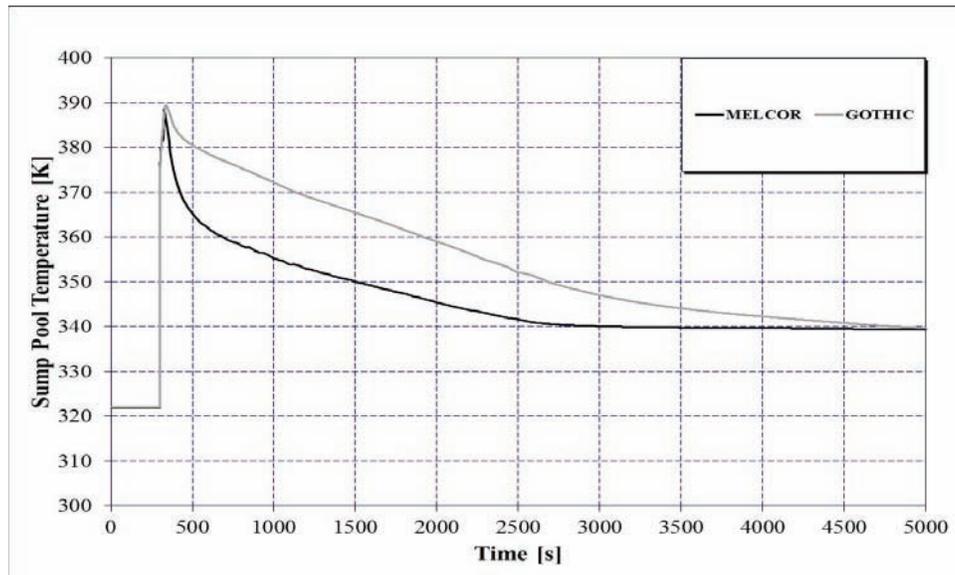


Figure 4. Containment model predicted sump temperature response, MELCOR vs. GOTHIC

Table VII. Important aspects of the predicted pressure response

Feature	Quantitative (t = 300.0 [s])	Qualitative
MELCOR Max.	272343.0 [Pa] at t + 18.4 [s]	Smaller peak, reached more quickly
GOTHIC Max.	298543.0 [Pa] at t + 26.0 [s]	Larger peak, at t + 18.4 [s]
Suppression	t + 365.0 [s] to t + 2580.8 [s]	Good code agreement, to within 0.5 psia
Switchover	At time t + 2580.8 [s]	RWST low-low, Recirc.starts, T _{spray} rises
MELCOR Min.	112385.0 [Pa]	Approx. coincident with switchover time
GOTHIC Min.	109627.0 [Pa]	Approx. coincident with switchover time
MELCOR Final	126864.0 [Pa]	Increases after switchover
GOTHIC Final	111006.0 [Pa]	Very little increase after sump switchover

Table VIII. Important aspects of the predicted sump pool temperature response

Feature	Quantitative (t = 300.0 [s])	Qualitative
MELCOR Max.	383 [K] at t + 25.4 [s]	Smaller peak reached more quickly
GOTHIC Max.	389 [K] at t + 38.0 [s]	Larger peak reached later in time
Cooling Trends	Peak to switchover	Sharp drops followed by linear decreases
MELCOR drop	20.5 [K] at t + 300.0 [s]	A more dramatic drop vs. GOTHIC
GOTHIC drop	7.61 [K] at t + 150.0 [s]	A less drastic drop vs. MELCOR
MELCOR linear	Cooling of 0.0186 [F/s]	A more gradual cooling rate than GOTHIC
GOTHIC linear	Cooling of 0.0244 [F/s]	A steeper cooling rate than MELCOR
Switchover	At time t + 2580.8 [s]	RWST low-low, Recirc. starts, T _{spray} rises
MELCOR Min.	339.43 [K]	Good agreement at end time of 5000.0 s
GOTHIC Min.	339.71 [K]	

After the time of ESF actuation (40 s to 50 s after break opening), MELCOR and GOTHIC both predict pressure suppressions of nearly identical character out to the time of sump switchover. During the same time period, both codes predict a non-linear sump pool temperature drop followed by an approximately linear temperature decrease. The magnitude and duration of the sharp drops as well as the slope of the lines is different (see Table VIII for quantitative descriptions). The important physics for this time period includes:

- Break source (though there is a lower mass/energy flow rate) and flashing treatment
- Condensing surface, spray, and fan cooler effects on fluid (atmosphere and pool) temperatures
- Water/structure (e.g. floors and walls) heat transfer, pool/atmosphere heat transfer
- Water influx to the sump pool from various sources (FPs, condensate run-off, spray droplet collection)

For this period, ESFs remove less and less thermal energy as containment atmosphere pressure and temperatures generally decline. Towards the end of this period, condensate film mass on thermal surfaces decreases and there is less film drainage to CV pools. As fluid and structural temperatures approach thermal equilibrium, the quantity of heat removed by floors, walls, and miscellaneous steel also decreases.

Sump switchover constitutes a change in boundary conditions as the spray droplet temperature transitions from that of the RWST to that of the containment sump. Since warmer water is recycled from the sump to the spray header, the sprays are a less effective mechanism for pressure suppression and contribute less (if at all) to sump pool temperature reduction.

5. Discussion

Physics crucial to containment pressure and sump pool temperature response have been identified. Thus, hypotheses may be made as to which code physics models are responsible for disagreements in Figure 3 and Figure 4. Note that irreconcilable code differences in user input requirements may contribute to disagreement and should be given due consideration.

For the pressure and sump pool temperature peaks, there is noticeably different magnitude and timing. GOTHIC predicts a pressure peak about 27579 Pa higher and about 7.5 s later than that of MELCOR. GOTHIC also predicts a sump temperature peak about 6 K higher and about 12.5 s later than that of MELCOR. Part of the explanation may involve the user-defined break enthalpy and the fact that MELCOR and GOTHIC cannot be given the break enthalpy information in exactly the same way.

GOTHIC accepts only specific enthalpy [e.g. J/kg] to define a flow boundary condition, whereas MELCOR deals in rate [e.g. J/s] or integral [e.g. J] quantities. More importantly, the thermodynamics of code flashing models should be examined for consistency. Also, since condensation is a major factor at this stage of the containment response, the heat and mass transfer models for condensation in the presence of noncondensable gas should be considered. The timing and magnitude of pool-to-structure heat transfer, particularly in the lower and annular compartments, should be studied. Finally, flow rates through major FPs that connect to the annular compartment should be compared.

Between ESF actuation and sump switchover, predictions of pressure suppression agree closely. However, poor agreement is observed with respect to sump pool temperature. Since the ESFs are operating during this period, the effect of sprays and fans on atmosphere and pool temperatures should be considered. Fans can cool the atmosphere and so indirectly impact sump pool temperature. Spray droplets can also change atmosphere temperatures before eventually reaching the sump and affecting pool mass/energy. Condensate film drainage begins in earnest during this stage of the transient and affects pool mass/energy as well. A comparative analysis of mathematical models for fans, sprays, and condensate film transport could help to explain the large disparity in sump temperature curves seen in Figure 4. Sensitivity studies wherein fans, sprays, and thermal surfaces are excluded in turn from the calculation may point out which phenomena contribute the most to disagreement.

After sump switchover, the outstanding question is: why does GOTHIC pressure stay flat while MELCOR pressure increases? It appears that the change in spray temperature boundary conditions at switchover time affects the MELCOR and GOTHIC models in different ways. This issue is explored further via sensitivity studies in a separate paper [1], but since the only substantial change in both simulations upon sump switchover involves the sprays they are likely responsible for the discrepancy.

A sensitivity study designed to explore code differences in greater depth is the subject of a separate paper [1] and will include a brief overview of pertinent code physics models. The goal is to suggest reasonable explanations for code disagreements in an attempt to better understand MELCOR and GOTHIC as containment analysis tools. Again it must be emphasized that since benchmark data is unavailable, no attempt can or will be made to judge which code yields more accurate predictions.

6. Conclusions

Two typical large, dry PWR containment models were built in MELCOR and GOTHIC for use in computational studies related to GSI-191 resolution. The two models are as consistent with one another as code limitations allow, thus facilitating a MELCOR-to-GOTHIC results comparison for simulation of a DEGB LOCA. Despite some irreconcilable differences in code phenomenological models and user input, MELCOR and GOTHIC predictions of containment response reasonably agree for parts of the accident sequence. However, there are discrepancies, especially with respect to sump pool temperature which is a major target of the GSI-191 analyses. Thus the code-to-code disagreement should be explored in greater depth.

Based on an understanding of MELCOR and GOTHIC, three categories of physical phenomena are judged as the most likely contributors to code disagreement:

- Break source effects (mass/enthalpy specification, flashing models, etc.)
- Thermal surface effects (condensation heat/mass transfer, film drainage, pool heat transfer)
- Engineered safety feature effects (physics models of fans and sprays, droplet math models)

It is possible to better ascertain the impact of each category via a sensitivity study that screens out the separate effects of each in turn. If MELCOR and GOTHIC come to better agreement under exclusion of certain physics it suggests that those physics were indeed a contributor to code disagreement. More than one category of phenomena can be excluded at a time if such calculations are informative. A separate paper [1] documents a sensitivity study that attempts to 1) identify primary sources of disagreement, and 2) link the disagreement to code physics models.

References

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