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United States Nuclear Regulatory Commission
Attention: Document Control Desk
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NPF-4/7
DPR-32/37

DOMINION ENERGY KEWAUNEE, INC. (DEK)
DOMINION NUCLEAR CONNECTICUT, INC. (DNC)
VIRGINIA ELECTRIC AND POWER COMPANY (DOMINION)
KEWAUNEE POWER STATION
MILLSTONE POWER STATION UNITS 2 AND 3
NORTH ANNA POWER STATION UNITS 1 AND 2
SURRY POWER STATION UNITS 1 AND 2
REQUEST FOR APPROVAL OF TOPICAL REPORT DOM-NAF-3, GOTHIC METHODOLOGY FOR ANALYZING THE RESPONSE TO POSTULATED PIPE RUPTURES INSIDE CONTAINMENT

As part of a continuing effort to improve thermal-hydraulics methods, Dominion Energy Kewaunee, Inc. (DEK), Dominion Nuclear Connecticut, Inc. (DNC) and Virginia Electric and Power Company (Dominion) are updating their capability for performing nuclear reactor containment analyses in support of their nuclear power stations. GOTHIC is a general-purpose, thermal-hydraulics computer code developed by the Electric Power Research Institute for applications in the nuclear power industry. The NRC has approved GOTHIC for use in containment analyses for several U.S. nuclear power plant licensees. DEK, DNC and Dominion have developed an analytical methodology using GOTHIC for performing licensing basis analyses for the containment response for pressurized water reactors with large, dry containments. The methodology is described in the Dominion Topical Report DOM-NAF-3, "GOTHIC Methodology for Analyzing the Response to Postulated Pipe Ruptures Inside Containment."

In a phone conversation of August 23, 2005, Dominion advised the NRC of its intention to submit license amendment requests (LARs) in connection with their responses to NRC Generic Letter 2004-02, "Potential Impact of Debris Blockage on Emergency Recirculation during Design Basis Accidents at Pressurized-Water Reactors." Specifically, Dominion would submit LARs for North Anna Power Station (NAPS) and Surry Power Station (SPS) that would be based on new containment analysis methods using GOTHIC. During this phone conversation, it was determined that it would facilitate NRC review for Dominion to provide a separate submittal for the thermal-hydraulic analyses topical report in advance of the LARs. Therefore, Dominion is

submitting DOM-NAF-3 for NRC review and approval. The topical report is contained in the attachment to this letter.

Although the docket number is identified for each DEK/DNC/Dominion unit, DEK, DNC and Dominion are requesting the approval for the generic application of this topical report. Plant specific applications of topical report DOM-NAF-3 will be implemented by DEK, DNC and Dominion according to the requirements of 10 CFR 50.59 for changes to FSAR/UFSAR evaluation methodologies. Dominion plans to reference DOM-NAF-3 in a LAR for SPS to be submitted in December 2005 and a LAR for NAPS to be submitted in February 2006.

If you have questions or require additional information, please contact Mr. Paul R. Willoughby at (804) 273-3572.

Very truly yours,

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Attachment

Commitments made in this letter: None

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ATTACHMENT

TOPICAL REPORT DOM-NAF-3

GOTHIC METHODOLOGY FOR ANALYZING THE RESPONSE TO POSTULATED PIPE RUPTURES INSIDE CONTAINMENT

DOMINION ENERGY KEWAUNEE, INC.
DOMINION NUCLEAR CONNECTICUT, INC.
VIRGINIA ELECTRIC AND POWER COMPANY
KEWAUNEE POWER STATION
MILLSTONE POWER STATION
NORTH ANNA POWER STATION
SURRY POWER STATION

DOM-NAF-3-0.0

GOTHIC Methodology for Analyzing the Response to Postulated Pipe Ruptures Inside Containment

Nuclear Analysis and Fuel Department
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October 2005

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Classification/Disclaimer

Abstract

As part of a continuing effort to develop and maintain in-house, thermal-hydraulic safety analysis capability, Dominion (including Virginia Electric and Power Company, Dominion Nuclear Connecticut, Inc., and Dominion Energy Kewaunee, Inc.) has developed a methodology for performing licensing basis analyses for the containment response to postulated pipe ruptures inside containment. The methodology employs the GOTHIC computer code and is applicable for analysis of large, dry containments for pressurized water reactors. GOTHIC is a general-purpose, thermal-hydraulics computer code developed by the Electric Power Research Institute for applications in the nuclear power industry. The NRC has approved GOTHIC for use in containment analyses for several U.S. nuclear power plant licensees. The GOTHIC analysis methodology developed by Dominion is described in this topical report and is submitted for generic NRC review and approval.

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List of Acronyms and Abbreviations

Term	Definition
AFW	Auxiliary feedwater
CAR	Containment air recirculation fans
CDT	Containment depressurization time (time to reach subatmospheric pressure)
CLS	Consequence limiting safeguards
CS	Containment spray
CVTR	Carolinas Virginia Tube Reactor
DEHLG	Double ended hot leg guillotine
DEPSG	Double ended pump suction guillotine
DLM	Diffusion layer model
ECCS	Emergency core cooling system
EPRI	Electric Power Research Institute
EQ	Equipment qualification
ESF	Engineered safeguards features
HDR	Heissdampfreaktor
HHSI	High head safety injection
IRS	Inside recirculation spray
LHSI	Low head safety injection
LOCA	Loss of coolant accident
MSLB	Main steam line break accident
NPSH	Net positive suction head
NPSHa	NPSH available
NRC	Nuclear Regulatory Commission
NSSS	Nuclear steam supply system
ORS	Outside recirculation spray
RCS	Reactor coolant system
RMT	Recirculation mode transfer
RS	Recirculation spray
RSHX	Recirculation spray heat exchanger
RWST	Refueling water storage tank
SG	Steam generator
SI	Safety injection
SPP	Subatmospheric peak pressure
SW	Service water
SWEC	Stone & Webster
TS	Technical Specifications
UFSAR	Updated Final Safety Analysis Report

1.0 Introduction

This topical report documents a methodology for performing containment analysis licensing calculations using the GOTHIC (Generation of Thermal-Hydraulic Information for Containments) computer code. GOTHIC is a general-purpose thermal-hydraulics code for containment analysis developed for the Electric Power Research Institute (EPRI) by Numerical Applications, Inc. (NAI). GOTHIC has been approved by the NRC for containment analysis applications at several U.S. licensees (see Section 2.2). Dominion plans to use the methodology in this report to replace the evaluation methods in the updated final safety analysis reports (UFSARs) for Surry, North Anna, and Millstone Units 2 and 3 for the containment design requirements listed in Section 2.3.

The topical report is broken into five major sections:

- Section 2 provides general information on the GOTHIC code, NRC licensing information, and the planned applications of GOTHIC for containment analyses at Dominion.

- Section 3 documents the GOTHIC analytical methodology applicable to large, dry PWR containments. References are made to NRC-approved applications for the containment response models (e.g., Direct/DLM condensation). A post-reflood mass and energy release methodology that couples the reactor coolant system, steam generator secondary side, and the containment is also presented.

- Section 4 documents Surry demonstration analyses of the methodology in Section 3, with comparisons to the Stone & Webster (SWEC) LOCTIC code, for LOCA peak pressure, containment depressurization, and NPSH available for the LHSI pumps. MSLB demonstration cases are also included. The results of Surry sensitivity studies on key parameters are included as a matrix to demonstrate that appropriate, conservative assumptions are specified in the analysis models.

- Section 5 documents the topical report conclusions.

- Section 6 includes the reference list.

2.0 GOTHIC Overview and Applications

2.1 Overview of the GOTHIC Computer Code

GOTHIC (Generation of Thermal-Hydraulic Information for Containments) is an integrated, general-purpose thermal-hydraulics code for performing licensing containment analyses for nuclear power plants. The code has been developed for the Electric Power Research Institute (EPRI) by Numerical Applications, Inc. References 1-3 document the bases for GOTHIC Version 7.2, the most recent EPRI-released code version. The following code description is obtained from the GOTHIC Technical Manual [1].

GOTHIC solves the conservation equations for mass, momentum and energy for multicomponent, multi-phase flow in lumped parameter and/or multi-dimensional geometries. The phase balance equations are coupled by mechanistic models for interface mass, energy and momentum transfer that cover the entire flow regime from bubbly flow to film/drop flow, as well as single phase flows. The interface models allow for the possibility of thermal non equilibrium between phases and unequal phase velocities, including countercurrent flow. GOTHIC includes full treatment of the momentum transport terms in multidimensional models, with optional models for turbulent shear and turbulent mass and energy diffusion. Other phenomena include models for commonly available safety equipment, heat transfer to structures, hydrogen burn and isotope transport.

A complete description of the qualification of the GOTHIC code for use in containment analysis is provided in the code qualification report [3]. The reader is referred to this document for a discussion of the degree and type of code qualification performed. This topical report refers to Reference 3 to support the selection of specific models in Dominion analyses.

Dominion has participated in the EPRI GOTHIC Advisory Group since the late 1980s to ensure a solid understanding of the code capabilities and limitations, to monitor industry applications, and to guide the code qualification effort. For the first licensing applications, Dominion plans to use GOTHIC version 7.2dom, which consists of the EPRI-released version 7.2 and two enhancements specific to Dominion that were implemented during testing of the GOTHIC containment model for Surry Power Station. The two code changes are summarized.

1) The first change improves the iterative solution for the heat exchangers so that a non-convergent condition is avoided. This condition was discovered during development testing of Surry containment models in GOTHIC version 7.2.
2) The second change adds a user-specified multiplier on the Film heat transfer option to allow sensitivity studies on the mass and energy release model. This feature allows the core conductor to be initialized without using internal heat generation.

Both changes were added to version 7.2 under the Dominion software quality assurance (QA) program, which is part of the overall Dominion QA program under 10 CFR 50 Appendix B. Dominion receives GOTHIC code error reports from EPRI and evaluates each error under the software QA program. Dominion may upgrade to new versions of GOTHIC or install patches to correct code errors as they are made available. The methodology is not restricted to a specific version of the code.

Dominion develops and maintains in-house analytical methodologies in accordance with NRC Generic Letter 83-11, Supplement 1 [4]. Dominion informed the NRC of its formal Generic Letter 83-11 program in Reference 5. The Dominion procedure for controlling safety analysis computer codes and models was transmitted to the NRC in Dominion letter 02-280 in response to NRC Request for Additional Information item 4d regarding topical report VEP-FRD-42, Revision 2 [6]. Section 3.1 of the staff SER for VEP-FRD-42, Revision 2, found the Dominion approach to be an acceptable evaluation process [7]. Future upgrades to new versions of GOTHIC or installation of patches to correct errors will be evaluated under the same NRC-accepted program.

2.2 NRC-Approved GOTHIC Containment Analyses

GOTHIC has been approved by the NRC for containment analysis applications at several U.S. licensees. Recent NRC approvals are documented in References 8-13. The list is not meant to be exhaustive but merely to demonstrate the recent acceptability of NRC to a range of containment licensing applications with GOTHIC. For containment modeling, Dominion has selected correlations that have been previously approved by the NRC and has confirmed the applicability of the models to large, dry PWR containments. For calculation of post-reflood mass and energy release, a simplified GOTHIC model of the reactor coolant system (RCS) and steam generator secondary side has been developed and coupled to the containment. Section 3.5 describes the methodology for modeling the mass and energy release. Section 4 describes model qualification analyses that were performed for Surry pump suction and hot leg breaks with comparisons to NRC-approved Westinghouse methodologies for post-reflood mass and energy releases [14, 16]. Framatome recently received NRC approval for use of a coupled mass and energy release model [30, 31].

2.3 Dominion Licensing Applications of GOTHIC

This report documents the analytical methodology for performing containment analysis for Dominion's large, dry PWR containments with the GOTHIC computer code. Dominion plans to use GOTHIC to perform UFSAR calculations for the following containment design requirements (some criteria are specific to subatmospheric containments):

1. LOCA containment peak pressure and temperature,
2. MSLB containment peak pressure and temperature,
3. LOCA containment depressurization time (CDT) for Surry and North Anna,
4. LOCA containment subatmospheric peak pressure (SPP) for Surry and North Anna,
5. Available net positive suction head (NPSHa) for pumps that take suction from the containment sump. For Surry and North Anna, a time-dependent NPSHa is calculated from a transient containment response for the inside recirculation spray (IRS), outside recirculation spray (ORS), and low head safety injection (LHSI) pumps,
6. Minimum and maximum sump water level and liquid temperature for input to other analyses (e.g., strainer debris head loss and component stress analyses),
7. Containment liner temperature verification,
8. Equipment qualification (EQ) temperature validation, and
9. Transient performance of closed cooling loops for heat exchangers associated with the ECCS and containment heat removal systems.

The LOCA peak pressure calculation is the simplest to perform because the maximum pressure occurs early in the transient (about 20 seconds for blowdown peaks), before the spray systems activate. The peak pressure is dependent on the containment volume, heat sink characteristics, the break energy, and how the break fluid is modeled. MSLB peak pressure calculations run longer because of the continuing release of high energy steam until the auxiliary feedwater (AFW) flow to the faulted steam generator is isolated.

Calculation of CDT and SPP is performed to demonstrate that the containment pressure is bounded by the assumption for containment leakage in the dose consequences analyses. Currently, the North Anna and Surry licensing bases requires the containment to be subatmospheric in one hour and remain subatmospheric thereafter [27, 28]. The CDT and SPP analyses both assume the single failure of one emergency bus, but other assumptions for safety injection flow rates and containment initial conditions are different in order to produce the most conservative effect (e.g., minimum containment initial temperature is conservative for SPP because of the larger air mass that challenges the long-term heat removal of one train of recirculation spray).

For long-term analyses (e.g., the CDT, SPP, EQ and MSLB), the spray systems and other heat removal components are incorporated, and the depletion of the refueling water storage tank (RWST) liquid inventory is modeled in order to predict the time of recirculation mode transfer (RMT), when the safety injection system swaps suction from the RWST to the containment sump, and the time of containment spray (CS) pump termination.

The NPSHa calculations for Surry and North Anna present a challenge in that the appropriate pump suction conditions must be determined based on mixing of cold water that is injected to the pump suction with hotter sump water, the incorporation of suction friction and form losses, and the explicit inclusion of containment overpressure. In addition, conservative modeling of spray systems, condensation heat transfer, and other features is applied different from the CDT and SPP cases (see Section 3.8).

3.0 GOTHIC Containment Analysis Methodology

This section provides the Dominions methodology for constructing GOTHIC models for performing licensing basis analysis for large, dry containments. The methods are intended to provide realistic but conservative results. Justification is based on previously accepted PWR containment methodologies and the extensive validation base for GOTHIC. Many of the input parameters required to construct GOTHIC containment model carry some uncertainty. The following sections provide the methods that have been adopted by Dominion to obtain conservative results for a given analysis objective. Some model components and parameters are not specifically listed, either because they have no impact on the analysis or the exact physical behavior or values are expected to be readily available.

3.1 Containment Noding

Plant licensing analyses use a single volume (node) for the containment building with separate treatment given to the sump and containment atmosphere regions. Inherent in this lumped parameter approach is the assumption that within each region the fluid is well mixed. During a LOCA or MSLB, the mixing induced by the break jet is significant. Later in the transient, containment sprays and/or containment fan coolers continue to promote mixing in the containment. The degree to which well-mixed conditions are attained depends on the location and size of the break, major obstructions in the containment, spray flow rate and pattern, and the location and ducting of fan coolers.

GOTHIC has the capability to model the containment in more detail and calculate the three-dimensional distribution of mass and energy within the containment. Three-dimensional GOTHIC models are referred to as subdivided analyses. To assess the impact of subdivided versus lumped parameter modeling, the CVTR (Carolinas Virginia Tube Reactor) tests were simulated with both types of models [3]. The CVTR tests were typical of a MSLB located high in the containment except that the steam was introduced through a diffuser that reduced the jet momentum and mixing. Results from the subdivided simulations indicate near well-mixed conditions in the upper containment above the operating deck but significantly lower and varied temperatures and steam concentration in the region below the operating deck. The degree of mixing was similar during the steam injection and while the containment sprays were active. In the CVTR containment, the operating deck is a major obstruction between the upper and lower containment and certainly contributed to the nonuniformity of the atmosphere. Experimental results for LOCA type conditions in the Marviken and Heissdampfreaktor (HDR) containments also indicate significant variation in conditions in the containment. While these test containments are more compartmentalized than a typical large dry containment, they indicate that some degree of non-uniformity is possible.

Results from lumped and subdivided GOTHIC models for the CVTR tests indicate that the predicted peak pressure and temperature from the lumped analysis are larger than in the subdivided analysis. Since the major energy removal mechanism during a blowdown is heat transfer to the containment structures due to convection and condensation, one might think that the maldistribution of steam and high temperature conditions would lead to less heat removal because less conductor surface area is exposed to the high energy conditions. However, the condensation rate is a strong function of the steam concentration, and the increased condensation rate in the regions of high steam concentration more than compensate for the smaller effective heat transfer area. Were this not the case, it would be necessary to use subdivided models that consider local effects such as break location and orientation or to add extra conservatism to the lumped model to account for these effects.

The foregoing justification for a single-volume approach to predict peak containment pressure and temperature applies to LOCA and MSLB conditions. For these accident scenarios, the high energy region in the containment is large even though the entire containment might not be fully mixed and the concrete structures are still absorbing heat when the short duration blowdown is over. For long-term analyses, the spray systems are activated, the open regions of the containment are expected to be well-mixed [18], and the single-volume lumped model should be representative of the actual conditions.

3.1.1 Free Volume

The containment free volume is the space occupied by the containment atmosphere. It can be difficult to calculate the free volume exactly because of the complex shapes of all the large and small equipment and structures inside the containment. For a given mass and energy release, a smaller free volume will typically give higher peak pressure and temperature. For containment pressure and temperature analysis, a low estimate is used for the containment free volume. For NPSHa calculations, an upper bounding value is specified to minimize the containment pressure.

3.1.2 Containment Height

The containment height, H, is used for two purposes:

1. The nominal floor area is calculated as $A_f = \frac{V}{H}$, where V is the specified free volume. The floor area is used in the calculation of the drop deposition rate due to gravitational settling.

2. The height is used to calculate the conductor film thickness in the DLM condensation options. Refer to Section 3.3.2 for the assumptions regarding the DLM characteristic height.

The containment height is calculated using the guidance in Section 3.4.1.2 to ensure that the spray height properly accounts for the spray heat and mass transfer in the covered region.

3.1.3 Hydraulic Diameter

GOTHIC uses the hydraulic diameter, D_h, to calculate the surface area of thermal conductors in contact with the atmosphere using

$$A_s = \frac{4V}{D_h} \qquad \text{Equation 1}$$

The user-specified hydraulic diameter is calculated from this formula using the containment free volume and the total surface area of the conductors in contact with the vapor.

3.1.4 Liquid-Vapor Interface Area

The liquid-vapor interface area is used to calculate the heat and mass transfer between the vapor and the liquid phase. It can be set to zero to prevent any heat and mass transfer at the interface or to a very large value to force thermal equilibrium between the vapor and liquid phases. The default value is the maximum of A_f and A_w, where A_w is the wettable area calculated from $\frac{4V}{D_h}$ less any conductor surface area that is too hot to allow a liquid film and A_f is the nominal floor area defined in Section 3.1.2.

This gives a large area for interfacial heat and mass transfer under the assumption that during a LOCA or MSLB nearly all of the surface area will be wet due to condensation or deposited water from the break. The default value has been used for all of the GOTHIC validation against experimental data for simulated line breaks in containments [3]. The GOTHIC default value will be used for the containment lumped volume for containment integrity analyses. For NPSHa, a minimum sump pool surface area is used to minimize the evaporative heat and mass transfer with the net effect of leaving more energy in the sump liquid as the containment depressurizes (and the vapor temperature is less than the liquid temperature). The liquid/vapor interface area inputs for the simplified RCS model are described in Section 3.5.3.3.2.

3.2 GOTHIC Model Elements

As described in Section 3.1, a single lumped volume models the containment building with separate treatment given to the sump and containment atmosphere regions. Containment passive heat sinks are included in the lumped volume. The RWST is modeled with a volume to provide an accurate prediction of inventory drawdown for determining spray flow rate as a function of level, the time of safety injection recirculation mode transfer (RMT), and the time of containment spray termination. An atmosphere boundary condition is used to maintain the RWST pressure as the tank drains.

Other volumes serve as junction connectors to model piping for the safety injection and spray systems. The volumes allow accurate modeling of cold injection flow to pump suctions. Additional details are included in Section 4 for the Surry demonstration analyses. Where appropriate, valves may be used to isolate components/volumes when not in use. Plant-specific models may be different because of design features that require a different treatment (e.g., pump start ramp times, pump heat, heat exchanger performance, and piping fill delays). These model details are not considered part of the analysis methodology

3.2.1 Junction Parameters

For a single volume containment model with most of the flows specified, most of the junction parameters are not influential. The few influential parameters are discussed.

- For junctions taking suction from the containment sump, the junction end elevation and end height are set so that the junction end is fully submerged.

- For a junction that models a suction line, the junction area, friction length and loss coefficients must be accurate and consistent so that the pressure drop from the sump to the pump will be accurately predicted for NPSHa analysis.

- For the junctions used to connect the various volume components of the RCS for the long-term mass and energy release, the areas and loss factors need to be consistent and reasonably accurate so that the model will correctly predict the flow through the SG loops and the flow split at the two ends of the break.

The volume average velocity in the containment is determined by the junction flows and the junction parameters. The volume average velocity is used in the calculation of heat and mass transfer coefficients and in the drop deposition models. Forced convection heat transfer is not credited so the only potential influence is the drop deposition. GOTHIC includes drop deposition

due to impaction. Impaction deposition increases with increasing velocity and increasing drop size. Impaction deposition will be significant only during the blowdown. This deposition will reduce the drop mass in the atmosphere and may cause a small increase in peak temperature and pressure.

The lumped volume velocity is calculated as

$$\overline{U} = \frac{\sum_{\substack{junctions \\ attached\ to\ V}} L_j u_j A_j}{V} \qquad \text{Equation 2}$$

where *L* is the junction inertia length, *u* is the junction velocity and *A* is the junction area. The intention of this formula is that the flow through junction area *A* expands to an area of *V/L*. To maximize the impaction deposition and maintain reasonable volume average velocities, the inertia length of the break junctions is set to the containment height and the junction area is set to the assumed break area. The lengths and areas of other junctions will have negligible effect on the impact deposition as long as physically reasonable values are used.

3.2.2 Accumulator Nitrogen

The NSSS or fuel vendor LOCA mass and energy release data include the water injected from the ECCS accumulators. The accumulator nitrogen is a contributor to the total containment pressure and therefore can affect containment depressurization time and NPSHa. A boundary condition injects the nitrogen volume into the containment atmosphere consistent with the timing in the vendor mass and energy release calculation. GOTHIC inputs for nitrogen pressure, temperature, and volume are based on allowable operating ranges in the plant Technical Specifications with consideration of uncertainty. Section 4.7 documents the conservative direction for these parameters from the Surry sensitivity studies for containment depressurization and NPSHa. The accumulators do not contribute nitrogen to the containment during a MSLB.

3.3 Passive Heat Sinks

3.3.1 Heat Sink Geometry and Nodalization

Thermal conductors are the primary heat sink for the blowdown energy. The conductors can be made of up any number of layers of different materials. One-dimensional conduction solutions are used to be consistent with the lumped modeling approach.

The thermal conductor is divided into regions, one for each material layer, with an appropriate thickness and material property for each region. GOTHIC accepts inputs for material density, thermal conductivity and specific heat. These values are obtained from published literature for the materials present in each conductor. Conductors with high heat flux at the surface and low thermal conductivity must have closely spaced nodes near the surface to adequately track the steep temperature profile. The node spacing is set so the node Biot number for each node is less than 0.1. The Biot number is the ratio of external to internal conductance.

It is not practical or necessary to model each individual piece of equipment or structure in the containment with a separate conductor. Smaller conductors of similar material composition can be combined into a single effective conductor. In this combination, the total mass and the total exposed surface area of the conductors is preserved. The thickness controls the response time for the conductors and is of secondary importance. The conductors are grouped by thickness and material type. The effective thickness for a group of wall conductors is calculated by Equation 3. The heat sink material types, surface areas, and thickness are derived based on plant-specific inventories. Concrete, carbon steel, and stainless steel are the most common materials.

$$t_{eff} = \frac{\sum_{i \in group} t_i A_i}{\sum_{i \in group} A_i} \qquad \text{Equation 3}$$

If there is a small air gap or a contact resistance between the containment liner and the concrete, it is modeled as a separate material layer at the nominal gap thickness with applicable material properties. This overestimates the contact resistance because convection and radiation effects will be ignored. A maximum gap conductance of 100 Btu/hr-ft^2-F is used, consistent with other recent containment analysis applications [20, 21]. The gap width is determined by dividing the gap thermal conductivity by the gap conductance.

All containment passive heat sinks are included in the lumped containment volume. The primary system metal and SG secondary shells are included in the simplified RCS model that is used for the calculation of long-term mass and energy release (see Section 3.5); however, these conductors are not used for condensation or convection heat transfer with the containment atmosphere.

3.3.2 Conductor Surface Heat Transfer

The Direct heat transfer option with the DLM (Diffusion Layer Model) condensation option is used for all containment passive heat sinks except the sump floor. With the Direct option, all condensate goes directly to the liquid pool at the bottom of the volume. The effects of the condensate film on the heat and mass transfer are incorporated in the formulation of the DLM option. Under the DLM option, the condensation rate is calculated using a heat and mass transfer analogy to account for the presence of noncondensing gases. It has been validated against seven test sets [3]. It also compares well with Nusselt's theory for the condensation of pure steam where the rate is controlled by the heat transfer through the condensate film. As shown in the GOTHIC Qualification Report [3], the DLM option generally underpredicts the condensation rate and has previously been accepted by the NRC for LOCA and MSLB containment analyses [8, 9].

The options for natural convection heat transfer for sensible heat transfer and radiant heat to steam are activated as allowed by NUREG-0588 [22]. A natural convection option is selected consistent with the conductor geometry and orientation. Although the Direct/DLM validation basis includes tests with forced convection heat and mass transfer, forced convection has not been accepted for peak temperature and pressure analysis and is not used.

A characteristic height can be specified for each heat transfer option to estimate the film thickness that builds up on the conductor. For typical large dry containment conditions, the heat and mass transfer is controlled by the boundary layer in the vapor phase and the resistance through the film is relatively small so the specified height is of secondary or less importance. When using the DLM option, the characteristic height is set to the containment volume height. This gives thick liquid films that will slightly reduce the heat and mass transfer rates once the film is fully established. This is conservative for containment pressure and temperature analysis. For NPSHa analysis, the heat transfer coefficient is multiplied by 1.2 for conservatism (see Section 3.8.2).

For a conductor representing the containment floor or sump walls that will eventually be covered with water from the break and condensate, the Split heat transfer option is used to switch the heat transfer from the vapor phase to the liquid phase as the liquid level in the containment builds. A quicker transition to liquid heat transfer is more conservative for containment analysis. The Split option is used with α_{lmax}, the maximum liquid fraction, set to

$$\alpha_{l_{max}} = \frac{d}{H} \qquad \text{Equation 4}$$

where d is the transition water depth and H is the volume height. A reasonable value for d of 0.1 inch switches the heat transfer from the vapor phase to the liquid phase as the liquid level in the containment reaches 0.1 inch. Other values may be appropriate depending on the geometry of the floor and sump.

For conductors with both sides exposed to the containment, the Direct option is applied to both sides. Alternatively, if the conductor is symmetric about the centerplane, a half-thickness conductor can be used with the total surface area of the two sides and an insulated back side heat transfer option. The conductor face that is not exposed to the atmosphere is assumed insulated. The Specified Heat Flux option is used with the nominal heat flux set to zero.

Containment walls above grade and the containment dome have a specified external temperature boundary condition with a heat transfer coefficient of 2.0 Btu/hr-ft^2-F to model convective heat transfer to the outside atmosphere. The GOTHIC heat transfer solution scheme allows for accurate initialization of the temperature distribution in the containment wall and dome prior to the transient initiation. This heat transfer coefficient is used in the current LOCTIC licensing basis for North Anna [27] and Surry [28] and remains appropriate for the containment interface with the outside air. Framatome also used this value in Section 6.1.1 of Reference 30.

3.3.3 Containment Liner Thermal Response

The containment liner temperature is verified to be less than the design limit by repeating the peak temperature analyses with one modification. A conservative containment liner response is obtained by adding a small conductor that has the same construction and properties as the liner conductor. A conductor surface area of 1 ft^2 is used to minimize impact on the lumped containment pressure and temperature response. The inside heat transfer option is the same as used for the actual liner conductor (Direct with DLM) with a multiplier of 1.2 for conservatism.

3.3.4 Equipment Qualification

GOTHIC can be used for verification of equipment qualification (EQ). Since both the maximum temperature and the time that the equipment is exposed to high temperature need to be considered, the particular break scenario and single failure for EQ may be different from that for the containment peak pressure analysis and will depend on the characteristics of the equipment.

The temperature response of the limiting equipment can be modeled by adding a small conductor for the equipment. The condensation option for the Direct heat transfer package is set to Uchida with a constant multiplier of 4.0 consistent with NUREG-0588 [22]. Both the natural and forced convection heat transfer options are activated. The characteristic velocity U (ft/sec) for calculating the heat transfer coefficient is specified using control variables as

$$U = 25\frac{\dot{M}_{BD}}{V} \qquad \text{Equation 5}$$

where $\dot{M}_{BD}$ is the blowdown rate in lbm/hr and V is the containment free volume consistent with NUREG-0588 [22]. A characteristic length appropriate for the particular equipment is input.

3.4 Containment Spray and Heat Removal

Dominion nuclear stations include a range of designs for containment spray systems and long-term containment heat removal. This section covers the general modeling practices for spray nozzles, spray pumps, spray system delivery times including piping fill time and pump start delays, containment air recirculation (CAR) fans, and heat exchangers that are used for containment heat removal. The representative demonstration analyses for Surry in Section 4 exercises all of the models except the CAR fans, which Surry does not have. Each plant-specific application will ensure appropriate, conservative modeling for all applicable heat removal components.

3.4.1 Spray Nozzles

GOTHIC includes models that calculate the sensible heat transfer between the drops and the vapor and the evaporation or condensation at the drop surface. The efficiency—the actual temperature rise over the difference between the vapor temperature and the drop inlet temperature—cannot be directly specified in GOTHIC. The efficiency is primarily a function of the drop diameter. The GOTHIC models account for the effect of the diameter through the Reynolds number dependent fall velocity and heat transfer coefficients. A heat and mass transfer analogy is used to calculate the effective mass transfer coefficient, which is used to calculate the evaporation or condensation.

The method for modeling sprays is to inject the drops into the containment via a junction using a nozzle component. The drop size and the fraction of the water flow to convert to drops to account for the height of the spray header are input by the user. The determination of conservative inputs is described in the following sections.

3.4.1.1 Spray Diameter

Spray nozzles typically deliver a spectrum of drop sizes. Smaller drops fall more slowly and reach equilibrium with the vapor more quickly than larger drops because of the larger surface area to mass ratio. GOTHIC does not directly model the drop size distribution. It is assumed that the specified diameter is the Sauter mean diameter. The Sauter mean diameter is calculated from its definition using Equation 6.

$$d_{32} = \frac{\int_0^\infty f(x)x^3dx}{\int_0^\infty f(x)x^2dx} \qquad \text{Equation 6}$$

where f is the frequency of drops of a particular size.

A given mass of drops at the Sauter mean diameter has the same surface to mass ratio as the actual drop spectrum. The consistency of the surface to mass ratio ensures that the heat transfer rate to heat capacity ratio is correct.

A given mass of drops at the Sauter mean diameter also has the same total projected area to mass ratio as the actual drop distribution. Since the deposition rate is given by a balance of the body force and the drag force on the projected area, the fall velocity and deposition rate of the Sauter mean drops are representative of the full drop spectrum. GOTHIC accounts for the growth or shrinkage of drops due to condensation or evaporation.

The drop fall velocity is a function of the drop drag coefficient. The coefficients used in GOTHIC are those recommended by Ishii [23] and include the effects of a large population of drops falling together.

The drop heat and mass transfer models have been validated using data from Spillman [24]. The GOTHIC predicted evaporation rate is in the middle of the range of evaporation rates from experimental data and rates from correlations. Since evaporation and condensation are controlled by the same mechanism (i.e., turbulent diffusion through the boundary layer), it is reasonable to expect that GOTHIC also fairly represents the condensation rate.

3.4.1.2 Spray Height

The lumped parameter approach assumes that conditions are uniform throughout the volume. When sprays are injected into a volume, the drops are assumed to be uniformly distributed throughout the volume regardless of the specified elevation of the junction that carries the spray flow. However, in the actual containment there are typically some regions that are not directly covered by the sprays. The containment geometry parameters must be set to properly account for the spray heat and mass transfer in the covered region.

The heat and mass transfer at the spray droplet surface is determined by the drop and atmosphere temperatures, the steam content of the atmosphere, the drop surface area and the heat and mass transfer coefficients. The heat and mass transfer coefficients depend on the fluid properties at the given temperatures, the drop diameter and pressure and the fall velocity of the spray droplets. Appropriate heat and mass transfer coefficients will be applied if the drop diameter is consistent with the actual spray drop size and if the fall velocity is correct. Spray drops typically reach their terminal velocity within a few feet of the nozzle and the fall velocity is assumed equal to the terminal velocity for lumped modeling in GOTHIC. The terminal velocity depends on the drop diameter and the atmosphere properties. GOTHIC will calculate appropriate heat and mass transfer coefficients if the spray drop diameter is set to the Sauter diameter in Section 3.4.1.1.

From the definition of the Sauter mean drop diameter, the total drop surface area exposed to the atmosphere will be correct if the total drop volume suspended in the atmosphere is correct. The total drop volume in the modeled containment volume is

$$V_d = V\alpha_d \qquad \text{Equation 7}$$

where V is the specified containment volume and α_d is the drop volume fraction in the volume. In the actual containment, the suspended drop volume is

$$V_d^c = V_s\alpha_d^s \qquad \text{Equation 8}$$

where V_s is the sprayed volume in the containment and α_d^s is the drop volume fraction in the sprayed volume.

Since we want the modeled drop volume to be the same as the actual drop volume in the containment, combining the above two equations gives

$$\frac{\alpha_d}{\alpha_d^s} = \frac{V_s}{V} \qquad \text{Equation 9}$$

Neglecting the relatively small amount of condensation on the drops, under steady conditions the drop deposition rate equals the spray injection rate. In the containment, the drop deposition rate is

$$\gamma = A_f^c\alpha_d^s U_\infty \rho_d = m_s \qquad \text{Equation 10}$$

where A_f^c is the floor area where the drops are deposited, U_∞ is the terminal velocity, ρ_d is the density of the water in the drops and m_s is the spray rate.

In GOTHIC, the deposition rate is calculated from

$$\gamma = A_f\alpha_d U_\infty \rho_d = m_s \qquad \text{Equation 11}$$

From the three equations immediately above, the relationship for the floor area is derived in Equation 12. This floor area will give the correct drop volume and surface area exposed to the containment atmosphere.

$$A_f = \frac{\alpha_d^s}{\alpha_d} A_f^c = \frac{V}{V_s} A_f^c$$ Equation 12

Since, by assumption in GOTHIC,

$$A_f = \frac{V}{H}$$ Equation 13

where H is the specified height for the containment volume, the height of the containment volume should be set to

$$H = \frac{V_s}{A_f^c}$$ Equation 14

Setting the containment volume height as recommended above has some side consequences that must be considered:

1. It will increase the pool surface area for heat and mass transfer. However, since the effective area of heat and mass transfer is the maximum of the pool area and the surface area defined by the hydraulic diameter ($4V/D_h$), as long as $4V/Dh > A_f$, there is no effect on peak pressure and temperature analyses.

2. For NPSH analysis, the water depth in the containment will have to be adjusted to account for the artificially increased pool area, A_f^c. Sensitivity studies have shown that NPSHa is not sensitive to a reduction in containment height, because the conservative reduction in drop diameter by a factor of 10 makes the spray drops 100% efficient for NPSH analysis (Section 3.8.2).

The spray volume, V_s, is set to the total volume below the spray headers under the assumption that the region interior to the headers is adequately covered by the spray. The deposition area, A_f^c, is set to the total horizontal area at the bottom of the sprayed regions where the sprays are expected to collect. For all calculations, the nozzle spray flow fraction is set to 1.0.

3.4.1.3 Spray Coverage

The spray header arrangement may result in less than 100% coverage of the containment area below the nozzles based on the nozzle spray cone geometries. However, the sprays induce substantial mixing in the containment [18]. Further, the sprays typically achieve 100% efficiency within a short distance from the nozzle [25]. The 100% spray efficiency assumption was approved in the Kewaunee licensing application of GOTHIC [8]. Therefore, unless the sprays are arranged so that isolated sections of the containment are not covered, the conservatism included by modeling the sprayed volume (Section 3.4.1.2) is sufficient to assure overall conservatism of the spray effectiveness.

3.4.2 Heat Exchangers

Heat exchangers that remove energy from the containment sump are modeled with the available heat exchanger options in GOTHIC. Use of a GOTHIC heat exchanger option dynamically couples the heat exchanger performance to the predicted primary and secondary fluid conditions. This can provide a small benefit compared to other codes (e.g., LOCTIC) that use bounding UA values to cover the fluid conditions predicted over the entire transient.

The GOTHIC heat exchanger type that closely matches the actual heat exchanger is selected. The inside and outside heat transfer areas are calculated from the heat exchanger geometry details. For tube and shell arrangements, the shell side flow area is set to the open area across the tubes at the midplane of the heat exchanger and the shell side hydraulic diameter is set to the tube outer diameter as recommended in Reference 17. The GOTHIC option for built-in heat transfer coefficients is used to determine heat transfer coefficients that depend on the primary and secondary side Reynolds and Prandtl numbers. The heat exchanger models in GOTHIC are for basic heat exchanger designs and may not account for the details of a particular heat exchanger (e.g., baffling in a tube-and-shell heat exchanger). A forcing function can be used on the primary and secondary side heat transfer coefficients to tune the heat exchanger performance to manufacturer or measured specifications. Alternatively, the heat transfer area can be adjusted to match the specified performance. Fouling factors and tube plugging are applied when conservative.

3.4.3 Containment Air Recirculation Fans

Containment air coolers are modeled using a GOTHIC FAN COOLER type heat exchanger. This heat exchanger model has been validated against experimental data for LOCA conditions [3]. The fan cooler heat exchanger model calculates the condensation on the tubes and fins in the presence of noncondensing gases. A heat and mass transfer analogy is used to estimate the mass transfer coefficient from standard heat transfer coefficients for heat exchangers. The GOTHIC built-in heat transfer coefficients are used for both the primary and secondary side.

The air/steam flow through the fan cooler can be specified with a volumetric fan. The mass flow rate through the fan is based on the specified volumetric flow rate and the vapor density in the upstream volume. If the actual cooler has the fan positioned upstream of the coils, the volumetric fan can be placed on the same junction as the heat exchanger to get the correct mass flow through the cooler. If the fan is positioned downstream of the coils, then an additional volume must be added to the model between the cooler and the return to the containment. The conditions in this volume will be representative of the cooler outflow and the volumetric fan should be placed on the junction for air return to the containment.

Fan coolers vary widely in the arrangement of the cooling coils and the water flow circuits through the coils. The GOTHIC fan cooler model has the flexibility to reasonably approximate any coil and flow configuration. However, there are minor variations in design that result in slight differences in manufacturers stated performance and GOTHIC results. The performance of the GOTHIC model for the fan cooler is tuned to match the manufacturer specification or test data. There are two forcing functions that can be used to tune the performance: a multiplier on the primary and secondary side heat transfer coefficients and a multiplier on the film thickness. The film thickness controls the resistance through the liquid film that builds on the fins and tubes. A multiplier on the film thickness will have an impact on cooler performance under design basis accident conditions but no significant affect at normal operating conditions. The cooler is first tuned by adjusting the multiplier on the primary and secondary side heat transfer coefficients to match the manufacturer specification or data for normal operating conditions. The film thickness multiplier can then be adjusted to match specified performance at the accident conditions.

3.5 Break Mass and Energy Release

3.5.1 Treatment of Break Effluent

Flow boundary conditions are used to model the break release paths. The boundary condition pressure, together with the break enthalpy, determines the phase split of the break flow and the phase densities and, therefore, the junction velocity. A lower pressure will result in more steam injection (assuming two-phase conditions) at a higher velocity. Since any injected water will quickly flash to the saturation temperature at the containment pressure and the break pressure cannot be lower than the containment pressure, the boundary condition pressure is set to the containment transient pressure by capturing the containment pressure in a control variable and then assigning the control variable as a forcing function on a nominal pressure of 1.0.

When superheated water is released from the reactor vessel or steam generator, it flashes until the temperature drops to the saturation temperature at the containment total pressure. This flashing causes rapid acceleration of the liquid and breaks the flow up into small drops. Based on experimental data for superheated water discharges, a drop size of 100 microns (0.003937 inch) is used [19]. This value is on the high side of the experimental data and has been approved by the NRC for LOCA and MSLB applications at Kewaunee [8, 9] and Fort Calhoun [10]. For LOCA analysis, the GOTHIC model assumes a constant drop size of 100 microns for the liquid release from the break until the end of the blowdown phase, at which time a continuous liquid is assumed. This assumption is reasonable since the pressure difference between the RCS and containment after the blowdown will not be significant enough to force a break up of the liquid.

GOTHIC includes a drop break up model that can be activated for the break junction rather than specifying the drop diameter. The model generates drops from the liquid flow from flashing of superheated water and due to hydrodynamic forces on the water. For flashing conditions, the model generates drops that are approximately 80 microns, which agrees with experimental data. The advantage of using the drop break up model is that the drop formation will automatically cease as the water temperature becomes subcooled. To make the drop break up model work properly, the upstream pressure must be approximately the actual pressure upstream of the break. If the containment pressure is used, the water will not be superheated and drops will not be formed. The drop break up model will not been used in any licensing calculations.

3.5.2 MSLB Mass and Energy Release

For MSLB, the mass and energy release data is obtained from the NSSS or fuel vendor using NRC-approved methods. The break junction uses 100-micron droplets for entrained liquid release, which was approved by the NRC staff in References 8-10. Consistent with current plant licensing bases, a range of break sizes from small split breaks to the largest double-ended break size is analyzed over the range of 0% to 102% of rated thermal power. Analysis of this range ensures that the most conservative results are predicted for containment pressure and temperature. Plant-specific applications will specify the NRC-approved methodology used to generate the mass and energy release data.

3.5.3 LOCA Mass and Energy Release

3.5.3.1 Blowdown, Refill and Reflood Stages

During a LOCA event, most of the vessel water will be displaced by the steam generated by flashing. The vessel is then refilled by the accumulators and the high and low pressure injection systems. GOTHIC is not suitable for modeling the refill period because it involves quenching of the fuel rods where film boiling conditions may exist. Current versions of GOTHIC do not have models for quenching and film boiling. Therefore, for the blowdown, refill and reflood stages, the mass and energy release rates are obtained from the NSSS or fuel vendor LOCA analysis using NRC-approved methods. The vendor release data includes the water from the ECCS accumulators, but the nitrogen release to containment is modeled separately in GOTHIC (see Section 3.2.2).

3.5.3.2 Post-Reflood Stage

At the end of reflood, the core has been recovered with water and the ECCS continues to supply water to the vessel. Residual stored energy and decay heat comes from the fuel rods. Stored energy in the vessel and primary system metal will also be gradually released to the injection water and released to the containment via steaming through the core or spillage into the containment sump. In addition, there may be some buoyancy-driven circulation through the intact steam generator loops that will remove stored energy from the steam generator metal and the water on the secondary side. Depending on the location of the break, the two-phase mixture in the vessel may pass through the steam generator on the broken loop and acquire heat from the stored energy in the secondary system. For these conditions, GOTHIC is capable of calculating the mass and energy release from the break into containment.

3.5.3.3 GOTHIC Long-Term Mass and Energy Release Modeling

The GOTHIC long-term mass and energy release accounts for the transfer of the decay heat and the stored energy in the primary and secondary systems to the containment after the end of reflood. The energy for each source term is acquired at the end of reflood from the fuel vendor's mass and energy release analysis. The rate of energy release is determined by a simplified GOTHIC RCS model that is coupled to the containment volume. Thus, the flow from the vessel to the containment is dependent on the GOTHIC-calculated containment pressure.

Lumped volumes are used for the vessel, downcomer, cold legs, steam generator secondary side, up-flow steam generator tubes and down-flow steam generator tubes. Separate sets of loop and secondary system volumes are used for the intact and broken loops with the connections between the broken loop and containment as necessary for the modeled break location. The NSSS or fuel vendor's calculated mass and energy inventory at the end of reflood establishes the liquid volume fractions and the fluid temperatures in the primary and secondary systems.

The primary and secondary system geometries, including primary system resistances, are consistent with the models used for non-LOCA accident analyses. In order to predict the natural circulation through the intact loops and the correct water level in the vessel and downcomer, the volumes are modeled with the correct elevations and heights. The vessel height may be adjusted so that the water and steam inventory at the end of reflood matches the vendor's boundary conditions, but this correction does not affect the hydraulic analysis.

Safety injection fluid is added to the downcomer volume (for the intact cold legs) and the broken loop cold leg. In both locations, the SI fluid mixes with the resident fluid and any vapor from the intact SGs. The SI flow is taken from the RWST until a low-low level is reached, at which time the SI fluid is taken from the containment sump.

3.5.3.3.1 Energy Terms

Thermal conductors are used to model the core (stored energy plus decay heat), primary metal, secondary metal, and heat transfer across the SG tubes.

<u>Primary Metal Stored Energy</u>

The distribution of energy throughout the primary system metal may not be provided in the vendor data at the end of reflood. Instead, a lumped metal energy is provided. The metal in contact with steam in the vessel and piping would be substantially hotter than the metal in contact with liquid. For example, the Surry lumped metal energy at the end of reflood corresponds to an average metal temperature about ~170 F above the RCS saturated liquid for a pump suction

break. Initializing GOTHIC with this temperature distribution leads to unrealistic boiling rates early in the post-reflood phase. The effective heat transfer coefficient in the boiling regime is very high and it is expected that the metal in contact with liquid would not be substantially hotter than the RCS liquid at the end of reflood. However, the metal in the steam region of the vessel could be substantially hotter, accounting for the high level of stored energy at the end of reflood.

The primary metal is modeled conservatively such that all of its stored energy is released when the vessel is fully depressurized. One thermal conductor is used for the energy stored in the primary system metal. The Film heat transfer option is used on the conductor side in contact with the RCS liquid so that boiling heat transfer can be modeled. The other side of the conductor is insulated. To consolidate conservatively all of the primary metal in one conductor in contact with liquid, the metal temperature is initialized a few degrees hotter (typically 5 F) than the saturation temperature and an effective mass is calculated using Equation 15 (assuming 5 F hotter metal).

$$M_{eff} = M_{nom} \frac{(T_{nom} - T_{\min})}{(T_{sat} + 5 - T_{\min})} \qquad \text{Equation 15}$$

where M_{nom} is the nominal lumped primary metal mass, T_{nom} is the lumped primary metal temperature based on M_{nom} and the vendor end-of-reflood primary metal energy, T_{min} is the saturation temperature of the fully depressurized vessel, and T_{sat} is the estimated vessel saturation temperature at the end of reflood. This approach gives reasonable boiling rates at the beginning of the post-reflood phase. It conservatively models the energy removal rate from the metal because it assumes that all of the primary system metal is in contact with water. This method ensures that all of the stored energy in the primary metal is removed when the vessel is fully depressurized and the acceptance criteria for containment depressurization and NPSHa are challenged.

Core Stored Energy

The fuel rods are modeled with a thermal conductor. The vendor's energy inventory at the end of reflood is used to set the initial temperature of the fuel rod conductor, consistent with the total heat capacity of the defined conductor. The Film heat transfer option is used on the rod surface in contact with the RCS liquid so that boiling heat transfer can be modeled. The other side of the conductor is insulated.

Decay Heat

The decay heat is modeled by specifying a time-dependent internal heat generation for the fuel conductor. The decay heat fractions are acquired from the 1979 ANSI/ANS Standard 5.1-1979 with 2σ uncertainty added [29]. These fractions are consistent with the current licensing analyses performed for Surry Power Station [16] using the methodology in WCAP-10325-P-A [15]. The decay heat rate is based on 102% of rated thermal power to account for calorimetric uncertainty.

Steam Generators

A thermal conductor is used to model the transfer of energy stored in the shell side of the steam generator to the SG secondary fluid. The initial temperature is set to match the available stored energy specified at the end of reflood by the fuel vendor analysis. The up flow and down flow tubes on the steam generators are modeled separately with thermal conductors. This allows for the possibility of boiling in the up flow tubes and superheating of the steam in the down flow tubes. The heat transfer from the secondary side to the primary side is modeled using conductors with the inside connected to the primary system tube volumes. The Film heat transfer option is used on both sides of the tube. This option automatically accounts for heat transfer to the liquid or vapor phase as appropriate and includes boiling heat transfer modes.

3.5.3.3.2 Pump Suction Breaks

Pump suction and cold leg breaks require special consideration because of the potential for significant energy transfer from the SG secondary fluid to the two-phase mixture leaving the core. The simplified RCS GOTHIC model is used to calculate the mass and energy release rate in the post-reflood phase. During the early part of this phase, there is substantial boiling in the vessel due to the decay heat and the release of stored energy in the fuel, vessel and internals. The boiling raises the two-phase level of the water in the vessel. The surface level affects the amount of water that is carried into the steam generators with the steam produced in the vessel and, consequently, the rate of energy removal from the steam generators. The stored energy in the steam generators will be released more quickly if there is significant water carried in to the steam generators. Another phenomenon that must be addressed is mixing in the cold legs and downcomer of steam from the intact SGs with cold SI. The GOTHIC treatment of both phenomena is addressed below.

Vessel Two-Phase Level

GOTHIC includes the capability to model pool swell due to boiling and vapor flow through the pool, but the volume must be subdivided for these models to be effective. For lumped volumes, the pool surface level is simply determined by the product of the liquid volume fraction and the volume height. If the volume is subdivided, with multiple levels, the level of the water in the upper volumes will be raised by the vapor that displaces the liquid in lower volumes. In addition, the Yeh [34] model is used to estimate that effective liquid level and vapor fraction in the water for any flow paths (junctions) connected to the cells above the lowermost layer.

To activate the Yeh model, the volume representing the RCS vessel is subdivided into two cells. The lower cell represents the lower plenum and core region up to the bottom of the upper plenum and the upper cell represents the upper plenum and upper head. All of the vessel heat sources are located in the lower cell so that all of the vapor flow is into the bottom of the upper cell. This will

maximize the pool level from the Yeh correlation and will maximize the pool swell due to void formation in the lower cell. The hydraulic diameter for the vessel cells will affect the bubble rise velocities and the pool swell. The core hydraulic diameter is specified to capture both effects.

Steam Condensation in Cold Legs

The mixing of cold safety injection (SI) water with the steam from the intact steam generators influences the condensation rate and therefore the flow rate through the steam generators. The release of stored energy in the steam generators will be accelerated if the flow through the steam generators is increased. Higher condensation in the downcomer and cold legs also increases the sump temperature for analysis of NPSH available. A subdivided model for the cold leg and the water injection would provide a realistic estimate of the mixing and condensation rate in the cold leg. However, with a simplified lumped volume modeling of the primary system components, the condensation rate is largely control by the specified liquid/vapor interface area.

For Surry, the maximum SI flow into a single loop is 1527 gpm through a 6" injection pipe, giving an injection velocity of about 19 ft/s. This jet enters the top of the cold leg. The jet momentum is expected to result in substantial mixing in the cold leg. Further, based on GOTHIC calculations, the steam velocity entering the cold legs is about 85 ft/s from early in the post-reflood phase up to ~800 seconds after the LOCA. These steam velocities are high enough to result in substantial drop entrainment and high condensation rates. Based on these conditions, it is expected that water in the cold leg would condense steam up to the point that it reaches that saturation temperature or all of the steam produced by the primary system, whichever is smaller.

Experimental evidence indicates that, during the post-reflood injection, the condensation rate is maximized. The tests documented in Reference 35 were for a 1/3 scale (10" diameter) cold leg. Table 3.5-1 compares the test conditions to the post-reflood conditions from a Surry GOTHIC analysis of a double-ended pump suction (DEPSG) break. The Surry water injection flow rate is for maximum SI. The range of conditions for Surry are from the end of reflood (i.e., activation of the GOTHIC simplified RCS model at ~200 seconds) to the start of SI recirculation flow at ~3600 seconds. Early in this period, the Surry steam flow rate is substantially higher than the experimental range. The injection temperature is lower than the experimental conditions but it is not expected to significantly influence the mixing phenomena. The higher steam flow rates would give more entrainment than the experiments, which promotes maximum condensation. The smaller pipe diameter used in the tests would exaggerate mixing somewhat at lower velocities when gravitational forces become relatively more important.

Table 3.5-1: Comparison of Accident and Experimental Conditions for Cold Leg Mixing

Parameter	Experiment [35]	Surry DEPSG
Pressure, psia	22, 50	12 to 50
Injection Water Velocity, ft/s	1-16	19
Injection Water Temperature, F	80, 120, 150	45 (RWST)
Injection Angle, degrees	90, 45	90
Steam Temperature, F	Sat, 500	Saturation - 400
Steam Flow, lbm/s	3.85, 8.25, 16.8 (full scale)	10 to 65

Based on the previous discussion, the GOTHIC downcomer volume uses a value of 1.0E+08 ft^2 for the liquid/vapor interface area to promote thermal equilibrium conditions, consistent with the experimental evidence. This assumption conservatively maximizes the steam condensation rate and the energy removal rate from the steam generators. Sensitivity studies indicate that the specified value is sufficient to ensure thermal equilibrium conditions in the downcomer volume. The complete mixing assumption between the steam from the intact cold legs and the SI water is also consistent with the NRC-approved methodology in the Westinghouse FROTH code [14].

The GOTHIC model can split the SI flow to the downcomer (for the intact cold legs) and to the broken cold leg based on the actual plant flow distribution. For the broken loop, equilibrium conditions are not assured and some of the injected water may exit the cold leg without significant interaction with the steam. Therefore, the GOTHIC broken cold leg volume assumes a value of 1.0E+08 ft^2 for the liquid/vapor interface area only when it is conservative to assume thermal equilibrium (e.g., to maximize sump temperature for NPSH analyses). For containment depressurization, a liquid/vapor interface area of 0 is specified in the broken cold leg volume, because it is conservative to add to the containment any steam that exits the downcomer (alternatively, the broken cold leg can be modeled with a junction to the containment).

3.5.3.3.3 Hot Leg Breaks

For a hot leg break, the core exit fluid preferably flows out of the broken hot leg, bypassing the steam generators. The flow to the intact SGs will be a very small fraction of the total core exit flow, calculated by the GOTHIC hydraulic model. Because all cold leg injection fluid must pass through the core, the core and vessel metal transfer all of their energy to the SI fluid which spills out of the break. The simplified GOTHIC RCS model is initialized consistent with the energy distribution provided by the vendor at the end of reflood (see Section 3.5.3.3.1).

The simplified GOTHIC RCS model developed for the pump suction break is used for analysis of the hot leg break, with differences for the definition of flow paths that discharge to the

containment. The hot leg model is also simpler in that it does not include two-phase level swell in the core because there is no need to model liquid entrainment into the steam generator tubes. It also does not assume thermal equilibrium in the downcomer, as very little steam flows through the intact steam generators since all subcooled ECCS water must flow through the core.

3.5.3.4 Qualification of the GOTHIC Mass and Energy Release Models

Section 4 describes a typical application of this methodology for Surry Power Station. The analyses demonstrate the conservative nature of the GOTHIC post-reflood mass and energy release rates for DEPSG and DEHLG breaks. This same type of benchmarking would be performed for each plant-specific application.

The integral mass and energy release rates for the two DEPSG break cases (i.e., containment depressurization and LHSI pump NPSHa) compare well to the current post-reflood methodology using the NRC-approved FROTH methodology in WCAP-8264-P-A [14] and WCAP-10325-P-A [16], as implemented using the SWEC LOCTIC containment response code. The SG secondary energy is removed very quickly by the liquid entrainment from the vessel into the intact loop SG tubes. At the time of interest for both LHSI pump NPSHa (i.e., switchover to sump recirculation) and containment depressurization (i.e., containment pressure at 14.7 psia), the SG secondary energy has been released to the containment and the core and primary metal conductors are at or just above the primary system liquid temperature. The integral mass and energy results are similar to the FROTH/LOCTIC analysis methodology.

For the DEHLG break (Section 4.3), the GOTHIC model employs a conservative assumption for the core conductor temperature at the end of reflood. In addition, the simplified RCS model continues to remove primary metal energy when containment pressure decreases below 14.7 psia. Compared to the Westinghouse methodology, more energy is removed from the primary system in the form of higher SI spillage temperatures. The mass release to the containment matches the LOCTIC analysis very closely.

3.6 Containment Initial Conditions

The initial containment atmospheric conditions are chosen consistent with the guidance in NUREG-0800, Sections 6.2.1 and 6.2.1.1.A [37]. The assumptions vary depending on the type of containment being analyzed. For atmospheric containments, the influence of the containment initial conditions was confirmed by running parametric studies using a typical GOTHIC model that assumes a Technical Specifications limit on total pressure and by varying one input while keeping the others constant. The most conservative settings for containment integrity analyses are summarized in Table 3.6-1. The term MAX indicates that the parameter is set to the largest allowable operating value (accommodating instrument uncertainty), while MIN indicates that the parameter is set to the smallest allowable operating value.

North Anna and Surry operate with subatmospheric containments with Technical Specifications limits on maximum and minimum containment air partial pressure. Establishing the air partial pressure limits requires some different input assumptions from Table 3.6-1. For example, LOCA peak pressure cases use the maximum containment temperature and maximum relative humidity. The maximum containment temperature provides the largest initial vapor pressure and the most stringent limitation on air partial pressure. Table 3.6-2 documents the containment initial condition assumptions for subatmospheric containments. Additional analyses are listed that affect the containment air partial pressure limits. These sensitivities are consistent with the current UFSAR LOCTIC analyses for Surry and North Anna.

Table 3.6-1: Containment Initial Conditions

Analysis	Pressure	Temperature	Humidity
LOCA Peak Pressure	MAX	MIN	MIN
MSLB Peak Pressure	MAX	MAX	MIN
LOCA Peak Temperature	MAX	MAX	MAX
MSLB Peak Temperature	MIN	MAX	MIN

Table 3.6-2: Containment Initial Conditions for Subatmospheric Plants

Analysis	Pressure	Temperature	Humidity
LOCA Peak Pressure	MAX	MAX	MAX
MSLB Peak Pressure	MAX	MAX	MAX
LOCA Peak Temperature	MAX	MAX	MAX
MSLB Peak Temperature	MIN	MAX	MIN
Containment Depressurization	MAX	MAX	MAX
Subatmospheric Peak Pressure	MAX	MIN	MAX
NPSH Available	MIN	MAX	MAX

Treatment of Instrument Uncertainties

The containment analysis includes design inputs for plant parameters that are controlled by Technical Specifications (TS). Examples include containment air partial pressure, containment temperature, RWST temperature, and service water temperature. The GOTHIC analyses account for instrument uncertainty on the TS surveillance parameters in one of two ways, with an example for each application:

1) Surveil the TS limit and apply the instrument uncertainty deterministically to develop a GOTHIC input.

   Example: A TS containment temperature maximum limit of 125 F with a 1 F uncertainty would be analyzed in GOTHIC at 126 F.

2) Set the plant surveillance limit with margin to the TS limit, which would be the GOTHIC input.

   Example: With a 1 F uncertainty, the plant surveillance would verify containment temperature is less than 124 F. GOTHIC input would be the TS limit of 125 F.

Both options provide flexibility to accommodate differences in plant surveillance practices while ensuring that the GOTHIC containment analyses are bounding for operation at the Technical Specification limits. Plant-specific applications can utilize either method.

3.7 Run Control Options

The GOTHIC default settings for the run controls are used. The default settings were used for all of the GOTHIC validation against experimental data [3]. The default settings are listed with a brief discussion of the significance of the parameter for containment analysis. Only those parameters that may affect the calculated results are discussed. The remaining typically control code output and have no impact on the computed results.

3.7.1 Revaporization Fraction

Default value: DEFAULT

The revaporization fraction is the fraction of the condensation rate that can be vaporized if the steam in the containment is superheated. Superheat conditions typically occur only for a MSLB. NUREG-0588 [22] allows a maximum revaporization rate of 8% corresponding to a revaporization factor of 0.08. If the atmosphere is superheated, the specified revaporization will be credited regardless of the degree of superheat.

Under the DEFAULT option, GOTHIC uses its built-in models for calculating the vaporization of the liquid in the containment. This model uses a heat and mass transfer analogy to estimate the mass transfer coefficient from the heat transfer coefficient. It accounts for the convective heat transfer and the evaporation in the presence of non-condensing gases. The rate of heat and mass transfer depend on the degree of superheating. That is, the vaporization rate will increase as the superheat increases.

For a MSLB simulation, the DEFAULT option typically gives containment pressures and temperatures that are very close (within 0.1 psia and 1°F) to the same model with the revaporization factor set to 8%. The default models are more physically based and recommended for MSLB analysis. The DEFAULT option was used in the NRC-approved Kewaunee submittal for power uprate [8, 9] and is part of the basis for all validation of the DLM condensation option.

3.7.2 Fog Model

Default value: OFF

The fog model is used to generate fog when the containment atmosphere becomes supersaturated. The fog model has been superseded by the mist model. The option is retained in the code to allow comparison with earlier versions. The fog model creates very small drops that, when combined with drops from the blow down or sprays, result in an average drop diameter that may not be representative of either the fog or the spray.

3.7.3 Maximum Mist Density

Default value: DEFAULT

With the mist model in GOTHIC, if the containment atmosphere becomes supersaturated, small water drops will be generated and the heat of vaporization is added to the vapor phase to eliminate the subcooling. If the vapor starts to become superheated, any mist will be evaporated using heat from the vapor phase. The mist droplets are assumed to be very small so that they move with the vapor and do not settle out. However, if the mist density exceeds the specified value for this control parameter, it is assumed that the mist begins to agglomerate and drops are formed that are added to the drop phase. The default value is 1 gm/m^3 based on meteorological data [26].

3.7.4 Drop Diameter from Mist

Default value: DEFAULT

As described in Section 3.7.3, when the mist density exceeds the specified maximum value, the excess mist is converted to drops at the diameter specified by this control parameter. The default value is 200 microns. This is larger than drops typically found in clouds (~20 microns [26]) but is purposely selected larger to avoid mixing very small drops with containment sprays. The drop formation at this diameter does not significantly affect the diameter of the drops from sprays because the formation rate is much smaller than the spray rate. However, the GOTHIC predicted drop diameter in the containment should be monitored to confirm that the drops are close to the expected value from the sprays.

3.7.5 Minimum Heat Transfer Coefficient

Default value: 0.0

This is the minimum heat transfer coefficient on the vapor side of the liquid vapor interface. There is also a corresponding minimum mass transfer coefficient by the heat and mass transfer analogy. For containment analysis, GOTHIC is allowed to calculate appropriate heat and mass transfer coefficients based on the vapor and liquid phase conditions.

3.7.6 Reference Pressure

Default value: DEFAULT

If a positive value is specified, the vapor density in the body force term in the momentum balances is calculated using the specified pressure and the local temperature. This option is a carry over from older code versions where the vapor pressure may have been inappropriately influenced by the presence of liquid pools. It is no longer useful and DEFAULT is specified so that the local pressure is always used for calculating the vapor density.

3.7.7 Force Entrainment Drop Diameter

Default value: DEFAULT

In subdivided models, the user has the option to force the conversion of liquid flow through a horizontal cell face to drops at the specified diameter. The default value is 0.1 inches. This parameter does not affect lumped models.

3.7.8 Vapor Phase Heat Correction

Default value: INCLUDE

In a cell with a liquid pool that extends above the cell midplane, the cell pressure will reflect the gravitational head of the water in the pool that is above the cell midplane. If this option is set to INCLUDE, this pool gravitational head is subtracted from the cell pressure to calculate the vapor phase pressure. This option is retained only for the purpose of comparing against older code versions that did not include the pressure adjustment. In all other cases the option is set to INCLUDE.

3.7.9 Kinetic Energy

Default value: IGNORE

For high speed flows the kinetic energy is significant and some of the fluid thermal energy is converted to kinetic energy as the flow is accelerated. This option will have minimal effect on containment analysis and is set to IGNORE.

3.7.10 Phase Options

Default values: INCLUDE

For single phase problems, one or two of the phases can be ignored to speed the computation. For containment analysis, all phases are important and the option is set to INCLUDE for all phases.

3.7.11 Force Equilibrium

Default value: IGNORE

If this option is set to INCLUDE, the phases will be forced into thermal equilibrium by using very large interface heat and mass transfer coefficients. The interphase drag coefficients for junctions will also be set to large values to force the phases to travel at a common velocity. This option is available for subcompartment analysis and is not used for containment analyses. When this option is set to IGNORE, there is no assumption regarding phase equilibrium in GOTHIC and the phase temperatures and velocities are determined by the phase balance equations and the interface transfer models.

3.7.12 Drop-Liquid Conversion

Default value: INCLUDE

If this option is set to IGNORE, then drop deposition and drop entrainment will not be allowed. Drops injected at the break or as sprays would remain suspended in the atmosphere indefinitely. For containment analysis, this option should be set to INCLUDE, allowing GOTHIC to deposit and entrain drops based on the mechanistic model in GOTHIC. Drop entrainment is not expected but drop deposition is a significant contributor to the containment response.

3.7.13 Version 6.1 Formulations

Default value: OFF

The development of version 6.1 included changes to some fundamental models in GOTHIC that resulted in some small but significant changes in the calculated results for some models. The involved code revisions in 7.0 and later were determined to be improvements and more faithful to the physics. This option was added to allow comparison of the newer code results with those from previous versions. For all other purposes this option is set to OFF.