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From: Joelle Starefos
To: Vijukrp@westinghouse.com
Date: 11/25/2003 9:18AM
Subject: Staff Comments on Containment Model

Ron,
Please find attached a copy of the report discussed during Friday's conference call. Please discuss with your staff and provide a response to address the concerns in Section 4, Summary and Conclusions. Please reference the long term cooling open item 15.2.7-1 when responding.
Thanks, Joelle

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An Assessment of the Westinghouse AP1000 Small-Break LOCA WGOTHIC Containment Model for Minimum Containment Pressure and Long-Term Cooling

Prepared by the

Containment and Accident Dose Assessment Section
Probabilistic Safety Assessment Branch
Division of Systems Safety and Analyses

November 2003

1.0 Introduction

Westinghouse uses three separate models for containment performance evaluations. The first model is a detailed nodal representation of the containment that is used to perform the maximum containment pressure calculation, based on Standard Review Plan (SRP) 6.2.1.1.A, "PWR Dry Containments, Including Subatmospheric Containments." The second model is a single node representation of the containment that is used to perform the minimum containment pressure calculation, based on SRP 6.2.1.5, "Minimum Containment Pressure Analysis for Emergency Core Cooling System Performance Capability Studies." A third model is used for long-term cooling calculations. This model is based on the detailed model without penalties for heat transfer or for mixing/stratification modeling. In addition the initial and boundary conditions are conservatively set to minimize the calculated pressure, as described in WCAP-14601, "AP600 Accident Analyses - Evaluation Models," Revision 2, May 1998.

The detailed model for the maximum pressure calculation has been reviewed and accepted by the staff for the AP600 and AP1000. The single node model for the minimum pressure calculation has also been reviewed and accepted by the staff for the AP600 and AP1000, for the limiting, large-break LOCA. The long-term cooling model has also been reviewed and accepted by the staff for the AP600.

However, for the AP1000 Westinghouse has proposed to use the long-term cooling model to perform the minimum pressure calculation for the small-break LOCA, a double ended break in the direct vessel injection (DEDVI) line, to evaluate ECCS performance. For the AP600 no credit for containment back pressure was taken for the small-break ECCS performance evaluation.

2.0 Regulatory Guidance

Staff guidance for the calculation of the minimum containment pressure for ECCS performance is provided in SPR Section 6.2.1.5. The staff reviews the conservative assumptions used by the applicant for the operation of heat removal systems and the treatment of passive heat sinks using the guidance provided in Branch Technical Position (BTP) CSB 6-1. This guidance is also included in Regulatory Guide 1.70, "Standard Format and Content of Safety Analysis Reports for Nuclear Power Plants — LWR Edition." Typically, the analysis is performed for the limiting, large-break LOCA with the input assumptions and models selected to minimize the calculated containment pressure.

The purpose of the calculation is to demonstrate compliance with 10 CFR 50.46(a)(1)(i), which allows the ECCS evaluation to use a realistic model that describes the behavior of the reactor coolant system during a LOCA, or 10 CFR 50.46(a)(1)(ii), which requires the ECCS performance evaluation to utilize a model based on 10 CFR 50 Appendix K.

For standard design certification reviews under 10 CFR Part 52, the guidance should be followed, as modified by the procedures in SRP Section 14.3, "Inspections, Tests, Analyses, and Acceptance Criteria - Design Certification," to verify that the design set forth in the standard safety analysis report, including inspections, tests, analysis, and acceptance criteria (ITAAC), site interface requirements and combined license action items, meet the acceptance criteria given in SRP 14.3 subsection II. SRP Section 14.3 contains procedures for the review of certified design material (CDM) for the standard design, including the site parameters, interface criteria, and ITAAC.

3.0 Technical Evaluation

The staff has considered the following material for this review, which examines the model for the calculation of the minimum containment pressure for ECCS performance for a small-break LOCA, and for the long-term cooling evaluation:

(1) Section 5.2.2, "WGOTHIC Containment Pressure Computation," WCAP-14601, "AP600 Accident Analyses - Evaluation Models," Revision 2, May 1998.

(2) Westinghouse letter DCP/NRC1631, September 29, 2003, response to DSER Open Item Number: 15.2.7-1 Item 7.

(3) Westinghouse letter DCP/NRC1636, October 13, 2003, response to DSER Open Item Number: 15.2.7-1 Item 7 Revision 1.

The reference model, for minimum pressure, is taken as the reviewed and accepted single node model as described in AP1000 Tier 2 DCD Section 6.2.1.5. The following parameters are noted, as compared to the detailed model, for maximum pressure, described in AP1000 Tier 2 DCD Section 6.2.1.1.3 :

- the containment volume is 1.1 times the reference value
- the passive heat sink surface areas are 2.1 times their reference values
- the material properties are biased high (conservative)
- the air annulus and the containment shell temperature are assumed to be 0 °F (the passive containment cooling system (PCS) is not modeled, as it would be a heat source for this temperature)
- the containment purge is operating at time zero, and closes 12 seconds after the pressure setpoint of 8 psig is reached
- the initial containment pressure and temperature are set to their low values (14.7 psia, 90 °F), consistent with SRP 6.2.1.5 guidance
- the containment relative humidity is set to 99%

In WCAP-14601, Westinghouse describes the long-term cooling model by comparing it to the maximum pressure calculation model. The staff identified the following differences in comparing the reference model to the long-term model:

- the containment volume is 1.05 times its best estimate value
- the initial containment temperature is 120 °F
- the passive heat sink areas are 1.05 times their best estimate values
- the PCS water flow is set to its maximum value; the external wetted surface is set to its maximum; no heat or mass transfer correlation penalties

In letter DCP/NRC1631, the following differences are noted in comparing the new model (to be used for the small-break LOCA ECCS evaluation and long-term cooling evaluation) to the previously described long-term model (WCAP-14601):

- the heat sinks neglected for the peak pressure analysis are included
- the initial containment temperature is set to its lowest value (unspecified)
- the relative humidity is set to 100%
- the environmental boundary conditions are biased to maximize heat transfer from the PCS (unspecified)

In letter DCP/NRC1636, the following comment by Westinghouse is noted:

- Westinghouse considers the Tagami[1] correlation inappropriate for small-break LOCA analysis and proposes to use the Uchida[2] correlation for passive heat structures

In DCP/NRC1636, Westinghouse comments that the Tagami correlation is inappropriate as the "correlation was developed to account for significant forced convection heat transfer that takes place during the blowdown portion of a large break LOCA." It is further argued that since the same energy is released into containment but over a longer period (from 30 seconds for a large break to 500 seconds for the small break), the average velocities inside containment would be about an order of magnitude lower and it is likely that the Tagami correlation would significantly overpredict the forced heat transfer. Westinghouse therefore proposes to use the Uchida correlation for the passive heat structures.

3.1 Tagami and Uchida Correlations

The range of breaks covered in the Tagami paper was from 10 mm diameter to 70 mm diameter, or a factor of 49 in area from the large to small diameter break. The Tagami paper has been characterized by Gido and Koestel[3] as tests "to obtain a wide range of conditions for the containment atmosphere at the end of blowdown." The tests showed that the heat transfer reached a maximum when the peak pressure occurred. The correlation relates the heat transfer rate to the total energy released during the blowdown, Q, into the containment volume, V, over the blowdown time period, t_p. The correlation, in English units (BTU/ft^2-h-°F), is:

$$h_{\text{Tagami}} = 72.5 \cdot \left(\frac{Q}{V \cdot t_p} \right)^{0.62}$$

The GOTHIC 4.0 Uchida correlation, which is a function of the steam (ρ_{vs}) to noncondensible (ρ_{vg}) density ratio (ρ_{vs}/ρ_{vg}) is, in English units (BTU/ft^2-h-°F):

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[1] T. Tagami, "Interim Report on Safety Assessments and Facilities Establishment Project in Japan for Period Ending June 1965 (No. 1)," prepared for the National Reactor Testing Station, February 28, 1966 (unpublished work).

[2] H. Uchida, A. Oyama, and Y. Toga, "Evaluation of Post-Incident Cooling Systems of Light-Water Power Reactors," Proc. Third International Conference on the Peaceful Uses of Atomic Energy, Volume 13, Session 3.9, United Nations, Geneva (1964).

[3] Gido, R.G., and Koestel, A., "Containment Condensing Heat Transfer," Second International Topical Meeting on Nuclear Reactor Thermal Hydraulics," Santa Barbara, California, January 1983.

$$h_{\text{Uchida-GOTHIC}} = 79.33 \cdot \left(\frac{\rho_{vs}}{\rho_{vg}}\right)^{0.8}$$

$h_{\text{Uchida-GOTHIC}}$ is limited to a maximum value of 278 BTU/ft²-h-°F ($\rho_{vs}/\rho_{vg} > 5$) and a minimum value of 2 BTU/ft²-h-°F ($\rho_{vs}/\rho_{vg} < 0.01$). ρ_{vs}/ρ_{vg} decreases as the accident progresses.

The heat transfer rate for a typical operating PWR (volume of $1.0\text{x}10^6$ ft³, energy release of $2.0\text{x}10^8$ BTU) maximum pressure GOTHIC analysis (based on a single node model) is shown in Figure 1.

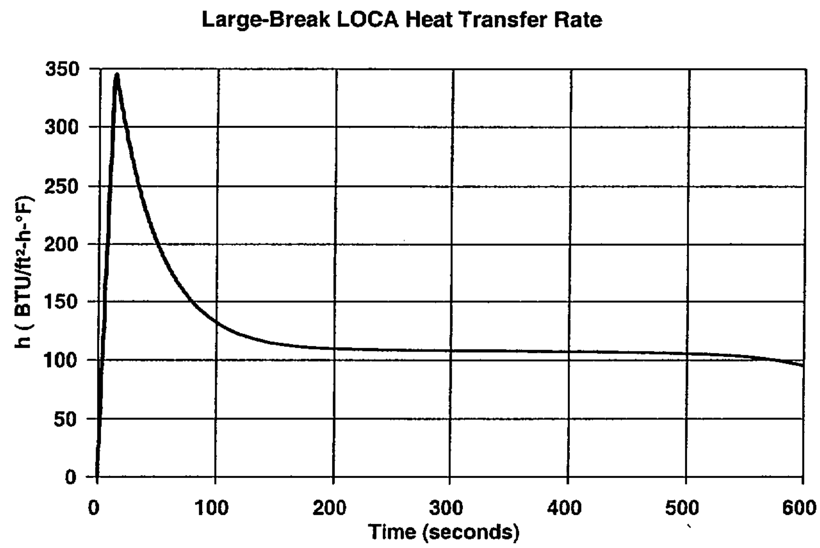

Figure 1 - Large-break LOCA model Tagami-Uchida heat transfer model

The heat transfer rate is linearly ramped to the h_{Tagami} value at the end of blowdown and then exponentially transitions into the Uchida correlation.

For the minimum pressure analysis, the SRP BTP CSB 6-1 recommended heat transfer rate starts at a value of 8 BTU/ft²-h-°F (four times the minimum Uchida value) and ramps up to a value set at four times the value calculated from the Tagami correlation at the end of blowdown. The BTP then recommends an exponential decay of the heat transfer rate to a value equal to 1.2 times the rate obtained from the Uchida correlation.

Based on data from the AP1000 DCD, the containment volume is about $2.0\text{x}10^6$ ft³ and the energy released during the blowdown from a large-break LOCA is about $3.0\text{x}10^8$ BTU. For the large-break, with a blowdown interval of about 25 seconds, h_{Tagami} is about 220 BTU/ft²-h-°F. For the small-break LOCA blowdown interval of about 500 seconds, with the same energy release, h_{Tagami} is about 35 BTU/ft²-h-°F.

For the small-break LOCA, the heat transfer rate developed from the Tagami correlation is smaller than the heat transfer rate obtained from the Uchida correlation. Westinghouse's assertion that using Tagami for the small-break LOCA minimum pressure calculation is inappropriate may be valid, however not as a result of Tagami overpredicting the forced convection heat transfer. The effect of the blowdown time on the Tagami correlation suggests that the correlation may include the effects of the heat transfer mode (velocity is not specifically included in the correlation). For long blowdown intervals the decrease in the heat transfer rate suggests less heat transfer from forced convection.

SRP BTP CSB 6-1 guidance for the use of the Tagami correlation does not appear to be applicable to small-break LOCA minimum pressure analyses to evaluate ECCS performance. A single node model using the Uchida correlation throughout the accident could be considered for licensing. The model would likely also include some conservatism on Uchida, perhaps a multiplier of 1.2. However, this would require additional study — beyond the scope of this review.

The long-term cooling model, based on the detailed nodal model developed for the peak pressure analysis, using the Uchida correlation for passive heat structures throughout the accident seems to be a reasonable starting point for the passive AP1000 design. Assurance of conservatism in the model inputs and initial conditions need to be addressed.

3.2 Heat Structures

Heat structures can be classified into two groups: (1) internal heat structures below the operating deck and non-containment shell heat structures above the operating deck, and (2) those heat structures associated with the WGOTHIC "clime" model. The "clime" model includes the inner condensation surface of the containment shell, the shell material (inner surface paint[4], steel, exterior surface paint[4]), the outer evaporation surface of the containment shell, the riser and chimney region, the baffle plates, the downcomer region, the shield building and finally the environment. A simplified representation of a "clime" is shown in Figure 2.

Condensation on the internal heat structures is usually modeled with the Tagami and Uchida correlations. Condensation on the inside of the containment shell is modeled with correlations developed specifically for the AP600/AP1000 PCS. Evaporation on the outside of the containment shell is modeled with correlations developed specifically for the AP600/AP1000 (with the exception of the chimney region which is conservatively modeled using the Uchida correlation). For the maximum pressure calculation, the AP600/AP1000 correlations include biases to account for uncertainties in the experimental data base. For the outer surface the bias is 0.84 and for the inner surface the bias is 0.73. These values bound the experimental data for the maximum pressure calculation.

[4] an inorganic zinc coating to improve surface wettability

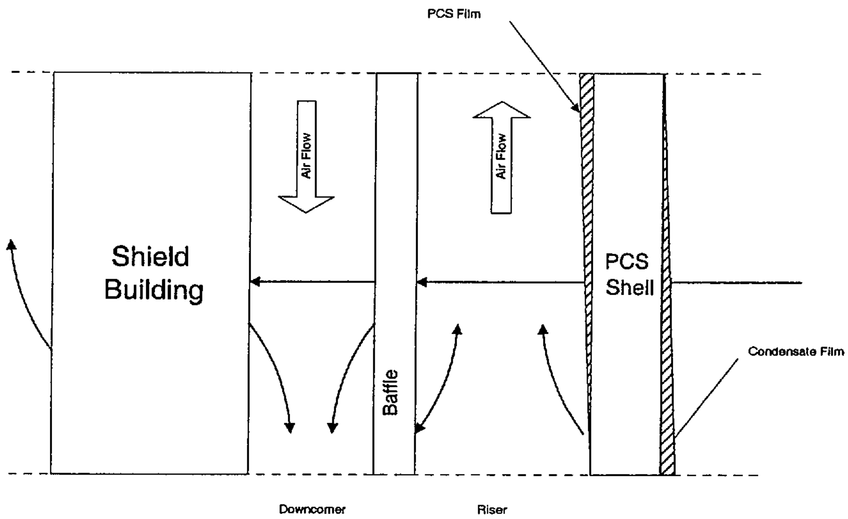

Figure 2 - Simplified representation of a WGOTHIC "clime"

Westinghouse has used, or proposed, three different means for treating the heat structures to be accounted for in the minimum pressure and long-term cooling analysis:

(1) for the current, accepted method: an area 2.1 times the area in the maximum pressure model

(2) for the AP600 long-term cooling model: 1.05 times the "best estimate" area value

(3) for the AP1000 minimum pressure and long-term cooling models: include those structures not previously considered (and include 1.05 times the "best estimate" area value)[5]

Westinghouse has used, or proposed, three different means for treating the "clime" heat structures, or PCS, to be accounted for in the minimum pressure and long-term cooling analysis:

(1) for the current, accepted method: the containment shell temperature is maintained at 0 °F, with no PCS

(2) for the AP600 long-term cooling model: maximum PCS flow, maximum external wetted area (the fraction of the shell covered by the PCS water, which is a function of the time varying PCS flow rate), and no bias on the heat or mass transfer correlations developed for the PCS

(3) for the AP1000 minimum pressure and long-term cooling models: use environmental boundary conditions which maximize heat transfer from the PCS (and include maximum PCS flow, maximum external wetted area — the fraction of the shell covered by the PCS water, which is a function of the time varying PCS flow rate), and no bias on the heat or

[5] Staff expects additional heat structure areas include 1.05 for conservatism

mass transfer correlations developed for the PCS)[6]

3.2.1 Treatment of Heat Structure Heat and Mass Transfer

The Uchida correlation with a multiplier of 1.2 (based on current guidance in SRP BTP CSB 6-1) should be used to model the heat structures below and above the operating deck, and the riser chimney region throughout the accident. In addition, unlike the maximum pressure calculation, heat transfer in dead-ended compartments below the operating deck should not be turned off at the end of blowdown.

The PCS heat and mass transfer correlations should be biased for the minimum pressure and long-term cooling models, based on the position taken by Westinghouse for the determination of the bias for the maximum pressure calculation:

> The outer surface free convection heat transfer multiplier and the outer surface forced convection heat transfer multiplier should be set to 1.19 (1.0/0.84).
>
> The inner surface free convection heat transfer multiplier should be set to 1.37 (1.0/0.73), and the inner surface forced convection multiplier set to 1.37 (for the maximum pressure model the value used is 1.0×10^{-10}, no credit for forced convection).

Westinghouse could revisit the experimental data base to determine these multipliers.

In addition, the material properties (for steel, concrete, air and the inorganic zinc coating) should be biased high for conservatism.

3.2.2 Treatment of PCS Flow

In the WGOTHIC evaluation model (for maximum pressure calculation), the fractions of the "clime" surfaces covered by the water film are held constant throughout the transient, independent of time, axial position, or variations in heat flux. Instead of time-varying these coverage areas, the applied PCS flow rate is limited to the mass expected to evaporate. Westinghouse developed an "evaporation limited" model to account for the wetted surface area change. This model computes, outside of WGOTHIC (see Section 7 in WCAP-15846[7]), a boundary condition, for use in WGOTHIC, in the form of an input PCS flow-versus-time table. This table specifies the PCS flow which is expected to evaporate and omits the PCS flow that is expected to run off the bottom of the vertical sidewall. This allows Westinghouse to maintain a single 90 percent wet "clime" model throughout a WGOTHIC analysis. Instead of time-varying areas, the WGOTHIC boundary conditions specify time-varying PCS flows. These flows are applied to the top of each wet clime stack. WGOTHIC reduces the flow entering each downstream "clime" in a stack by the amount evaporated upstream. When the flow rate drops below the minimum necessary to maintain a stable film, the wetted perimeter in the "clime" is reduced. Therefore, "wet climes" need not be completely covered by the PCS water film.

The use of the maximum PCS flow rate and maximum wetted surface area are acceptable for

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[6] Staff expects conservatism maintained in PCS flow rate modeling, with new boundary conditions

[7] WCAP-15846, "WGOTHIC Application to AP600 and AP1000," Revision 0, April 2002.

the minimum pressure and long-term cooling models. The iterative analysis used to adjust the PCS flow rate, to ensure no excess water (limited to the mass expected to evaporate), is not required for the minimum pressure and long-term cooling models, since more energy would be removed — conservative for these applications. However, the analysis must be reviewed by Westinghouse to ensure "clime" numerical stability is maintained.

Heat transfer credit for the PCS should start earlier than is currently assumed for the maximum pressure calculation. The start time could be as early as the start of the accident or delayed for the time necessary to cover the containment dome and exclude the time needed for the PCS film to traverse the vertical height of the containment shell.

The PCS water temperature and the environment boundary conditions are stated to be biased in a conservative manner, which would be low values. These values were not presented in the documents available for review. SRP BTP CSB 6-1 guidance states that "A reasonably low ambient temperature external to the containment should be used." The average low temperature during the coolest part of the year within the plant siting envelope, with its associated PCS water storage tank temperature, could be acceptable for the minimum pressure and long-term cooling models. Westinghouse should provide their values and rationale for staff review.

3.2.3 Treatment of Heat Structure Areas and Modeling

The heat structure areas for the containment shell above the operating deck and the PCS downcomer, baffle, riser and chimney structures are fairly well known, and easy to calculate. For conservatism the areas should be multiplied by 1.1, based on the multiplier that should be for the containment net volume (see Section 3.4 below).

The heat structure areas for the containment shell below the operating deck are also fairly well known, and easy to calculate. For conservatism the areas should be multiplied by 1.1. In addition, the air-gap between the steel and the concrete should be reduced from the 20-mil thickness used in the maximum pressure calculation. A zero thickness air-gap would be conservative. A nominal thickness could be considered.

The remaining heat structures (see Table 1 for examples) need to be accounted for in a conservative manner. For the maximum pressure calculations, Westinghouse conservatively ignores smaller structures like gratings, cable trains and small piping. During the AP600 review, these smaller structures were identified and originally included in the maximum pressure model. However, it would have been necessary to include these structures in the AP600 ITAAC (for validation and verification of the assumptions used in the licensing analyses) and Westinghouse later omitted them from the model. For the AP600 minimum pressure calculation the remaining heat structures' areas were multiplied by 2.1 for conservatism.

Table 1 Identification of Containment Heat Sinks

Containment Building	liner plate and external concrete walls, floor, sump, and linear anchors
Containment Internal Structures	internal separation walls and floors, refueling pool and fuel transfer pit walls, and shielding walls
Supports	reactor vessel, steam generator, pumps, tanks, major components, pipe supports, and storage racks
Uninsulated Systems and Components	cold water systems, heating, ventilation and air conditioning systems, pumps, motors, fan coolers, recombiners, and tanks

Miscellaneous Equipment	ladders, gratings, electrical cables, trays, and cranes

To accept inclusion of these small structures for the AP1000 minimum pressure and long-term cooling models, Westinghouse would be required to identify them, include them in the AP1000 ITAAC and ensure that none are missed — it would be non-conservative to ignore heat structures for the minimum pressure calculation. If Westinghouse wants to maintain these heat structures in the models and commits to including them in the ITAAC, then the staff would revisit the heat structure and containment net volume multipliers to develop acceptable values for conservatism.

Westinghouse should use the current approach for the smaller heat structures. However, since Westinghouse has some knowledge of the smaller heat structures, an estimate of the multiplier on the current (those used for the maximum pressure calculation) heat structure areas could be made and justified if the value is shown to be less than 2.1 (the currently accepted value).

3.3 Break Flow

The mass and energy releases into containment should be calculated in a conservative manner to minimize the containment pressure. The blowdown mass and energy should be calculated with the accepted AP1000 small-break LOCA model (NOTRUMP) using the same guidance and assumptions previously accepted for minimum pressure calculations (the critical flow model and the RCS and the reactor core initial conditions). For the long-term (post blowdown) the WCOBRA/TRAC code is used to evaluate the ECCS performance.

SRP BTP CSB 6-1 also includes guidance on "Containment Steam Mixing With Spilled ECCS Water." The spillage of subcooled ECCS water into the containment provides an additional heat sink as the subcooled ECCS water mixes with the steam in the containment. The effect of the steam-water mixing should be considered in the containment pressure calculations.

In 1979, Westinghouse implemented a "spill-to-spray" model into the 1978 Westinghouse ECCS evaluation model.[8] The model takes the spilled subcooled ECCS water and treats it in the same manner as a containment spray. The effect is to lower the containment pressure by about 2 psi when compared to spilling the ECCS water directly to the sump.

For the AP1000 DEDVI line break, ECCS spillage will occur and needs to be addressed in the minimum pressure and long-term cooling models. The ECCS water is a single-phase fluid at low temperature, about 80 °F, and at high pressure. For the AP600 and AP1000 long-term cooling models, Westinghouse assumes the ECCS to spill directly to the sump and not interact with the containment atmosphere. In response to a staff RAI, Westinghouse provided a study in DCP/NRC1636 addressing ECCS spillage. When the ECCS water is assumed to disperse into the atmosphere (using the WGOTHIC break flow model which is based on a 100-micron drop size), the containment pressure is reduced by about 2 psi, similar to the "spill-to-spray" model developed in 1979.

Some fraction of the ECCS spillage should be modeled to interact with the containment atmosphere, as a result of jet breakup or interaction with structures. The DCP/NRC1636

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[8] Letter SE-SA/I-2637, dated January 10, 1979, from S.D. Kopelic, B.S. Monty and R.A. Muench, Westinghouse Electric Corporation, Power Division, to C. Berlinger, U.S. Nuclear Regulatory Commission.

sensitively study provides a bounding analysis for this effect. A conservative, but not bounding, assessment could be prepared by Westinghouse for staff consideration. For conservatism, Westinghouse should maintain its treatment of ECCS spillage as implemented in 1979 (with the WGOTHIC break flow model being acceptable for this evaluation).

3.4 Containment Initial Conditions

The initial containment conditions of 14.7 psia, 90 °F and 100% relative humidly are acceptable and consistent with the guidance in the SRP, and are conservative for the minimum pressure calculation. In addition, the containment purge system should be assumed to be operating and isolate on the high pressure signal.

SRP BTP CSB 6-1 guidance for the containment volume states that the maximum net free containment volume should be used. This maximum free volume should be determined from the gross containment volume minus the volumes of internal structures such as walls and floors, structural steel, major equipment, and piping. The individual volume calculations should reflect the uncertainty in the component volumes. The typical volume increase used in previous licensing analyses is a factor of 1.1 times the volume used for the maximum pressure calculation. This value should be used for the AP1000.

If Westinghouse wants to maintain the smaller heat structures in the models and commits to including them in the ITAAC, then the staff would revisit the heat structure and containment net volume multipliers to develop acceptable values for conservatism.

4.0 Summary and Conclusions

The following conservatism assumptions should be incorporated into the AP1000 minimum pressure and long-term cooling models, with the detailed maximum pressure model as the reference point:

- The containment net volume should be increased by a factor of 1.1.
- The containment shell and PCS heat structure areas should be increased by a factor of 1.1.
- The remaining heat structure areas should be increased by a factor of 2.1, or a lower value if justified based on an accounting of expected structures in the final as-built plant.
- The Uchida correlation with a multiplier of 1.2 should be used for passive heat structures (non PCS structures) throughout the accident.
- The PCS heat and mass transfer correlation multipliers should be appropriately biased to account for the uncertainty in the experiential data base, and forced convection should be included on the PCS inner surface.
- Heat transfer in dead-ended compartments below the operating deck should not be turned off at the end of blowdown.

- The air-gap between the steel and the concrete should be reduced from the 20-mil thickness used in the maximum pressure calculation. A zero thickness air-gap would be conservative. A nominal thickness could be considered.

- The material properties (for steel, concrete, air and the inorganic zinc coating) should be biased high for conservatism.

- Heat transfer credit for the PCS should start earlier than is currently assumed for the maximum pressure calculation. The start time could be as early as the start of the accident or delayed for the time necessary to cover the containment dome and exclude the time needed for the PCS film to traverse the vertical height of the containment shell.

- Westinghouse should maintain its treatment of ECCS spillage as implemented in 1979 (with the WGOTHIC break flow model being acceptable for this evaluation).

- The containment purge system should be assumed to be operating and isolate on a high pressure signal.

- The initial and boundary conditions for the PCS water and environment should be provided with their justification for staff review.