



Westinghouse Electric Company
Nuclear Power Plants
P.O. Box 355
Pittsburgh, Pennsylvania 15230-0355
USA

U.S. Nuclear Regulatory Commission
ATTENTION: Document Control Desk
Washington, D.C. 20555

Direct tel: 412-374-4728
Direct fax: 412-374-5005
e-mail: vijukrp@westinghouse.com

Your ref: Docket No. 52-006
Our ref: DCP/NRC1692


April 2, 2004

SUBJECT: Transmittal of Revised Responses to AP1000 DSER Open Items

This letter transmits Westinghouse revised responses for Open Items in the AP1000 Design Safety Evaluation Report (DSER). A list of the revised DSER Open Item responses transmitted with this letter is Attachment 1. The non-proprietary responses are transmitted as Attachment 2.

Please contact me at 412-374-4728 if you have any questions concerning this submittal.

Very truly yours,


R. P. Vijuk, Manager
Passive Plant Engineering
AP600 & AP1000 Projects

/Attachments

1. List of the AP1000 Design Certification Review, Draft Safety Evaluation Report Open Item Responses transmitted with letter DCP/NRC1692
2. Non-Proprietary AP1000 Design Certification Review, Draft Safety Evaluation Report Open Item Responses dated April 2, 2004

DA03

April 2, 2004

Attachment 1

**List of
Non-Proprietary Responses**

Table 1 “List of Westinghouse’s Responses to DSER Open Items Transmitted in DCP/NRC1692”	
6.4-1, Revision 2 15.3-1, Revision 3 15.3.6-1, Revision 2	

Westinghouse Non-Proprietary Class 3

**DCP/NRC1692
Docket No. 52-006**

April 2, 2004

Attachment 2

**AP1000 Design Certification Review
Draft Safety Evaluation Report Open Item Non-Proprietary Responses**

AP1000 DESIGN CERTIFICATION REVIEW

Draft Safety Evaluation Report Open Item Response

DSER Open Item Number: 6.4-1 Revision 2

Original RAI Number(s): 451.006, 451.006 Rev. 1

Summary of Issue:

The staff has not completed its review of the applicant's control room atmospheric dispersion factors (see Section 2.3.4 of this report). These factors are an input to the radiological analyses. Pending resolution of the staff's concerns with the hypothetical reference control room χ/Q values, review of the control room habitability radiological consequences analyses for design basis accidents is also incomplete as discussed in DSER Open Item 15.3-2. Therefore, the resolution of issues associated with the analysis of the dose to MCR personnel during design-basis accidents is DSER Open Item 6.4-1.

Westinghouse Response:

This item will be resolved through the resolution of DSER Open Item 2.3.4-1.

Westinghouse Response (Revision 2):

Revision 2 of this response is to reference 15.3-1 Response Revision 3, rather than Revision 2.

Open Item 15.3-1 Response Revision 3 includes revision to the allowable control room χ/Q values resulting from revision of the containment aerosol removal analysis. The methodology for determining control room χ/Q as discussed in Open Item 2.3.4-1 Response Revision 3 and DCD Appendix 15A remains applicable for AP1000.

Design Control Document (DCD) Revision:

None

PRA Revision:

None

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DSER Open Item Number: 15.3-1 Response Revision 3

Original RAI Number(s): 470.009, 470.011

Summary of Issue:

The staff has not completed its evaluation of the applicability of the AP600 aerosol removal coefficients to the AP1000 design. The staff will evaluate the impact of the differences in the AP1000 design as compared to the AP600 on the modeling of aerosol removal and will perform independent analyses of the estimated aerosol removal rates. Upon resolution of issues with the determination of aerosol removal rates in containment, as discussed in RAIs 470.009 and 470.011, the staff will complete its evaluation of the bounding accident sequence and the aerosol behavior and removal rates corresponding to the selected bounding accident sequence in the containment following a DBA. This is Open Item 15.3-1.

Westinghouse Response:

The Westinghouse responses to RAI 470.009 transmitted by Westinghouse letter DCP/NRC1535, November 26, 2002 and RAI 470.011 Rev. 1 transmitted by Westinghouse letter DCP/NRC1571, April 11, 2003 address previous NRC comments related to this issue.

NRC Additional Comments (Nov 6, 2003 telecon):

- a) Clarify the use of shape factor described in section 15B.2.1.1 of the DCD.
- b) Discuss the sensitivity of aerosol removal to aerosol void fraction identified in section 15B.4.2.3.

Westinghouse Response to NRC Additional Comments (Nov 6, 2003 telecon):

- a) Section 15B.2.1.1 and 15B.3 of the DCD will be revised as shown below.
- b) Section 15B.2.4.3 of the DCD will be revised as shown below.

NRC Additional Comments (March 10, 15 and 16, 2004 telecons):

- a) Provide additional justification for aerosol removal by thermophoresis. In particular, address how the heat transfer rate from the air to the containment wall is calculated and applied in the determination of aerosol removal by thermophoresis.
- b) The particle density fraction (0.8) and void content (water) used by Westinghouse are not sufficiently conservative; NRC would agree with particle density fraction of 0.6 and void content of air.

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- c) The core inventory of Iodine and Cesium used in the AP1000 analysis seems high compared to these values for cores that NRC has reviewed for operating plants.

NRC Additional Comments (March 30 and 31, 2004 telecons):

Only convection heat transfer should be used in determining the lambda due to thermophoresis.

Explain the effect of the revised lambda and atmospheric dispersion factors on accidents other than LOCA.

Explain the long term trend of the overall lambda for AP1000 as compared to that for AP600.

Westinghouse Response (Rev 3) to NRC Additional Comments (March 10, 15, 16, 30 and 31, 2004 telecons):

Revision 3 of this response provides a revised version of the following discussion to address the NRC additional comments from the March 30 and 31 telecons. In particular, the STARNAUA analysis of aerosol removal by thermophoresis now uses only the convective heat transfer at the containment wall as calculated by MAAP4. Explanations are added regarding accidents other than LOCA, and regarding the long term trend of the AP1000 overall lambda. The control room dose analysis assumption regarding unfiltered air inleakage for the case when the active ventilation system is assumed operable is reduced from 140 cfm to 110 cfm. The lower value is still conservative with respect to what has been achievable in operating plants. Tracer gas testing for unfiltered air inleakage will be conducted to confirm the assumed inleakage.

- a) The aerosol removal analysis in DCD Revision 10 used an incorrect input for the heat transfer from the containment air to the containment shell. The STARNAUA analysis has now been performed using correct input for this heat transfer that drives the thermophoresis removal mechanism. The following discussion provides the results of the new STARNAUA analysis and the results of new dose calculations using the aerosol removal rates from the new STARNAUA analysis.

Definition of thermophoresis

If a temperature gradient exists in an air volume, a particle in that volume tends to migrate towards the cooler region. The motion is the result of gas molecules on the warm side striking the particle with a greater average momentum than those on the cooler side. This phenomena is defined as thermophoresis. Thermophoresis will exist when there is a temperature gradient in the gas regardless of whether the gradient is caused by conduction or by natural and/or forced convection.

Determination of temperature gradient

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Boundary layer theory for convective flow and heat transfer in a gas at a solid surface indicates that the heat transfer rate is ultimately determined by the thermal conduction in the sublayer at the heat transfer surface, which is given by:

$$q = -k_{\text{air}} \cdot A \cdot \frac{dT}{dy}$$

where q is the heat transfer rate, k_{air} is the thermal conductivity of air and dT/dy is the temperature gradient at the heat transfer surface (i.e., $y=0$). However, in engineering applications, convective heat transfer problems are solved not by the equation above, but by:

$$q = h \cdot A \cdot (T_a - T_s)$$

where h is the heat transfer coefficient, T_a is the ambient temperature and T_s is the temperature of heat transfer surface. The reason is that dT/dy at the surface is unknown and is hard to determine in tests. On the other hand, the unknown h can be calculated easily by many empirical or semi-empirical correlations. Once q is calculated using second equation above, it can be substituted into the first equation to calculate the temperature gradient at the wall, i.e.,

$$\left| \frac{dT}{dy} \right| = \frac{q}{k_{\text{air}} \cdot A}$$

Detailed development of this relationship can be found in heat transfer textbooks (e.g., Heat Transfer, J.P. Holman, 4th edition, 1976, McGraw Hill).

Value for a realistic temperature gradient

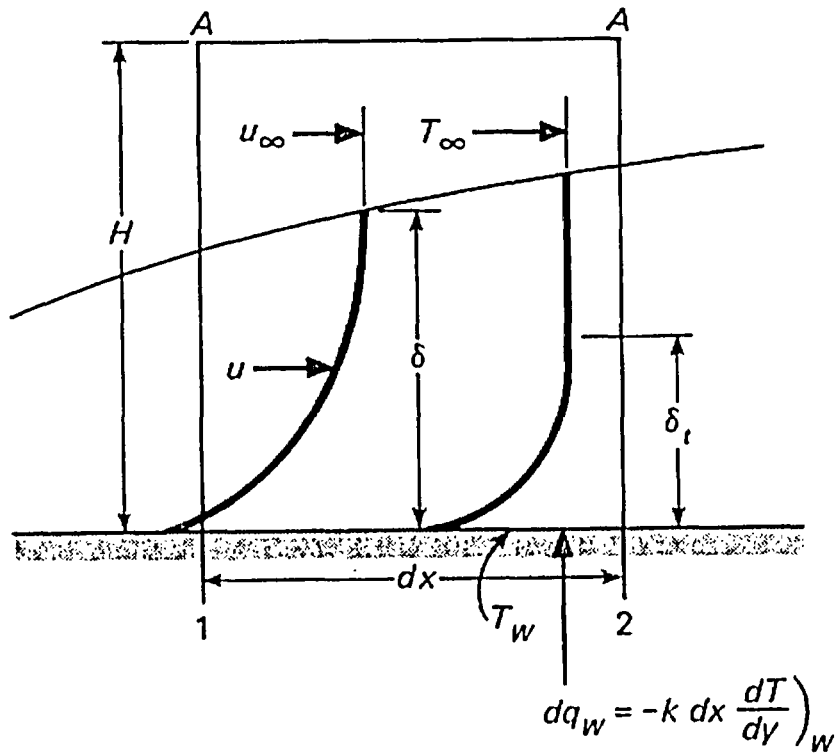
A high temperature gradient at the wall is not unreasonable even for natural convection situations; on pages 248-250 of the Holman textbook cited above is an example for natural convection of air on a heated vertical surface. The heat flux in this example is 800 W/m^2 and the conductivity of air is given as $0.032 \text{ W/m}^\circ\text{C}$. This results in a temperature gradient at the wall of 25°C/mm .

The natural convection heat transfer for the AP1000 severe accident scenario is this same order of magnitude (few hundred W/m^2), so the temperature gradient is also the same order of magnitude as in the textbook example.

The figure below from the Holman textbook illustrates the thermal and momentum boundary layers.

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Calculation of heat transfer from containment air to the wall

The convective heat transfer to the containment shell was determined from the MAAP4 simulation of sequence 3BE-01. The containment gas temperature and the film temperature on the wall are shown in Figure 1 for this sequence. Figure 2 shows the temperature difference between the gas and the film which is the driving mechanism for heat transfer. Figure 3 shows the MAAP4 calculated convective heat transfer to the film on the containment inner surface.

References

1. Holman, J.P., Heat Transfer, McGraw Hill, 4th Ed, 1976.

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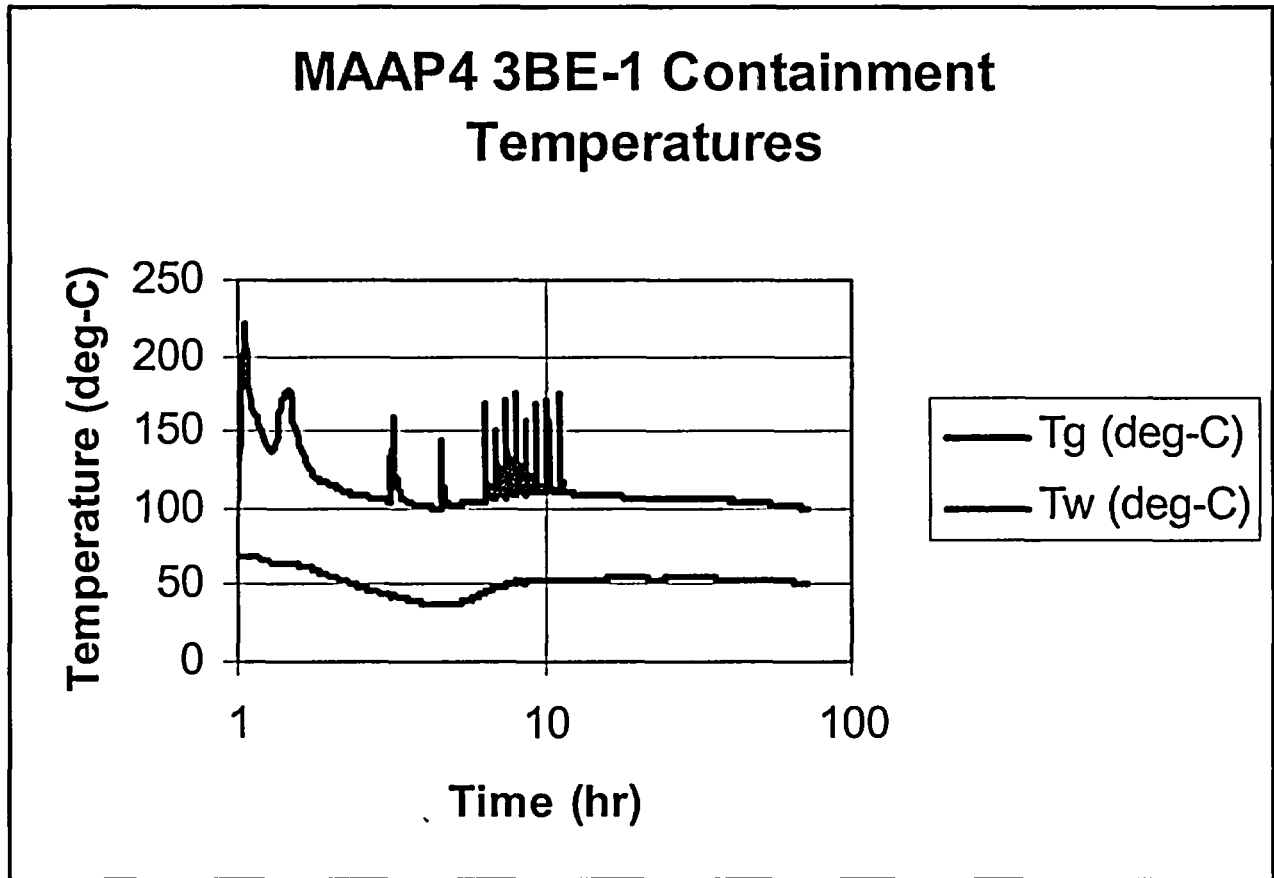


Figure 1: MAAP4 Containment Temperature for Sequence 3BE-1

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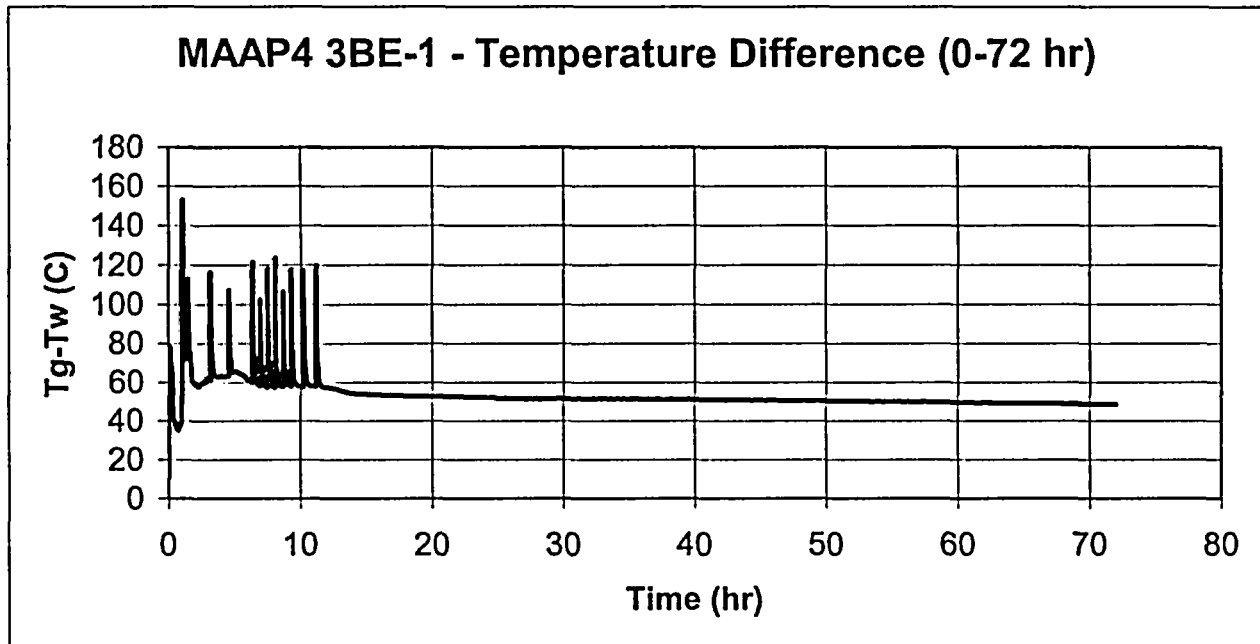


Figure 2: MAAP4 Temperature Difference Between Containment Atmosphere and Liquid Film at the Wall (0 – 72 hours)

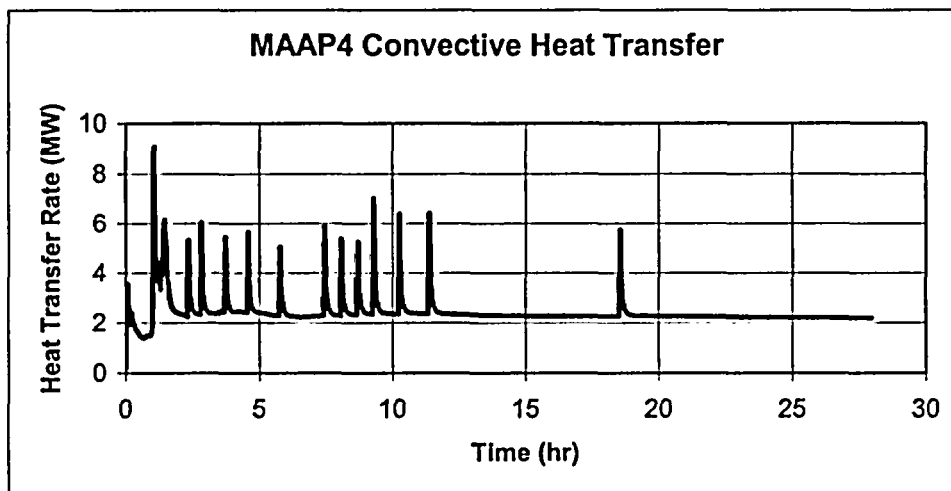


Figure 3: MAAP4 Convective Heat Transfer Between Containment Atmosphere and Liquid Film at the Wall (0 – 28 hours)

The convective heat flux from MAAP4 is used in the STARNAUA analysis determination of thermophoretic aerosol removal. The heat transfer rate is converted to heat flux by dividing

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by the containment wall area. The temperature gradient in the air near the containment shell is calculated by dividing the heat flux by conductivity of the air. This is a direct determination of the temperature gradient and can be quite large even for modest heat transfer coefficients and temperature differences, as shown above.

This temperature gradient is used in the Thermophoresis correlation to get thermophoretic deposition velocity. STARNAUA applies this deposition velocity to determine the rate at which aerosol particles are deposited on the water film surface at the wall by multiplying the thermophoretic deposition velocity by the particle concentration and wall surface area. The particle concentration used here is based on a well mixed containment atmosphere. Mixing in the bulk containment is driven by the convective forces resulting from steaming into containment and heat transfer at the boundaries of the containment atmosphere. Even with a high thermophoretic deposition of particles near the wall, the particles in the bulk space will travel fast enough to the region near the wall to maintain a continuous deposition. One can easily derive that the thermophoretic velocity of particles is on the order of a fraction of cm per second. It is very small when compared to particle movement in the bulk space, which is on the order of meters per second or higher. Therefore, thermophoresis will not cause a particle free zone near the surface.

Evaluation of Mixing and Stratification in the AP1000 Containment

As part of the AP600 Design Certification process, a test facility was constructed to characterize the passive containment cooling system. The Large Scale Test facility (Ref: M.D. Kennedy, et al, "Westinghouse-GOTHIC Comparisons with Passive Containment Cooling Tests Using a One-to-Ten Scale Test Facility", Nuclear Technology, Vol. 113, January 1996) was constructed to test a range of containment designs from the Heavy Water Reactor Facility which was a 1:10 scale, to the AP600 which was a 1:8 scale. The vessel was designed with a prototypic height to diameter ratio. The facility was equipped with a water film distribution system on the outside of the shell, and a steam injection system to simulate the mass and energy releases during a large pipe break inside containment. Several tests were performed including steady-state tests to determine the heat and mass transfer characteristics inside and outside the containment shell, transient simulations to determine the containment pressure response to simulated releases, and releases of non-condensable gas along with the steam to determine the degree of mixing and stratification inside the containment.

For the steam-only tests, it was determined that the volume above the operating deck was typically well mixed with somewhat higher temperature above the steam release point along the centerline of the vessel, and lower temperatures along the walls. Flow patterns were observed to be upflow along the centerline and downflow along the walls. The volumes below the operating deck were stagnant, air-rich, and generally much colder than the volume above the deck. Gas velocities were found to be related to the velocity and orientation of the steam jet, but were generally found to be on the order of ~1 m/s.

For the non-condensable gas injection tests, helium was used to simulate hydrogen that would be evolved during a severe accident. For these tests, helium was injected along with

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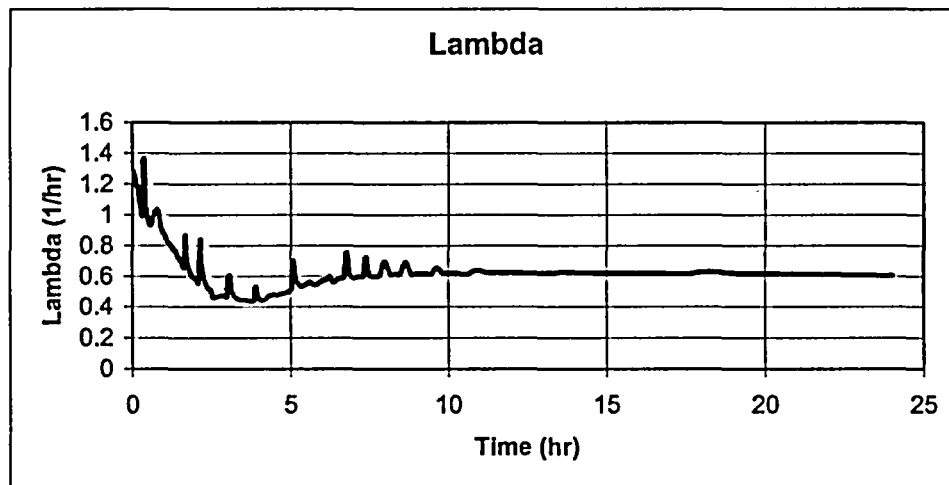
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the steam jet. Gas samples were taken at various points in the containment. For all these tests, the gases were found to be well-mixed above the operating deck. Once again, the volume below the operating deck was air-rich and colder. Very little helium was observed in this volume.

It is expected that any aerosol particles suspended in the containment atmosphere would follow the flow patterns observed in these tests, at similar velocities. Since the bulk flow velocity is much higher than the thermophoretic velocity which is on the order of fractions of cm/sec, the containment will be well-mixed with regard to the distribution of aerosol particles. The results of these tests are applicable to the AP1000 since the scaled parameters and test conditions cover the ranges expected for the AP1000 containment under accident conditions. These tests form the basis of the WGO THIC and MAAP4 code validation for AP1000 containment analysis.

Revised STARNAUA Analysis Results

The overall aerosol removal coefficients (λ) calculated by STARNAUA are shown in the figure below. These removal coefficients are used in the LOCA dose analysis to determine the offsite and control room doses.



It is noted that the AP1000 overall λ decreases only slightly after about 7 hours out to 24 hours. For AP600 the overall λ decreased about 10% over this time period. This difference is assessed as follows.

The removal λ (or decay λ) for containment aerosols during the phase when the source is terminated is defined by the following equation:

$$\lambda = -(1/n) (dn/dt) - L \quad (1)$$

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where n is aerosol mass concentration and L is fractional containment leak rate. Equation (1) is used in STARNAUA to calculate overall aerosol removal λ .

The consideration of aerosol mass conservation yields:

$$V(dn/dt) = -(v_s A_s + v_t A_t + v_d A_d)n - L \cdot V \cdot n \quad (2)$$

where V is the containment volume, v and A are removal velocities of aerosols and the corresponding receiving surface areas, respectively. The subscripts s , t , and d stand for sedimentation, thermophoresis and diffusiophoresis, respectively.

The combination of Equations (1) and (2) yields an equivalent expression for λ , i. e.,

$$\lambda = v_s(A_s/V) + v_t(A_t/V) + v_d(A_d/V) \quad (3)$$

Examining Equation (3), we can conclude that λ changes with the sum of all three removal velocities since all three area to volume ratios are constant.

The expressions for the three aerosol removal velocities are given in DCD Sections 15B.2.1.1, 15B.2.1.2 and 15B.2.1.3, respectively. According to the expressions, sedimentational velocity is particle size dependent. Diffusiophoretic velocity, however, is not size dependent, but proportional to the condensation rate. Thermophoretic velocity is somewhat size dependent (much smaller dependency than sedimentation) and proportional to the convective heat transfer rate. As a result, the sedimentational velocity is expected to decrease as larger particles settle out in time. For both AP600 and AP1000 the thermal hydraulic conditions for thermophoresis and for diffusiophoresis are nearly constant in this time period. Because sedimentation is a larger contributor to the overall λ for AP600 (~1/3) as compared to AP1000 (~1/5) the result is the larger decrease in overall λ observed for AP600 during this time period. Also, in the dose analysis, aerosol removal is only credited until a DF of 1000 is achieved; for the AP1000 analysis reported below this occurs at 12.9 hours.

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Revised Dose Analyses

The radiological consequences of the LOCA have been recalculated taking into account the revised aerosol removal coefficients. In order to continue to obtain doses that are within the dose acceptance limits, the atmospheric dispersion factors have been redefined for the Site Boundary, the Low Population Zone outer boundary, and the Control Room. These revised atmospheric dispersion factors are provided below:

Site Boundary 6.0E-4 sec/m³ (8.0E-4 was the previous value)

Low Population Zone

0 – 8 hours	3.0E-4 sec/m ³	(5.0E-4 was the previous value)
8 – 24 hours	2.2E-4 sec/m ³	(3.0E-4 was the previous value)
24 – 96 hours	1.0E-4 sec/m ³	(1.5E-4 was the previous value)
96 – 720 hours	8.0E-5 sec/m ³	(this value was not changed)

Control Room

Atmospheric Dispersion Factors at HVAC Intake (sec/m ³)				
	Plant Vent or PCS Air Diffuser as Release Point		Ground Level Containment Release Points	
	New Value	Old Value	New Value	Old Value
0 -2 hr	2.45E-3	2.5E-3	2.45E-3	2.5E-3
2-8 hr	1.65E-3	1.7E-3	1.65E-3	1.7E-3
8-24 hr	6.6E-4	1.0E-3	6.6E-4	1.0E-3
24-96 hr	5.0E-4	8.0E-4	5.0E-4	8.0E-4
96-720 hr	4.0E-4	7.0E-4	4.0E-4	8.0E-4

Atmospheric Dispersion Factors at Control Room Door (sec/m ³)				
	Plant Vent or PCS Air Diffuser as Release Point		Ground Level Containment Release Points	
	New Value	Old Value	New Value	Old Value
0 -2 hr	8.0E-4	1.0E-3	8.0E-4	1.5E-3
2-8 hr	6.0E-4	8.0E-4	6.0E-4	8.0E-4
8-24 hr	3.0E-4	4.0E-4	3.0E-4	4.0E-4
24-96 hr	2.0E-4	3.0E-4	2.0E-4	4.0E-4
96-720 hr	1.5E-4	2.5E-4	1.5E-4	4.0E-4

Additionally, the unfiltered inleakage to the Control Room when the HVAC is assumed to be in operation was reduced from 140 cfm to 110 cfm.

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The LOCA doses resulting from leakage of activity from the containment are recalculated to be:

Site Boundary	24.5 rem TEDE
Low Population Zone	24.2 rem TEDE
Control Room	4.5 rem TEDE (with Emergency Habitability System in service)
Control Room	4.61 rem TEDE (with HVAC in service)

The radiological consequences analyses performed for all other accidents have used the previously defined offsite atmospheric dispersion factors. Also, certain other accidents (e.g., the Rod Ejection Accident) have used the previously defined atmospheric dispersion factors for the Control Room. Since the atmospheric dispersion factor changes identified above are all more restrictive than the previously assumed values, the doses calculated for these events are conservative and would only be reduced if the above changes in dispersion factors were incorporated in the analyses.

Similarly, while the revised LOCA analysis assumes an unfiltered inleakage to the control room of 110 cfm for the case in which the active ventilation system is operable, the assumed inleakage for the other accident analyses is 140 cfm. Thus, these other dose analyses are conservative and the calculated doses would decrease if the reduction in unfiltered inleakage is taken into account.

- b) Westinghouse believes that the use of a particle density fraction of 0.8 is consistent with empirical data. While the 0.8 particle density fraction together with the assumption that the aerosol void are water-filled are believed to be appropriate for the AP1000 post-LOCA containment environment, this analysis of aerosol removal has been performed using a reduced particle density fraction of 0.6 combined with the assumption that the voids are air-filled.
- c) Core nuclide inventories vary with both power and burnup. For nuclides with relatively short half-lives (e.g., I-131 and I-133), the inventory in the core is dependent primarily on power level with core burnup having little impact. However, for nuclides that have long half-lives (e.g., I-129, Cs-134, and Cs-137) or are stable (e.g., I-127), both the core power level and core burnup will strongly affect the nuclide inventory in the core. The AP1000 power level is comparable to currently operating Westinghouse four-loop plants and is designed to operate with an 18-month fuel cycle. If this is compared with a Westinghouse three-loop plant operating with an annual fuel cycle, the short-lived nuclides will be found to be roughly proportional to power level but the long-lived and stable nuclides will be significantly greater for the AP1000 because of the longer operating time over which these nuclides are created.

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Design Control Document (DCD) Revision:

Revisions will be made to Tier 1 Table 5.0-1, Tier 2 Section 2.3.4, Table 2-1, Section 6.4.4, Section 15.6.5.3.5, Section 15.6.5.3.8, Table 15.6.5-2, Table 15.6.5-3, Table 15A-5, Table 15A-6, and Appendix 15B, as shown on the following pages.

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Table 5.0-1 (cont.) Site Parameters	
Soil	
Average Allowable Static Soil Bearing Capacity	Greater than or equal to 8,600 lb/ft ² over the footprint of the nuclear island at its excavation depth
Maximum Allowable Dynamic Bearing Capacity for Normal Plus Safe Shutdown Earthquake (SSE)	Greater than or equal to 120,000 lb/ft ² at the edge of the nuclear island at its excavation depth
Shear Wave Velocity	Greater than or equal to 8000 ft/sec based on low-strain, best-estimate soil properties over the footprint of the nuclear island at its excavation depth
Liquefaction Potential	None
Seismic	
SSE	SSE free field peak ground acceleration of 0.30 g at foundation level of nuclear island with modified Regulatory Guide 1.60 response spectra (See Figures 5.0-1 and 5.0-2.)
Fault Displacement Potential	None
Atmospheric Dispersion Factors (X/Q)	
Site Boundary (0-2 hr)	$\leq 8.06.0 \times 10^{-4} \text{ sec/m}^3$
Site Boundary (annual average)	$\leq 2.0 \times 10^{-5} \text{ sec/m}^3$
Low Population Zone Boundary	
0 - 8 hr	$\leq 5.03.0 \times 10^{-4} \text{ sec/m}^3$
8 - 24 hr	$\leq 2.02.2 \times 10^{-4} \text{ sec/m}^3$
24 - 96 hr	$\leq 1.51.0 \times 10^{-4} \text{ sec/m}^3$
96 - 720 hr	$\leq 8.0 \times 10^{-5} \text{ sec/m}^3$

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Table 5.0-1 (cont.) Site Parameters					
Control Room Atmospheric Dispersion Factors (χ/Q) for Accident Dose Analysis					
χ/Q (s/m ³) at HVAC Intake for the Identified Release Points ⁽¹⁾					
	Plant Vent or PCS Air Diffuser ⁽³⁾	Ground Level Containment Release Points ⁽⁴⁾	PORV and Safety Valve Releases ⁽⁵⁾	Steam Line Break Releases	Fuel Handling Area ⁽⁶⁾
0 - 2 hours	2.45E-3	2.45E-3	2.0E-2	2.4E-2	6.0E-3
2 - 8 hours	1.657E-3	1.657E-3	1.8E-2	2.0E-2	4.0E-3
8 - 24 hours	6.610E-4	6.610E-4	7.0E-3	7.5E-3	2.0E-3
1 - 4 days	58.0E-4	58.0E-4	5.0E-3	5.5E-3	1.5E-3
4 - 30 days	47.0E-4	48.0E-4	4.5E-3	5.0E-3	1.0E-3
χ/Q (s/m ³) at Control Room Door for the Identified Release Points ⁽²⁾					
0 - 2 hours	81.0E-4	8.015E-4	4.0E-3	4.0E-3	6.0E-3
2 - 8 hours	68.0E-4	68.0E-4	3.2E-3	3.2E-3	4.0E-3
8 - 24 hours	3.040E-4	3.040E-4	1.2E-3	1.2E-3	2.0E-3
1 - 4 days	23.0E-4	24.0E-4	1.0E-3	1.0E-3	1.5E-3
4 - 30 days	12.5E-4	1.540E-4	8.0E-4	8.0E-4	1.0E-3

Notes:

- These dispersion factors are to be used 1) for the time period preceding the isolation of the main control room and actuation of the emergency habitability system, 2) for the time after 72 hours when the compressed air supply in the emergency habitability system would be exhausted and outside air would be drawn into the main control room, and 3) for the determination of control room doses when the nonsafety ventilation system is assumed to remain operable such that the emergency habitability system is not actuated.
- These dispersion factors are to be used when the emergency habitability system is in operation and the only path for outside air to enter the main control room is that due to ingress/egress.
- These dispersion factors are used for analysis of the doses due to a postulated small line break outside of containment. The plant vent and PCS air diffuser are potential release paths for other postulated events (loss-of-coolant accident, rod ejection accident, and fuel handling accident inside the containment); however, the values are bounded by the dispersion factors for ground level releases.
- The listed values represent modeling the containment shell as a diffuse area source, and are used for evaluating the doses in the main control room for a loss-of-coolant accident, for the containment leakage of activity following a rod ejection accident, and for a fuel handling accident occurring inside the containment.
- The listed values bound the dispersion factors for releases from the steam line safety and power-operated relief valves, and the condenser air removal stack. These dispersion factors would be used for evaluating the doses in the main control room for a steam generator tube rupture, a main steam line break, a locked reactor coolant pump rotor, and the secondary side release from a rod ejection accident. Additionally, these dispersion coefficients are conservative for the small line break outside containment.
- The listed values bound the dispersion factors for releases from the fuel storage and handling area. The listed values also bound the dispersion factors for releases from the fuel storage area in the event that spent fuel boiling occurs and the fuel building relief panel opens on high temperature. These dispersion factors are used for the fuel handling accident occurring outside containment and for evaluating the impact of releases

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associated with spent fuel pool boiling.

2.3.4 Short-Term Diffusion Estimates

In the absence of a specific site for use in determining values for short-term diffusion, a study was performed to determine the atmospheric dispersion factors (χ/Q values) that would envelope most current plant sites and that could be used to calculate the radiological consequences of design basis accidents. The χ/Q values thus derived for offsite are provided in Table 2-1.

This set of offsite χ/Q values is representative of potential sites for construction of the AP1000. The values are appropriate for analyses to determine the radiological consequences of accidents. These values were selected to bound ~~80 to 90~~ 70 to 80 percent of U.S. sites.

The χ/Q values for the control room air intake or the door leading to the control room are dependent not only on the site meteorology but also on the plant design and layout. These χ/Q values are addressed in Appendix 15A. Separate sets of χ/Q values are identified for each combination of activity release location and receptor location.

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Table 2-1 (Sheet 2 of 3)	
SITE PARAMETERS	
Plant Grade Elevation	Less than plant elevation 100' except for portion at a higher elevation adjacent to the annex building
Precipitation	
Rain	19.4 in./hr (6.3 in./5 min)
Snow/Ice	75 pounds per square foot on ground with exposure factor of 1.0 and importance factors of 1.2 (safety) and 1.0 (non-safety)
Atmospheric Dispersion Values - $\chi/Q^{(e)}$	
Site boundary (0-2 hr)	$\leq 6.08\text{-}0 \times 10^{-4} \text{ sec/m}^3$
Site boundary (annual average)	$\leq 2.0 \times 10^{-5} \text{ sec/m}^3$
Low population zone boundary	
0 - 8 hr	$\leq 3.05\text{-}0 \times 10^{-4} \text{ sec/m}^3$
8 - 24 hr	$\leq 2.23\text{-}0 \times 10^{-4} \text{ sec/m}^3$
24 - 96 hr	$\leq 1.04\text{-}5 \times 10^{-4} \text{ sec/m}^3$
96 - 720 hr	$\leq 8.0 \times 10^{-5} \text{ sec/m}^3$
Population Distribution	
Exclusion area (site)	0.5 mi

Notes:

- (a) Maximum and minimum safety values are based on historical data and exclude peaks of less than 2 hours duration.
- (b) Maximum and minimum normal values are the 1 percent exceedance magnitudes.
- (c) With ground response spectra (at foundation level of nuclear island) as given in Figures 3.7.1-1 and 3.7.1-2.
- (d) The noncoincident wet bulb temperature is applicable to the cooling tower only.
- (e) For AP1000, the terms "site boundary" and "exclusion area boundary" are used interchangeably. Thus, the χ/Q specified for the site boundary applies whenever a discussion refers to the exclusion area boundary.

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Table 2-1 (Sheet 3 of 3)					
SITE PARAMETERS					
Control Room Atmospheric Dispersion Factors (χ/Q) for Accident Dose Analysis					
χ/Q (s/m ³) at HVAC Intake for the Identified Release Points ⁽¹⁾					
	Plant Vent or PCS Air Diffuser ⁽³⁾	Ground Level Containment Release Points ⁽⁴⁾	PORV and Safety Valve Releases ⁽⁵⁾	Steam Line Break Releases	Fuel Handling Area ⁽⁶⁾
0 - 2 hours	2.45E-3	2.45E-3	2.0E-2	2.4E-2	6.0E-3
2 - 8 hours	1.657E-3	1.657E-3	1.8E-2	2.0E-2	4.0E-3
8 - 24 hours	6.610E-43	6.610E-43	7.0E-3	7.5E-3	2.0E-3
1 - 4 days	58.0E-4	58.0E-4	5.0E-3	5.5E-3	1.5E-3
4 - 30 days	47.0E-4	48.0E-4	4.5E-3	5.0E-3	1.0E-3
χ/Q (s/m ³) at Control Room Door for the Identified Release Points ⁽²⁾					
	Plant Vent or PCS Air Diffuser ⁽³⁾	Ground Level Containment Release Points ⁽⁴⁾	PORV and Safety Valve Releases ⁽⁵⁾	Steam Line Break Releases	Fuel Handling Area ⁽⁶⁾
0 - 2 hours	8.010E-43	8.015E-43	4.0E-3	4.0E-3	6.0E-3
2 - 8 hours	68.0E-4	68.0E-4	3.2E-3	3.2E-3	4.0E-3
8 - 24 hours	3.040E-4	3.040E-4	1.2E-3	1.2E-3	2.0E-3
1 - 4 days	23.0E-4	24.0E-4	1.0E-3	1.0E-3	1.5E-3
4 - 30 days	12.5E-4	1.540E-4	8.0E-4	8.0E-4	1.0E-3

Notes:

1. These dispersion factors are to be used 1) for the time period preceding the isolation of the main control room and actuation of the emergency habitability system, 2) for the time after 72 hours when the compressed air supply in the emergency habitability system would be exhausted and outside air would be drawn into the main control room, and 3) for the determination of control room doses when the non-safety ventilation system is assumed to remain operable such that the emergency habitability system is not actuated.
2. These dispersion factors are to be used when the emergency habitability system is in operation and the only path for outside air to enter the main control room is that due to ingress/egress.
3. These dispersion factors are used for analysis of the doses due to a postulated small line break outside of containment. The plant vent and PCS air diffuser are potential release paths for other postulated events (loss-of-coolant accident, rod ejection accident, and fuel handling accident inside the containment); however, the values are bounded by the dispersion factors for ground level releases.

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4. The listed values represent modeling the containment shell as a diffuse area source, and are used for evaluating the doses in the main control room for a loss-of-coolant accident, for the containment leakage of activity following a rod ejection accident, and for a fuel handling accident occurring inside the containment.
5. The listed values bound the dispersion factors for releases from the steam line safety & power-operated relief valves and the condenser air removal stack. These dispersion factors would be used for evaluating the doses in the main control room for a steam generator tube rupture, a main steam line break, a locked reactor coolant pump rotor, and for the secondary side release from a rod ejection accident. Additionally, these dispersion coefficients are conservative for the small line break outside containment.
6. The listed values bound the dispersion factors for releases from the fuel storage and handling area. The listed values also bound the dispersion factors for releases from the fuel storage area in the event that spent fuel boiling occurs and the fuel building relief panel opens on high temperature. These dispersion factors are used for the fuel handling accident occurring outside containment and for evaluating the impact of releases associated with spent fuel pool boiling.

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6.4.4 System Safety Evaluation

Doses to main control room personnel were calculated for both the situation in which the emergency habitability system (VES) is relied upon to limit the amount of activity the personnel are exposed to and the situation in which the nuclear island nonradioactive ventilation system (VBS) is available to pressurize the main control room with filtered air and provide recirculation cleanup. Doses were calculated for the following accidents:

	<u>VES Operating</u>	<u>VBS Operating</u>
Large Break LOCA	4.78 rem TEDE	4.80 rem TEDE
Fuel Handling Accident	4.5 rem TEDE	2.4 rem TEDE
Steam Generator Tube Rupture		
(Pre-existing iodine spike)	4.8 rem TEDE	3.4 rem TEDE
(Accident-initiated iodine spike)	2.1 rem TEDE	1.8 rem TEDE
Steam Line Break		
(Pre-existing iodine spike)	3.4 rem TEDE	2.1 rem TEDE
(Accident-initiated iodine spike)	3.7 rem TEDE	4.9 rem TEDE
Rod Ejection Accident	2.1 rem TEDE	1.3 rem TEDE
Locked Rotor Accident		
(Accident without feedwater available)	0.9 rem TEDE	0.9 rem TEDE
(Accident with feedwater available)	0.7 rem TEDE	1.6 rem TEDE
Small Line Break Outside Containment	1.2 rem TEDE	0.3 rem TEDE

For all events the dose are within the dose acceptance limit of 5.0 rem TEDE. The details of analysis assumptions for modeling the doses to the main control room personnel are delineated in the LOCA dose analysis discussion in subsection 15.6.5.3.

No radioactive materials are stored or transported near the main control room pressure boundary. As discussed and evaluated in subsection 9.5.1, the use of noncombustible construction and heat and flame resistant materials throughout the plant reduces the likelihood of fire and consequential impact on the main control room atmosphere. Operation of the nuclear island nonradioactive ventilation system in the event of a fire is discussed in subsection 9.4.1.

The exhaust stacks of the onsite standby power diesel generators are located in excess of 150 feet away from the fresh air intakes of the main control room. The onsite standby power system fuel oil storage tanks are located in excess of 300 feet from the main control room fresh air intakes. These separation distances reduce the possibility that combustion fumes or smoke from an oil fire would be drawn into the main control room.

The protection of the operators in the main control room from offsite toxic gas releases is discussed in Section 2.2. The sources of onsite chemicals are described in Table 6.4-1, and their locations are shown on Figure 1.2-2. Analysis of these sources is in accordance with Regulatory Guide 1.78 (Reference 5) and the methodology in NUREG-0570, "Toxic Vapor Concentrations in the Control Room Following a Postulated Accidental Release" (Reference 6), and the analysis shows that these sources do not represent a toxic hazard to control room personnel. A supply of protective clothing, respirators, and self-contained breathing apparatus adequate for 11 persons is stored within the main control room pressure boundary.

The main control room emergency habitability system components discussed in subsection 6.4.2.3 are arranged as shown in Figure 6.4-2. The location of components and piping within the main

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control room pressure boundary provides the required supply of compressed air to the main control room pressure boundary, as shown in Figure 6.4-1.

During emergency operation, the main control room emergency habitability system passive heat sinks are designed to limit the temperature inside the main control room to remain within limits for reliable human performance (References 2 and 3) over 72 hours. The passive heat sinks limit the air temperature inside the instrumentation and control rooms to 120°F and dc equipment rooms to 120°F. The walls and ceilings that act as the passive heat sinks contain sufficient thermal mass to accommodate the heat sources from equipment, personnel, and lighting for 72 hours.

The main control room emergency habitability system nominally provides 65 scfm of ventilation air to the main control room from the compressed air storage tanks. Sixty scfm of ventilation flow is sufficient to pressurize the control room to at least positive 1/8-inch water gauge differential pressure with respect to the surrounding areas in addition to limiting the carbon dioxide concentration below one-half percent by volume for a maximum occupancy of 11 persons and maintaining air quality within the guidelines of Table 1 and Appendix C, Table C-1, of Reference 1.

Automatic transfer of habitability system functions from the main control room/technical support center HVAC subsystem of the nuclear island nonradioactive ventilation system to the main control room emergency habitability system is initiated by either the following conditions:

- “High-high” particulate or iodine radioactivity in MCR air supply duct
- Loss of ac power for more than 10 minutes

The airborne fission product source term in the reactor containment following the postulated LOCA is assumed to leak from the containment and airborne fission products are assumed to result from spent fuel pool steaming. The concentration of radioactivity, which is assumed to surround the main control room, after the postulated accident, is evaluated as a function of the fission product decay constants, the containment leak rate, and the meteorological conditions assumed. The assessment of the amount of radioactivity within the main control room takes into consideration the radiological decay of fission products and the infiltration/exfiltration rates to and from the main control room pressure boundary.

A single active failure of a component of the main control room emergency habitability system or nuclear island nonradioactive ventilation system does not impair the capability of the systems to accomplish their intended functions. The Class 1E components of the main control room emergency habitability system are connected to independent Class 1E power supplies. Both the main control room emergency habitability system and the portions of the nuclear island nonradioactive ventilation system which isolates the main control room are designed to remain functional during an SSE or design-basis tornado.

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15.6.5.3.5 Main Control Room Dose Model

There are two approaches that may be used for modeling the activity entering the main control room. If power is available, the normal heating, ventilation, and air-conditioning (HVAC) system will switch over to a supplemental filtration mode (Section 9.4). The normal HVAC system is not a safety-class system but provides defense in depth.

Alternatively, if the normal HVAC is inoperable or, if operable, the supplemental filtration train does not function properly resulting in increasing levels of airborne iodine in the main control room, the emergency habitability system (Section 6.4) would be actuated when high iodine activity is detected. The emergency habitability system provides passive pressurization of the main control room from a bottled air supply to prevent inleakage of contaminated air to the main control room. There is a 72-hour supply of air in the emergency habitability system. After this time, the main control room is assumed to be opened and unfiltered air is drawn into the main control room by way of an ancillary fan. After 7 days, offsite support is assumed to be available to reestablish operability of the control room habitability system by replenishing the compressed air supply or to bring the normal control room HVAC into operation with the supplemental filtration train.

~~The second approach, with the emergency habitability system in use, results in the more conservative determination of doses for this event.~~

The main control room is accessed by a vestibule entrance which restricts the volume of contaminated air that can enter the main control room from ingress and egress. The equivalent inflow of unfiltered air due to expected ingress/egress has been determined to be 5.0 cfm.

Activity entering the main control room is assumed to be uniformly dispersed. No credit is taken for the removal of airborne activity in the main control room although elemental iodine and particulates would be removed by deposition and sedimentation.

The main control room dose calculation models are provided in Appendix 15A for the determination of doses resulting from activity which enters the main control room envelope.

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15.6.5.3.8 LOCA Doses

15.6.5.3.8.1 Offsite Doses

The doses calculated for the exclusion area boundary and the low population zone boundary are listed in Table 15.6.5-3. The doses are within the 10 CFR 50.34 dose guideline of 25 rem TEDE. The reported exclusion area boundary doses are for the time period of 0.8 to 2.81.2 to 3.2 hours. This is the 2-hour interval that has the highest calculated doses. The dose that would be incurred over the first 2 hours of the accident is well below the reported dose.

At the time the LOCA occurs, there is the potential for a coincident loss of spent fuel pool cooling with the result that the pool could reach boiling and a portion of the radioactive iodine in the spent fuel pool could be released to the environment. The loss of spent fuel pool cooling has been evaluated for a duration of 30 days. There is no contribution to the 2-hour site boundary dose because pool boiling would not occur until after 8 hours. The 30-day contribution to the dose at the low population zone boundary is less than 0.01 rem TEDE and, when this is added to the dose calculated for the LOCA, the resulting total dose remains less than that reported in Table 15.6.5-3.

15.6.5.3.8.2 Doses to Operators in the Main Control Room

The doses calculated for the main control room personnel due to airborne activity entering the main control room are listed in Table 15.6.5-3. Also listed on Table 15.6.5-3 are the doses due to direct shine from the activity in the adjacent buildings and sky-shine from the radiation that streams out the top of the containment shield building and is reflected back down by air-scattering. The total of the three dose paths is within the dose criteria of 5 rem TEDE as defined in GDC 19.

As discussed above for the offsite doses, there is the potential for a dose to the operators in the main control room due to iodine releases from postulated spent fuel boiling. The calculated dose from this source is less than 0.01 rem TEDE and, when this is added to the dose calculated for the LOCA, the resulting total dose remains less than that reported in Table 15.6.5-3.

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Table 15.6.5-2 (Sheet 3 of 3)

ASSUMPTIONS AND PARAMETERS USED IN CALCULATING RADIOLOGICAL CONSEQUENCES OF A LOSS-OF-COOLANT ACCIDENT

Miscellaneous assumptions and parameters

– Unfiltered air inleakage (cfm)	440110
– Offsite power	Not applicable
– Atmospheric dispersion factors (offsite)	See Table 15A-5
– Nuclide dose conversion factors	See Table 15A-4
– Nuclide decay constants	See Table 15A-4
– Offsite breathing rate (m ³ /sec)	
0 - 8 hr	3.5 E-04
8 - 24 hr	1.8 E-04
24 - 720 hr	2.3 E-04

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Table 15.6.5-3	
RADIOLOGICAL CONSEQUENCES OF A LOSS-OF-COOLANT ACCIDENT WITH CORE MELT	
	TEDE Dose (rem)
Exclusion zone boundary dose (0.8—2.8/1.2 – 3.2 hr) ⁽¹⁾	24.52
Low population zone boundary dose (0 - 30 days)	24.23.2
Main control room dose (emergency habitability system in operation)	
– Airborne activity entering the main control room	4.56 rem
– Direct radiation from adjacent structures	0.15 rem
– Sky-shine	0.01 rem
– Total	4.676 rem
Main control room dose (normal HVAC operating in the supplemental filtration mode)	
– Airborne activity entering the main control room	4.61 rem
– Direct radiation from adjacent structures	0.15 rem
– Sky-shine	0.01 rem
– Total	4.77 rem

Note:

1. This is the 2-hour period having the highest dose.

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Table 15A-5	
OFFSITE ATMOSPHERIC DISPERSION FACTORS (X/Q) FOR ACCIDENT DOSE ANALYSIS	
Site boundary χ/Q (s/m ³) 0 – 2 hours ⁽¹⁾	6.08.0x10 ⁻⁴
Low population zone χ/Q (s/m ³)	
0 – 8 hours	3.05.0x10 ⁻⁴
8 – 24 hours	2.23.0x10 ⁻⁴
24 – 96 hours	1.04.5x10 ⁻⁴
96 – 720 hours	8.0x10 ⁻⁵

Note:

1. Nominally defined as the 0- to 2-hour interval but is applied to the 2-hour interval having the highest activity releases in order to address 10 CFR Part 50.34 requirements.

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Table 15A-6

CONTROL ROOM ATMOSPHERIC DISPERSION FACTORS (χ/Q) FOR ACCIDENT DOSE ANALYSIS

χ/Q (s/m³) at HVAC Intake for the Identified Release Points⁽¹⁾

	Plant Vent or PCS Air Diffuser ⁽³⁾	Ground Level Containment Release Points ⁽⁴⁾	PORV and Safety Valve Releases ⁽⁵⁾	Steam Line Break Releases	Fuel Handling Area ⁽⁶⁾
0 - 2 hours	2.45E-3	2.45E-3	2.0E-2	2.4E-2	6.0E-3
2 - 8 hours	1.657E-3	1.657E-3	1.8E-2	2.0E-2	4.0E-3
8 - 24 hours	6.610E-43	6.610E-43	7.0E-3	7.5E-3	2.0E-3
1 - 4 days	58.0E-4	58.0E-4	5.0E-3	5.5E-3	1.5E-3
4 - 30 days	47.0E-4	48.0E-4	4.5E-3	5.0E-3	1.0E-3

χ/Q (s/m³) at Control Room Door for the Identified Release Points⁽²⁾

	Plant Vent or PCS Air Diffuser ⁽³⁾	Ground Level Containment Release Points ⁽⁴⁾	PORV and Safety Valve Releases ⁽⁵⁾	Steam Line Break Releases	Fuel Handling Area ⁽⁶⁾
0 - 2 hours	81.0E-43	8.015E-43	4.0E-3	4.0E-3	6.0E-3
2 - 8 hours	68.0E-4	68.0E-4	3.2E-3	3.2E-3	4.0E-3
8 - 24 hours	3.040E-4	3.040E-4	1.2E-3	1.2E-3	2.0E-3
1 - 4 days	23.0E-4	24.0E-4	1.0E-3	1.0E-3	1.5E-3
4 - 30 days	12.5E-4	1.540E-4	8.0E-4	8.0E-4	1.0E-3

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Notes:

1. These dispersion factors are to be used 1) for the time period preceding the isolation of the main control room and actuation of the emergency habitability system, 2) for the time after 72 hours when the compressed air supply in the emergency habitability system would be exhausted and outside air would be drawn into the main control room, and 3) for the determination of control room doses when the non-safety ventilation system is assumed to remain operable such that the emergency habitability system is not actuated.
2. These dispersion factors are to be used when the emergency habitability system is in operation and the only path for outside air to enter the main control room is that due to ingress/egress.
3. These dispersion factors are used for analysis of the doses due to a postulated small line break outside of containment. The plant vent and PCS air diffuser are potential release paths for other postulated events (loss-of-coolant accident, rod ejection accident, and fuel handling accident inside the containment); however, the values are bounded by the dispersion factors for ground level releases.
4. The listed values represent modeling the containment shell as a diffuse area source, and are used for evaluating the doses in the main control room for a loss-of-coolant accident, for the containment leakage of activity following a rod ejection accident, and for a fuel handling accident occurring inside the containment.
5. The listed values bound the dispersion factors for releases from the steam line safety & power-operated relief valves and the condenser air removal stack. These dispersion factors would be used for evaluating the doses in the main control room for a steam generator tube rupture, a main steam line break, a locked reactor coolant pump rotor, and for the secondary side release from a rod ejection accident. Additionally, these dispersion coefficients are conservative for the small line break outside containment.
6. The listed values bound the dispersion factors for releases from the fuel storage and handling area. The listed values also bound the dispersion factors for releases from the fuel storage area in the event that spent fuel boiling occurs and the fuel building relief panel opens on high temperature. These dispersion factors are used for the fuel handling accident occurring outside containment and for evaluating the impact of releases associated with spent fuel pool boiling.

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APPENDIX 15B

REMOVAL OF AIRBORNE ACTIVITY FROM THE CONTAINMENT ATMOSPHERE FOLLOWING A LOCA

The AP1000 design does not depend on active systems to remove airborne particulates or elemental iodine from the containment atmosphere following a postulated loss-of-coolant accident (LOCA) with core melt. Naturally occurring passive removal processes provide significant removal capability such that airborne elemental iodine is reduced to very low levels within a few hours and the airborne particulates are reduced to extremely low levels within 12 hours.

15B.1 Elemental Iodine Removal

Elemental iodine is removed by deposition onto the structural surfaces inside the containment. The removal of elemental iodine is modeled using the equation from the Standard Review Plan (Reference 1):

$$\lambda_d = \frac{K_w A}{V}$$

where:

- λ_d = first order removal coefficient by surface deposition
- K_w = mass transfer coefficient (specified in Reference 1 as 4.9 m/hr)
- A = surface area available for deposition
- V = containment building volume

The available deposition surface is 219,000 ft², and the containment building net free volume is 2.06 x 10⁶ ft³. From these inputs, the elemental iodine removal coefficient is 1.7 hr⁻¹.

Consistent with the guidance of Reference 1, credit for elemental iodine removal is assumed to continue until a decontamination factor (DF) of 200 is reached in the containment atmosphere. Because the source term for the LOCA (defined in subsection 15.6.5.3) is modeled as a gradual release of activity into the containment, the determination of the time at which the DF of 200 is reached needs to be based on the amount of elemental iodine that enters the containment atmosphere over the duration of core activity release.

15B.2 Aerosol Removal

The deposition removal of aerosols from the containment atmosphere is accomplished by a number of processes including sedimentation, diffusiophoresis, and thermophoresis. All three of the deposition processes are significant contributors to the overall removal process in the AP1000. The large contributions from diffusiophoresis and thermophoresis to the total removal are a direct consequence of the high heat transfer rates from the containment atmosphere to the containment wall that characterize the passive containment cooling system.

Because of the AP1000 passive containment cooling system design, there are high sensible heat transfer rates (resulting in higher thermophoretic removal of aerosols) when condensational heat transfer is low (and the aerosol removal by diffusiophoresis is also low). The reverse is also true. Thus, there is an

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appreciable deposition removal throughout the accident from either diffusiophoresis or thermophoresis, in addition to the removal by sedimentation.

15B.2.1 Mathematical Models

The models used for the three aerosol removal processes are discussed as follows.

15B.2.1.1 Sedimentation

Gravitational sedimentation is a major mechanism of aerosol removal in a containment. A standard model (Stokes equation with the Cunningham slip correction factor) for this process is used. The Stokes equation (Reference 2) is:

$$v_s = \frac{2\rho_p g r^2 C_n}{9\mu}$$

where:

v_s	=	settling velocity of an aerosol particle
ρ_p	=	material density of the particle
g	=	gravitational acceleration
r	=	particle radius
μ	=	gas viscosity
C_n	=	Cunningham slip correction factor, a function of the Knudsen number (Kn) which is the gas molecular mean free path divided by the particle radius

However, the Stokes equation makes the simplifying assumption that the particles are spherical. The particles are expected to be nonspherical, and it is conventional to address this by introducing a "dynamic shape factor" (Reference 2) in the denominator of the Stokes equation, such that the settling velocity for the nonspherical particle is the same as for a spherical particle of equal volume. The value of the dynamic shape factor (ϕ) thus depends on the shape of the particle and, in general, must be experimentally determined.

The concept of dynamic shape factor can also be applied to a spherical particle consisting of two components, one of which has the density of the particle material, while the other component has a different density (Reference 9). In this manner, the impact of the void fraction in the particle can be modeled. Thus, the revised Stokes equation is:

$$v_s = \frac{2\rho_p g r^2 C_n}{9\mu\phi}$$

The derivation of ϕ follows.

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The two-component particle is considered to have a density ρ_{av} and an effective radius of r_e . Assuming that the second component of the particle is the void volume and letting the void fraction be ϵ , then the average density of the particle is:

$$\rho_{av} = \text{the average density of the particle} = \rho_p (1-\epsilon) + \rho_v \epsilon$$

where:

$$\begin{aligned}\rho_v &= \text{density of the void material (0.0 for gas filled, 1.0 for water filled)} \\ \epsilon &= \text{void fraction} \\ \rho_p &= \text{material density (solid particle with no voids)}\end{aligned}$$

The definition of ϕ is obtained from the Stokes equation and the equation for mass of a sphere:

$$\frac{2\rho_p g r^2 C_n}{9\mu\phi} = \frac{2\rho_{av} g r_e^2 C_n}{9\mu}$$

which reduces to:

$$\rho_p r^2 = \phi \rho_{av} r_e^2$$

and

$$\frac{4\rho_p \pi r_0^3}{3} = \frac{4\rho_{av} \pi r_e^3}{3}$$

which reduces to:

$$\rho_p r_0^3 = \rho_{av} r_e^3$$

Then:

$$\phi = \frac{\rho_p r^2}{\rho_{av} r_e^2}$$

and

$$r_e = r \left(\frac{\rho_{av}}{\rho_p} \right)^{-1/3}$$

From these two relationships, the dynamic shape factor is given by:

$$\phi = \left(\frac{\rho_{av}}{\rho_p} \right)^{-1/3}$$

15B.2.1.2 Diffusiophoresis

Diffusiophoresis is the process whereby particles are swept to a surface (for example, containment wall) by the flow set up by a condensing vapor (Stefan flow). The deposition rate is independent

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of the particle size and is proportional to the steam condensation rate on the surface. The standard equation for this phenomenon is due to Waldmann and Schmitt (Reference 3):

$$v_d = \frac{\sqrt{M_v}}{\sqrt{M_v} + \chi_{a/v} \sqrt{M_a}} \frac{W}{\rho_v}$$

where:

v_d = diffusiophoretic deposition velocity

$\chi_{a/v}$ = ratio of mole fraction of air to mole fraction of steam in the containment atmosphere

M_v = molecular weight of steam

M_a = molecular weight of air

W = steam condensation rate on the wall

ρ_v = mass density of steam in the containment atmosphere

Because of the design of the passive containment cooling system, steam condensation rates are high at certain times in the design basis LOCA; thus at these times, diffusiophoretic deposition rates are significant.

15B.2.1.3 Thermophoresis

Thermophoresis is the process whereby particles drift toward a surface (for example, the containment wall) under the influence of a temperature gradient in the containment atmosphere at the surface. The effect arises because the gas molecules on the hot side of the particles undergo more collisions with the particle than do those on the cold side. Therefore, there is a net momentum transfer to the particle in the hot-to-cold direction. There are several models in the literature for this effect; the one used is the Brock equation in a form due to Talbot et al. (Reference 4). As indicated below, this model is in agreement with experimental data. The thermophoretic deposition rate is somewhat dependent on particle size and is proportional to the temperature gradient at the wall, or equivalently, the sensible heat transfer rate to the wall. The Talbot equation is:

$$v_{th} = \frac{2 C_s C_n (\mu_g / \rho_g) [\alpha + C_T Kn] dT}{[1 + 2(\alpha + C_T Kn)][1 + 3 C_M Kn]} \left(\frac{1}{T} \right) \frac{dT}{dy}$$

where:

v_{th} = thermophoretic deposition velocity

α = k_g/k_p which is the ratio of the thermal conductivities of the gas (evaluated at the gas temperature at each time step) and the aerosol particle (k_p is set equal to the thermal conductivity of water – the results are not sensitive to k_p or α .)

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$Kn =$	Knudsen number (equal to the gas molecular mean free path divided by the particle radius)
$C_n =$	Cunningham slip correction factor, a function of the Knudsen number
$\mu_g =$	gas viscosity
$\rho_g =$	gas density
$C_s =$	slip accommodation coefficient (Reference 4 gives the best value as 1.17.)
$C_T =$ (2.18.)	thermal accommodation coefficient (Reference 4 gives the best value as 2.18.)
$C_M =$ as 1.14.)	momentum accommodation coefficient (Reference 4 gives the best value as 1.14.)

The temperature gradient at the wall, dT/dy , can be evaluated as

$$\frac{dT}{dy} = \frac{\phi_s}{k_g}$$

where ϕ_s is the sensible heat flux to the wall, and k_g is the thermal conductivity of the gas. It is obtained as the difference between the total and condensation heat fluxes. The sensible heat flux used in the analysis is the convective heat transfer calculated as discussed in subsection 15B.2.4.7.

15B.2.2 Other Removal Mechanisms

In addition to the above mechanisms, there are others that were not considered, including turbulent diffusion and turbulent agglomeration. The neglect of these mechanisms adds further conservatism to the calculation.

15B.2.3 Validation of Removal Mechanisms

The aerosol processes are well established and have been confirmed in many separate effects experiments, which are discussed in standard references (References 2 through 4). The Stokes formula for sedimentation velocity has been well confirmed for particles whose diameters are less than about 50 μm . In the present calculations, these make up basically all of the aerosol.

There are some separate effects validations of the diffusiophoretic effect, but the best confirmation comes from integral experiments such as the LACE tests (Reference 5). Calculations of these and other integral tests accurately predict the integrated mass of plated aerosol material only if diffusiophoresis is taken into account. If it is neglected, the predicted plated mass is about two orders of magnitude too small, compared to the observed plated mass.

The Talbot equation for the thermophoretic effect has been experimentally confirmed to within about 20 to 50 percent over a wide range of particle sizes (Reference 4). The temperature gradient at the wall, which drives this phenomenon, can be approximated by the temperature difference between the bulk gas and the

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wall divided by an appropriate length scale obtained from heat transfer correlations. Alternatively, because sensible heat transfer rates to the wall are available, it is easier and more accurate to use these rates directly to infer the temperature gradient.

15B.2.4 Parameters and Assumptions for Calculating Aerosol Removal Coefficients

The parameters and assumptions were selected to conservatively model the environment that would be expected to exist as a result of a LOCA with concurrent core melt.

15B.2.4.1 Containment Geometry

The containment is assumed to be a cylinder with a volume of 55,481 m³ (1.959 x 10⁶ ft³). This volume includes those portions of the containment volume that would be participating in the aerosol transport and mixing; this excludes dead-ended volumes and flooded compartments. The horizontal surface area available for aerosol deposition by sedimentation is 2900 m² (31,200 ft²). This includes projecting areas such as decks in addition to the floor area and excludes areas in dead-ended volumes and areas that would be flooded post-LOCA. The surface area for Brownian diffusive plateout of aerosols is 8008 m² (86,166 ft²).

15B.2.4.2 Source Size Distribution

The aerosol source size distribution is assumed to be lognormal, with a geometric mean radius of 0.22 μm and a geometric standard deviation equal to 1.81. These values are derived from an evaluation of a large number of aerosol distributions measured in a variety of degraded-fuel tests and experiments. The sensitivity of aerosol removal coefficient calculations to these values is small.

15B.2.4.3 Aerosol Void Fraction

Review of scanning electron microscope photographs of deposited aerosol particles from actual core melt and fission product vaporization and aerosolization experiments (the Argonne STEP-4 test and the INEL Power Burst Facility SFD 1-4 test) indicates that the deposited particles are relatively dense, supporting a void fraction of 0.2.

The above-mentioned test results indicate that a void fraction of 0.2 is appropriate for modeling the aerosols resulting from a core melt. As part of the sensitivity study that was performed for the AP600 project, a case was run with a void fraction of 0.9. That analysis showed that the high void fraction resulted in an integrated release of aerosols over a 24-hour period that was less than 14 percent greater than that calculated when using the void fraction of 0.2. Thus, it is clear that the removal of aerosols from the containment atmosphere is not highly sensitive to the value selected for the void fraction. This is largely due to the fact that, while the selected value for void fraction has a significant impact on the calculated sedimentation removal, the impact on thermophoresis and diffusiophoresis removal is slight or none. The impact for AP1000 of using the higher value for void fraction would be less than was determined for the AP600 since sedimentation removal comprises a smaller fraction of the total removal calculated for the AP1000.

For additional conservatism the AP1000 aerosol removal analysis uses a void fraction of 0.4 and assumes the voids are filled with air.

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15B.2.4.4 Fission Product Release Fractions

Core inventories of fission products are from ORIGEN calculations for the AP1000 at end of the fuel cycle. Fractional releases to the containment of the fission products are those specified in subsection 15.6.5.3.

15B.2.4.5 Inert Aerosol Species

The inert species include SnO_2 , UO_2 , Cd, Ag, and Zr. These act as surrogates for all inert materials forming aerosols. The ratio of the total mass of inert species to fission product species was assumed to be 1.5:1. This value and the partitioning of the total inert mass among its constituents are consistent with results from degraded fuel experiments (Reference 6).

15B.2.4.6 Aerosol Release Timing and Rates

Aerosol release timing is in accordance with the source term defined in subsection 15.6.5.3. Aerosol release takes place in two main phases: a gap release lasting for 0.5 hour, followed by an early in-vessel release of 1.3 hours duration. During each phase, the aerosols are assumed to be released at a constant rate. These rates were obtained for each species by combining its core inventory, release fraction, and times of release. Only cesium and iodine are released during the gap release phase. During the in-vessel release phase, the other fission product and inert species are released as well.

15B.2.4.7 Containment Thermal-hydraulic Data

The thermal-hydraulic parameters used in the aerosol removal calculation are the containment gas temperature, the containment pressure, the steam condensation rate on the wall, the steam mole fraction, and the total-convective heat transfer rate, all as functions of time. The AP1000-specific parameters were obtained using MAAP4 (Reference 7) for the 3BE-1 severe accident sequence (medium LOCA with failure to inject water from the refueling water storage tank into the reactor vessel). The thermal-hydraulic data are thus consistent with a core melt sequence.

15B.2.5 Aerosol Removal Coefficients

The aerosol removal coefficients are provided in Table 15B-1 starting at the onset of core damage through 24 hours. The removal coefficients for times beyond 24 hours are not of concern because there would be so little aerosol remaining airborne at that time. The values range between $0.60.443 \text{ hr}^{-1}$ and 1.325 hr^{-1} during the time between the onset of core damage (0.167 hour) and 24 hours.

These removal coefficients conservatively neglect steam condensation on the airborne particles, turbulent diffusion, and turbulent agglomeration. Additionally, the assumed source aerosol size is conservatively small being at the low end of the mass mean aerosol size range of 1.5 to $5.5 \mu\text{m}$ used in NUREG/CR-5966 (Reference 8). Selection of smaller aerosol size would underestimate sedimentation.

Unlike the case for the elemental iodine removal, there is no limit assumed on the removal of aerosols from the containment atmosphere.

15B.3 References

1. NUREG-0800, Section 6.5.2, Revision 2, "Containment Spray as a Fission Product Cleanup System."

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2. Fuchs, N. A., The Mechanics of Aerosols, Pergamon Press, Oxford, 1964.
3. Waldmann, L., and Schmitt, K. H., "Thermophoresis and Diffusiophoresis of Aerosols," Aerosol Science, C. N. Davies, ed., Academic Press, 1966.
4. Talbot, L., Chang, R. K., Schefer, R. W., and Willis, D. R., "Thermophoresis of Particles in a Heated Boundary Layer," J. Fluid Mech. 101, 737-758 (1980).
5. Rahn, F. J., "The LWR Aerosol Containment Experiments (LACE) Project," Summary Report, EPRI-NP-6094D, Electric Power Research Institute, Palo Alto, Nov. 1988.
6. Petti, D. A., Hobbins, R. R., and Hargman, D. L., "The Composition of Aerosols Generated during a Severe Reactor Accident: Experimental Results from the Power Burst Facility Severe Fuel Damage Test 1-4," Nucl. Tech. 105, p.334 (1994).
7. MAAP4 - Modular Accident Analysis Program for LWR Power Plants, Computer Code Manual, May 1994.
8. Powers D. A., and Burson, S. B., "A Simplified Model of Aerosol Removal by Containment Sprays," NUREG/CR-5966, June 1993.
9. Powers, D. A., "Monte Carlo Uncertainty Analysis of Aerosol Behavior in the AP600 Reactor Containment under Conditions of a Specific Design-Basis Accident, Part 1," Technical Evaluation Report, Sandia National Laboratories, June 1995.

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Table 15B-1		
AEROSOL REMOVAL COEFFICIENTS IN THE AP1000 CONTAINMENT FOLLOWING A DESIGN BASIS LOCA WITH CORE MELT		
Time Interval (hours)		Removal Coefficient (hr^{-1})
0.167	- 0.32	1.25
0.32	- 0.47	1.5
0.47	- 0.61	1.4
0.61	- 0.84	1.5
0.84	- 1.0	1.4
1.0	- 1.24	1.3
1.24	- 1.29	1.0
1.29	- 1.49	1.2
1.49	- 1.55	0.6
1.55	- 1.58	1.0
1.58	- 1.6	1.1
1.6	- 1.8	1.2
1.8	- 2.2	1.15
2.2	- 2.6	1.1
2.6	- 4.2	1.05
4.2	- 5.0	1.1
5.0	- 8.2	1.15
8.2	- 24	1.1

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Table 15B-1

AEROSOL REMOVAL COEFFICIENTS IN THE AP1000 CONTAINMENT FOLLOWING A DESIGN BASIS LOCA WITH CORE MELT

Time Interval (hours)	Removal Coefficient (hr ⁻¹)
0.167 - 0.218	1.127
0.218 - 0.335	1.032
0.335 - 0.401	1.320
0.401 - 0.430	1.150
0.430 - 0.455	1.042
0.455 - 0.501	0.992
0.501 - 0.644	0.944
0.644 - 0.676	0.993
0.676 - 0.758	1.020
0.758 - 0.822	1.028
0.822 - 0.859	0.986
0.859 - 0.894	0.935
0.894 - 0.981	0.897
0.981 - 1.072	0.860
1.072 - 1.179	0.821
1.179 - 1.261	0.797
1.261 - 1.361	0.774
1.361 - 1.454	0.748
1.454 - 1.539	0.713
1.539 - 1.644	0.679
1.644 - 1.740	0.770
1.740 - 1.796	0.668
1.796 - 1.906	0.620
1.906 - 2.141	0.579
2.141 - 2.237	0.753
2.237 - 2.334	0.590
2.334 - 2.532	0.525

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2.532	3.033	0.469
3.033	3.134	0.599
3.134	3.335	0.480
3.335	3.891	0.443
3.891	4.446	0.468
4.446	5.084	0.491
5.084	5.181	0.663
5.181	6.776	0.567
6.776	6.867	0.752
6.867	7.394	0.602
7.394	7.486	0.724
7.486	7.983	0.604
7.983	8.153	0.696
8.153	8.646	0.619
8.646	8.814	0.690
8.814	9.632	0.621
9.632	9.797	0.657
9.797	10.879	0.620
10.879	12.395	0.628
12.395	16.957	0.623
16.957	24.0	0.618

PRA Revision:

None

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DSER Open Item Number: 15.3.6-1 Revision 2

Original RAI Number(s): 470.009, 470.011

Summary of Issue:

The staff has not completed its evaluation of the applicant's assumptions on aerosol removal in containment, as discussed in RAIs 470.009 and 470.011. To verify the applicant's assessment, the staff will perform independent radiological consequence calculations for a postulated design-basis LOCA coincident with the loss of spent fuel pool cooling capability once these issues are resolved. This is Open Item 15.3.6-1.

Westinghouse Response:

The Westinghouse responses to RAI 470.009 transmitted by Westinghouse letter DCP/NRC1535, November 26, 2002 and RAI 470.011 Rev. 1 transmitted by Westinghouse letter DCP/NRC1571, April 11, 2003 address previous NRC comments related to this issue.

Westinghouse Response (Revision 2):

Revision 2 of this response is to reference 15.3-1 Response Revision 3, rather than Revision 2.

The aerosol removal analysis is revised as discussed in the response to Open Item 15.3-1 Revision 3.

Design Control Document (DCD) Revision:

None

PRA Revision:

None