Attachment 10

PSAT Calculation 04002H.08

"Aerosol Decontamination Factor in Main Steam Lines"

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CALCULATION TITLE PAGE

CALCULATION NUMBER: PAST 04002H.08

CALCULATION TITLE:

"Aerosol Removal Efficiency in Main Steam Lines and Main Condenser"

	ORIGINATOR Print/Sign	Date	CHECKER Print/Sign	Date	IND REVIEWER Print/Sign	Date
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REASON FOR REVISION: Nonconformance Rpt

0 - Initial Issue N/A

1 - To correct the mean free path for steam (and the associated Cunningham slip factor) and to add credit for deposition in the main condenser NCR-96-01

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Purpose

The purpose of this analysis is to model the behavior of the aerosols in the main steam lines and main condenser and to calculate the removal efficiencies of the aerosols.

Methodology

The problem to be solved can be described as follows:

During a postulated DBA accident, the aerosols suspended in the drywell may be entrained in the flow that enters the main steam lines through the MSIV leakage. These aerosols will then experience removal processes, such as sedimentation, diffusion, diffusiophoresis and thermophoresis, and so on. Since the leakage flow is small but the size of a main steam line is large, the bulk flow velocity (driven by the leakage flow) in the main steam line is very small. Due to the fact that the average velocity of the aerosols entrained in the leakage flow is the same as the bulk velocity of the flow, the

average residence time for particles (i.e., the time the aerosols spend within the volume the main steam lines) can be very long for any typical length of the main steam lines. It is expected that most of the aerosols entering the main steam lines will be removed by the mechanisms mentioned above before leaving the steam lines into the main condenser through drain lines.

To calculate retention of aerosols in the main steam lines, the average residence time for the aerosols is determined first. Then, the removal rates of the aerosols are calculated. Finally, integration of the removal rate over the average residence time yields the amount of the aerosols removed from the total aerosols entering the main steam lines. This integration is performed in Appendix A using a spread-sheet model with an independent check performed using a different model in Appendix C.

Once the removal in the steam lines has been calculated, the corresponding removal in the main condenser can be calculated. The average residence time in the main condenser will be at least two orders of magnitude greater than the average residence time in the main steam lines because of the difference in the volumes (a factor of 177 referring to Items 3.7 and 3.8 of Reference 1) and because the main condenser is cooler, reducing the volumetric flow out of the main condenser. The difference in residence time makes the retention process in the main condenser somewhat different from that of the steam lines. Instead of a concentration gradient (and deposition gradient) being established along the flowpath as with the main steam lines, the condenser is a large, open volume with many internal structures similar to the drywell (compare Items 3.1 and 3.2 of Reference 1 for relative size). Therefore, to calculate aerosol deposition in the main condenser (i.e., an aerosol removal "lambda"), the same approach will be used as for the drywell (Reference 2), with certain exceptions as explained in Appendix B to this calculation.

Once an aerosol removal lambda is calculated for the main condenser, an effective "filter efficiency" can be calculated for the main condenser from the expression for decontamination factor, DF, where:

DF = (aerosol mass entering)/(aerosol mass leaving)
= aerosol source rate/[(aerosol concentration)(main condenser volumetric leak rate)]

For an equilibrium system (which the condenser has time to be):

$$\text{Aerosol concentration} = \frac{\text{aerosol source rate}}{\text{(aerosol removal lambda)(main condenser volume)}},$$

And, therefore:

DF = (aerosol removal lambda)(main condenser volume) / (main condenser volumetric leak rate)
= aerosol removal lambda/fractional volumetric leak rate from the main condenser

The fractional leak rate from the main condenser is known; i.e., it is the inverse of the residence time or Item 3.25 of Reference 1 divided by Item 3.8 of Reference 1:

Fractional volumetric leak rate from the main condenser = 250 cfh/122400 ft^3
= 2E-3/hr

Therefore, the DF is 500 times the aerosol removal lambda. The equivalent filter efficiency is simply 1-1/DF = 1 - (2E-3/aerosol removal lambda). This "filter efficiency" can then be combined with the "filter efficiency" of the steam lines using the following expression (recognizing that 0.5% of the steam line flow will bypass the main condenser using the ratio of Item 7.6 of Reference 1 to the sum of Items 7.6 and 7.7 of Reference 1 for what will leak to the HP turbine, instead):

Overall main steam line/main condenser "filter efficiency" =
1 - (1 - main steam line filter efficiency)[.995(1 - main condenser filter efficiency) + .005]

This expression assumes that what bypasses the main condenser sees no removal whatsoever (beyond the main steam line "filtration") which is very conservative.

Assumptions

Assumption 1: Thermal hydraulic conditions in the main steam lines are assumed to be 558.5 °K in temperature and 1 atm in pressure over the time period in the accident of interest, i.e., from 0 to about 28 hours to be consistent with other aerosol removal calculations (e.g., drywell aerosol calculation in Reference 2).

Justification: The initial temperature in the main steam lines is the same as that during normal operation, so it equals 558.5 °K, which is the steam saturation temperature at the RCS pressure of 1015 psia (the pressure is given in Reference 1 as Item 8.9). After the MSIV closes following a postulated severe accident, the pressure in the main steam lines drops to about atmospheric pressure, while the wall temperature remains unchanged at least for a while. The temperature is expected to drop as time goes on, but the drop is

ignored here since the process will be very slow due to the insulation. Ignoring the temperature drop leads to a smaller decontamination factor, as will be shown later, and is thus conservative.

Assumption 2: The gas flow in the main steam lines, which carries the aerosols is a "plug flow" (i.e., a uniform flow along the length of the main steam line with velocity based on the volumetric flow from MSIV leakage) with the possibility of localized laminar natural circulation flow.

Justification: The possible driving forces for the gas movement in the main steam lines are the following:

- The MSIV leakage, which is 100 scfh according to Reference 1,
- Wall temperature variation along the pipe.

The limited volumetric flow from MSIV leakage leads to plug flow, since the leakage rate is small while the pipe size is large. Some of the leakage may enter the main steam line as a jet-like flow if there is a leak pathway with large enough area and a large enough aspect ratio. Otherwise, the leakage will tend to diffuse into the main steam line through multiple pathways with the total leakage flow rate less than 100 scfh.

If the leakage flow is jet-like, jet-induced vortices will occur in the immediate vicinity of the leak pathway. It is expected that these vortices will efficiently mix the incoming leakage flow with the bulk gas. If there are multiple leak paths, the leakage flow mix with the bulk gas even more efficiently. Thus, the MSIV leakage is considered to result in plug flow in the main steam line starting from the immediate vicinity of the MSIV.

Variation of the wall temperature along the pipe, on the other hand, tends to cause local circulation. Since the main steam lines are insulated, heat loss during the post accident phase will be very slow. At the same time, the pipe wall is an excellent thermal conductor, which should result in smoothing out the temperature variation along the wall, especially when the heat loss is limited. Thus, the temperature variation is unlikely to be significant, and temperature variation induced local circulation, if it exists, is unlikely to be turbulent.

Assumption 3: Aerosols in the main steam lines travel, on average, at the plug flow velocity along the axis of the pipe.

Justification: The average axial velocity of the aerosols in the main steam lines is the combination of the convective flow velocity and the axial diffusion velocity of the aerosols. In general, the axial diffusion can be ignored, because it is much smaller than the convective flow velocity. But, when the convective flow velocity is very small (e.g., the plug flow velocity), whether or not the axial diffusion velocity can be ignored needs to be examined.

Consider a cross-section in the main steam line with the aerosols well-mixed per Assumption 1. The convective aerosol mass flux across the cross-section is uc, where u is the plug flow velocity and c is the aerosol concentration. The aerosol mass flux due to the aerosol axial diffusion is $-D(\partial c/\partial x)$, where D is the diffusion coefficient for aerosols and x is along the axis of the pipe. So, the average aerosol mass flux across the cross-section is $uc - D(\partial c/\partial x)$, and the average axial velocity of aerosols at that location is $u-(D/c)(\partial c/\partial x)$.

It will be shown later that the plug flow velocity in this analysis is about a half centimeter per second ($u \approx 0.5$ cm/s). Typically, the diffusion coefficient for a 0.1 micron particle is of the order of 10^{-6} cm^2/s (see Table 2.1 on page 33 of Reference 3) and the bigger the particle, the smaller the diffusion coefficient. The aerosol concentration is, at most, of the order of a few grams per cubic centimeter. So, even for an aerosol concentration gradient of several $(g/cm^3)/cm$, the diffusion velocity will be 5 to 6 orders of magnitude lower than the convective velocity. It should be pointed out that the gas diffusion coefficient is about 6 orders of magnitude higher than the particle diffusion coefficient (i.e., about 1 cm^2/s, see Table A-8 on page 545 of Reference 4). So, the axial diffusion velocity may not be negligible for gas transport (e.g., organic iodine) in the main steam lines.

Should any local circulation occur in the main steam lines, it would be laminar flow per Assumption 2 and will not affect the average velocity of the aerosols (which is the plug flow velocity) The circulation does not increase the average velocity of aerosols, but

rather moves some particles faster than the average and moves other particles slower than average or even backwards.

Assumption 4: Gas flows in the main steam lines are not affected by the conditions in the turbine building where the out leakage of the main steam lines (or stop valve) is located.

Justification: If the pressure in the turbine building is higher than that in the main steam lines, gas will enter the main steam lines via stop valve leakage and there will be no more leakage to the turbine building. All the MSIV leakage flow will then take the drain line pathway to the condenser, which is a large holdup volume for the aerosols that are still suspended after going through removal processes in the main steam lines and the drain lines.

If the pressure in the turbine building is lower than that in the main steam lines, the leakage flow rate out of the main steam lines into the turbine building will not exceed the MSIV leakage flow rate, at least for long, as a result of mass conservation.

Even if the leak path opening in the stop valve were large enough so that countercurrent gas flows could occur, there is no mechanism in the turbine building to sustain such flows. Further, it would be impossible for countercurrent flows to affect gas flows over any significant portion of the main steam line.

Assumption 5: Aerosol sedimentation is considered to be the only removal mechanism for aerosols in the main steam lines.

Justification: The main steam lines are insulated; heat transfer and condensation in the main steam lines are small and thus are not considered. As a result, diffusiophoresis and thermophoresis of aerosols are ignored. As discussed above, the particle diffusion coefficient is very small, and the flow in the main steam is a plug flow. Therefore, diffusion of aerosols on to the pipe walls is also ignored. Neglecting these aerosol removal mechanisms is conservative in the calculation of the main steam line decontamination factor.

Assumption 6: Aerosol size distribution is log normal, with an aerodynamic mass median diameter and a geometric standard deviation taken from Reference 2.

Justification: As discussed in Reference 5 (page 12-13), the overwhelming majority of aerosols are observed to have a lognormal size distribution. It is also a common practice to assume such a distribution for the fission product aerosols in nuclear safety studies. A lognormal distribution is defined by the geometric mean radius and the geometric standard deviation. The values of these parameters in this calculation are based on the drywell analysis of Reference 2, which, in turn, used an aerosol source size distribution based on data from several degraded fuel experiments [Reference 6]. It should be pointed out that the aerosol size distribution specified as input to Reference 2 yields a mass mean diameter of about 1.3 microns. For comparison, the mass mean diameters used in NUREG/CR-5966 [Reference 7] range from 1.5 to 5.5 microns and the geometric standard deviations range from 1.6 to 3.7 (see page 84). Thus, the size distribution used in this calculation is conservative compared with Reference 7.

Assumption 7: The aerosol sedimentation height of the main condenser is assumed to begin at the top of the tubes and to extend upward to the centerline of the bellows (Elevation 609'1" - Item 7.8 of Reference 1). Assume further that this region starts at an elevation above the condenser centerline (Elevation 573'3" - Item 7.9 of Reference 1) which is equal to the difference between the bottom of the hotwell (Elevation 564'9" - Item 7.10 of Reference 1) and the condenser centerline (i.e., 8.5') or Elevation 581'9". This gives a sedimentation height of 609'1" - 581'9" = 27'4" = 8.3 m.

Justification: Use of a sedimentation height of 27'4" in a condenser with an overall height (bottom of hotwell to centerline of bellows) of 44'4" is highly conservative. This means that the sedimentation height is nearly 62% of the total height of the main condenser.

Reference

Reference 1: PSAT 04000U.03, "Design Data Base for Application of the Revised DBA Source Term to the TVA Browns Ferry Nuclear Power Plant", Revision 2

Reference 2: PSAT 04001H.02, "Aerosol Decay Rates (Lambda) in Drywell", Revision 0

Reference 3: S.K. Friedlander, "Smoke, Dust and Haze - Fundamentals of Aerosol Behavior", John Wiley & Sons, New York, 1977

Reference 4: J.P. Holman, "Heat Transfer", 5th Edition, McGraw-Hill, New York, 1981

Reference 5: Fuchs, N. A., "The Mechanics of Aerosols", Dovers Publications, Inc., New York, 1964

Reference 6: Polestar Memo from R. Sher to D. E. Leaver, "Aerosol Source Size Parameters", July 28, 1995

Reference 7: Powers, D. A. and Burson, S. B., "A Simplified Model of Aerosol Removal by Containment Sprays", NUREG/CR-5966, SAND92-2689, June 1993

Reference 8: Arnand, N.K., et al., "DEPOSITION: Software to Calculate Particle Penetration through Aerosol Transport Systems", NUREG/GR-0006, April 1993

Calculation

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NOTICE

The Non-Proprietary Version of Calculation Number
PSAT 04002H.08 Rev. 1
(Attachment 10 to Non-Proprietary PSAT 04000U.04)
does not include any of the appendices identified in the Table of Contents.
Appendices A, B, and C are Proprietary.