Attachment 4

PSAT Calculation 04001H.02

"Aerosol Decay Rates (Lambda) in Drywell"

CALCULATION TITLE PAGE

CALCULATION NUMBER: PSAT 04001H.02

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Purpose

The purpose of this analysis is to calculate the aerosol decay (removal) rates in the drywell due to natural removal mechanisms that remove fission and non-fission product aerosols from the drywell atmosphere.

Methodology

The problem to be solved can be described as follows:

During a design base accident (DBA), fission product aerosols are released from the damaged core into the drywell, together with significant amounts of steam and non-condensable gases. The steam and gases, as well as the heat transfer to the gases in the drywell, will cause an increase in drywell pressure and result in a significant sweeping flow into the wetwell through the vent/downcomers that connect the drywell and wetwell. Leakage flows into the main steam lines through the MSIVs and directly to the reactor building are also expected. All these flows will dilute or remove the aerosols in the drywell and, at the same time, the aerosols will experience other removal processes, such as sedimentation, diffusiophoresis, thermophoresis, etc., the rates of which are to be determined in this analysis.

Based on the mass conservation law, the suspended aerosol mass in the drywell is governed by the following equation:

Suspended mass = Injected mass - Leaked mass - Removed mass

The injected mass of aerosols include both fission and non-fission product aerosols from the primary system. The leaked mass accounts for the aerosols entrained in the leak flows through several leakage pathways, such as the vent and bypass that connect the drywell and wetwell, the MSIV leakage, and the drywell leakage, and the removed mass represents the aerosols deposited on the surfaces in the drywell due to sedimentation, diffusiophoresis, thermophoresis, and other aerosol removal processes. All of the quantities in the equation can be functions of time.

The above equation is solved by the STARNAUA code [reference 1] in which the aerosol removal processes mentioned above are modeled, and the suspended aerosol concentration is calculated for the specified timing and rates of injected aerosols and the specified aerosol leakage rates through different pathways.

Assumptions

Assumption 1: The drywell is well-mixed during the entire time period of the accident.

Justification: Given the fact that steam, non-condensable gases (e.g., hydrogen) and fission product gases and aerosols are blowing into the drywell atmosphere, while significant heat and mass transfers are going on in the drywell, this assumption is reasonable.

Assumption 2: Condensation and sensible heat transfer onto the drywell walls are neglected.

Justification: Since the drywell walls are insulated, the initial blowdown before any release of fission product aerosols is expected to heat up the walls very quickly so that further heat transfers (both condensational and sensible) to the wall during and after the release of fission product aerosols will not be significant. Nevertheless, this assumption is conservative in the sense that it will result in a smaller aerosol decay rate.

Assumption 3: Hygroscopicity of aerosols is ignored and relative humidity in the drywell is assumed to be 98% through-out the accident.

Justification: The cesium and iodine species (mostly CsI and CsOH) released into the drywell are likely to be soluble and the hygroscopic effect

on the growth of the soluble aerosols is significant, which enhances the removal of such aerosols by increasing sedimentation. The assumption to ignore the hygroscopicity will then be conservative. A relative humidity of 98%, on the other hand, has no impact on this analysis since both the hygroscopic effect on aerosol growth and diffusiophoresis (that is indirectly affected by the relative humidity) are not considered. Neglecting diffusiophoresis is also conservative.

Assumption 4: The amount and timings of the fission product releases are obtained from NRC documents. The release fractions are obtained from NUREG-1465 [reference 2] (see Tables 3.8 and 3.12) and the core inventories are from Table 4.6 NUREG/CR-4624 [reference 3], all of which are summarized in Table 1 below. The timings are also obtained from NUREG-1465. Two phases of the fission product release are assumed. First, the gap release starts at 30 seconds after the initiation of the accident and lasts 1800 seconds. It is then followed by the early in-vessel release that lasts 1.5 hours.

According to NUREG-1465, the iodine specie released to the containment is in the forms of particulate and gases (organic and elemental). 95% of the iodine released to the containment is aerosol, while 5% is gases. Of the iodine gases, 97% are elemental and 3% are organic. Organic iodine behaves like a noble gas, so it is assumed to be non-removable. Elemental iodine, on the other hand, tends to deposit on aerosols or other surfaces, and is assumed to be removed similarly to the aerosols.

Discussion: The core inventories in NUREG/CR-4624 were actually from NUREG/CR-2181 done in 1982. Since then, the total burn-up of the fuel assemblies in a fuel cycle in Browns Ferry has increased, which will result in an increase in the fission product core inventories. However, as far as the calculation of the aerosol decay rates is concerned, it is conservative to use smaller core inventories, since the only possible impact from an increased core inventory is to get a higher aerosol concentration and, consequently, a larger aerosol decay rate. On the other hand, the assumption of smaller core inventories is not overly conservative in this analysis since the aerosol removal processes are less significant than the removal due to the sweeping flow from the drywell to the wetwell.

Assumption 5: The amount of non-fission product aerosols released to the containment is the same as that of fission product aerosols (i.e.,

about 77 kg). They are released uniformly during the in-vessel release period, similar to the fission product aerosol release. The average density of the non-fission product aerosols is assumed to be 5.6 g/cm^3.

Justification: The assumption that the ratio of fission to non-fission in-vessel releases is 1:1 is obtained from reference 4. It should be pointed out that it was mentioned in NUREG-1465 that about 780 kg of in-vessel non-fission masses was calculated in NUREG-0956 for one Peach Bottom sequence. Since the Peach Bottom reactor is almost identical to the Browns Ferry reactor that is analyzed here, the same order of magnitude of non-fission product release is expected. But, the non-fission product release that we assume is only 10% of what was calculated in NUREG-0956. Our assumption should then be conservative, since a larger amount of non-fission product release will enhance overall aerosol agglomeration and, therefore, increase aerosol sedimentation. As for the density, most of the non-fission product aerosols are Zr, Fe_2O_3 and UO_2 species whose densities are 6.4, 5.24 and 10.09 g/cm^3, respectively. So, a density of 5.6 g/cm^3 for the non-fission product aerosols represents a conservative value, considering that the Zr inventory in the core is almost three times higher than that of the iron (table 4.5, reference 3).

Table 1. Fission Product Releases Into Containment

Group	Title	Elements in group	Gap release[1]	Early in-vessel release[1]	Core inventory (kg)
1	Noble Gases	Xe, Kr	0.05	0.95	413
2	Halogens	I, Br	0.05	0.25	16.6
3	Alkali Metals	Cs, Rb	0.05	0.20	230
4	Tellurium Group	Te, Sb, Se	0	0.05	34.9
5	Barium, Strontium	Ba, Sr	0	0.02	167.7
6	Noble Metals	Ru, Rh, Rd, Mo, Tc, Co	0	0.0025	584
7	Lanthanides	La, Zr, Nd, Eu, Nb, Pm, Pr, Sm, Y, Cm, Am	0	0.0002	837
8	Cerium Group	Ce, Pu, Np	0	0.0005	992

[1] Fractions of core inventories.

Assumption 6: The flow exchange between the drywell and the wetwell is ignored after containment heat removal (or reflood) is over.

Justification: According to PSAT 04000U.03 [reference 5] (Items 3.10 and 3.11), before 7890 seconds the flow exchange between the drywell and the wetwell is only in one direction, i.e., from the drywell to the wetwell. So, the flow can be considered as a leakage flow out of the drywell. After 7890 seconds the flow from the drywell to the wetwell is balanced by the flow from the wetwell to the drywell. To fully model the two-way flow exchange, the calculation of aerosol behavior in both the drywell and the wetwell needs to be conducted in parallel, which will be very difficult. This assumption, evidently, simplifies the problem. The implication of the effect on the drywell aerosol decay rate calculation needs to be discussed when the result is used. Nevertheless, it should be pointed out that the aerosol decay rate in the wetwell is almost always higher than that in the drywell, since

- the aerosols entering the wetwell from the drywell are more or less scrubbed, especially if the suppression pool is sub-cooled.

- the wetwell has a smaller airspace volume than the drywell (1:1.28), and a larger sedimentation area than the drywell (1.67:1). Thus the wetwell is more favorable for aerosol sedimentation.

Assumption 7: Aerosol size distribution is log normal, with a geometric mean radius of 0.22 micron and a geometric standard deviation of 1.81.

Justification: As discussed in Reference 6 (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 for them to be used in this calculation are based on an analysis of data from several degraded fuel experiments [reference 7]. It should be pointed out that the aerosols size distribution specified here yields a mass mean diameter of about 1.3 microns. For comparison, the mass mean diameters used in NUREG/CR-5966 [reference 8] range from 1.5 to 5.5 microns and the geometric standard deviations range from 1.6 to 3.7 (see page 84). Thus, our assumption is evidently at the lower end of what were used in reference 8, and is thus conservative compared with reference 8.

Reference

Reference 1: PSAT C101.02, "STARNAUA - A Code for Evaluating Severe Accident Aerosol Behavior in Nuclear Power Plant Containment: A Validation and Verification Report, Revision 0, May 1995

Reference 2: Soffer, L., et al., "Accident Source Terms for Light-Water Nuclear Power Plants", NUREG-1465, February 1995

Reference 3: Denning, R. S., et al., "Radionuclide Release Calculations for Selected Severe Accident Scenarios, BWR, Mark I Design", NUREG/CR-4624, BMI-2139, Vol. 1, July 1986

Reference 4: Letter from J. C. DeVine, Jr. to Leonard Soffer, "Additional ALWR Program comments on the NRC draft source term report, NUREG 1465", July 30, 1993

Reference 5: PSAT 04000U.03, "Design Data Base for Application of the Revised DBA Source Term to the TVA Browns Ferry Nuclear Power Plant", Revision 0

Reference 6: Fuchs, N. A., "The Mechanics of Aerosols", Dovers Publications, Inc., New York, 1964

Reference 7: Polestar Memo from R. Sher to D. E. Leaver, "Aerosol Source Size Parameters", July 28, 1995

Reference 8: Powers, D. A. and Burson, S. B., "A Simplified Model of Aerosol Removal by Containment Sprays", NUREG/CR-5966, SAND92-2689, June 1993

Calculation

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Table 4. Sedimentation Lambda as A Function of Time

Time[1] (second)	Sed. Lambda (1/hour)	Tot. Lambda (1/hour)	Time[1] (second)	Sed. Lambda (1/hour)	Tot. Lambda (1/hour)
48	0.30	0.30	8627	0.90	0.90
550	0.29	0.29	9868	0.80	0.80
1115	0.30	0.30	11786	0.70	0.70
2426	0.40	1.41	14615	0.60	0.60
3229	0.50	1.51	18774	0.50	0.50
4016	0.60	1.61	25011	0.40	0.40
4916	0.70	1.71	35598	0.30	0.30
6321	0.80	1.81	57247	0.20	0.20
7393	0.90	8.45	99807	0.12	0.13
7902	0.99	0.99			

The STARNAUA output files are given in Appendices C and D. The headings are added to the plot file in Appendix C to make it understandable. The STARNAUA output file, on the other hand, has been shortened to avoid an unnecessarily long printout. The time in those output files is the STARNAUA time that starts at core uncovery, 30 seconds after the initiation of the accident.

[1]Accident time, which is STARNAUA time + 30 seconds.

APPENDIX A

APPENDIX B: "STARNAUA Input files"

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APPENDIX C: "STARNAUA Plot File"

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APPENDIX D: "STARNAUA Output File"

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