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ATTENTION: T. R. QUAY

SUBJECT: POSITION PAPER ON THE REMOVAL OF AEROSOLS FROM THE
AP600 CONTAINMENT ATMOSPHERE FOLLOWING A POSTULATED
LOCA WITH CORE MELT USING ONLY NATURAL REMOVAL
PROCESSES OF SEDIMENTATION AND DEPOSITION

Dear Mr. Quay:

The AP600 design depends on the natural processes of sedimentation and deposition to remove aerosols from the containment atmosphere following a postulated LOCA with core melt rather than depending on active systems.

The enclosed position paper discusses the methodology and assumptions used for the determination of the aerosol removal coefficients of 0.63 hr^{-1} for the first two hours after onset of core damage and 0.81 hr^{-1} for the remainder of the first 24 hours of the accident.

These aerosol removal coefficients are considered appropriate for use in the evaluation of design basis LOCA radiological consequences. It is noted that the conservatism in the design basis LOCA dose analysis is provided by the conservative assumption of core melt (in the separate analysis that is performed to determine the core damage for a design basis LOCA, it must be demonstrated that the coolable core geometry is retained and that peak clad temperature does not exceed 2200°F) together with the very conservative dose evaluation methodology - including use of the worst two hour dose interval. Providing additional, arbitrary conservatism by reducing the calculated aerosol removal rate is unnecessary and is inconsistent with the objectives of NUREG-1465 to provide "more realistic portrayal of the amount of fission products present in the containment."

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Add: T.R. Quay

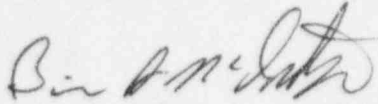
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I will contact you to arrange the necessary discussions and meetings to reach resolution on this important issue.



Brian A. McIntyre, Manager
Advanced Plant Safety And Licensing

/nja

Enclosure

cc: T. Kenyon - NRC
N. Liparulo, Westinghouse (w/o enclosures)

AP600 Specific Values for Aerosol Removal Following a Design Basis Loss-of-Coolant Accident with Core Melt

1.0 Introduction

The AP600 design does not depend on active systems to remove airborne particulates from the containment atmosphere following a postulated Loss-of-Coolant Accident (LOCA) with core melt. It has been determined that naturally occurring passive aerosol removal processes provide significant removal capability, with calculated aerosol removal coefficients (λ) of 0.63 hr^{-1} for the first two hours and 0.81 hr^{-1} for the time period from 2 to 24 hours. With these removal coefficients and the core melt source term model from NUREG-1465 [1] the airborne particulates are reduced to extremely low levels within twelve hours.

The above λ values were calculated by STARNAUA, a mechanistic containment aerosol code that has been well validated [2,3].

2.0 Aerosol Removal Mechanisms

The STARNAUA code includes models for deposition removal of aerosols by sedimentation, diffusiophoresis, and thermophoresis. These mechanisms are briefly discussed below and are discussed in greater detail in reference [2]. All three of the deposition processes are significant contributors to the overall removal process in the AP600. The calculation of aerosol removal for the AP600 showed that 46.6% was due to sedimentation, 30.7% was due to diffusiophoresis, and 22.7% was from thermophoresis. 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 (PCCS).

Because of the AP600 PCCS design, there are high sensible heat transfer rates (resulting in higher thermophoretic removal of aerosols) at those times when condensational heat transfer is low (and the aerosol removal by diffusiophoresis is also low). The reverse is also true. Thus, there is an appreciable deposition removal throughout the accident from either diffusiophoresis or thermophoresis, in addition to the removal by sedimentation.

The contribution of each removal mechanism to the overall aerosol removal is based on modeling of the post-accident environment and the aerosol generation to concur with the most accurate available information. The models used for the three removal processes are:

2.1 Sedimentation

Gravitational sedimentation is a major mechanism of aerosol removal in a containment. In STARNAUA a standard model (Stokes equation with the Cunningham slip correction factor) for this process is employed. STARNAUA also has the capability of accounting for the condensational growth of hygroscopic aerosol particles in a steam atmosphere. The increased particle size leads to faster deposition. Such important aerosol species as CsI and CsOH are hygroscopic. In the AP600 calculation the hygroscopic effect was not considered. Therefore the calculation for gravitational sedimentation is conservative.

The Stokes equation is [4]:

$$v_s = \frac{2\rho_p g a^2}{9\mu} [Cn (Kn)]$$

where

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

2.2 Diffusiophoresis

Diffusiophoresis is the process whereby particles are swept to a surface (e.g. containment wall) by the flow set up by a condensing vapor (Stefan flow). The deposition rate is independent 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 [5], and is used in STARNAUA. The Waldmann-Schmitt equation is:

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

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; it can be expressed in terms of the condensational heat transfer rate to the wall if that is the thermal hydraulic input variable that is available.
 ρ_v = mass density of steam in the containment atmosphere

Because of the design of the PCCS, steam condensation rates are high at certain times in the DBA LOCA, thus at these times diffusio-phoretic deposition rates are significant.

2.3 Thermophoresis

Thermophoresis is the process whereby particles drift toward a surface (e.g. 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 in STARNAUA is the Brock equation in a form due to Talbot et al. [6]. 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:

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

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)
 Kn = Knudsen number, previously defined
 $C_n(Kn)$ = Cunningham slip correction factor, previously defined
 μ_g = gas viscosity
 ρ_g = gas density
 C_s , C_T , and C_M are the slip, thermal, and momentum accommodation coefficients, respectively [6]. Talbot et al. give their best values as $C_s = 1.17$, $C_T = 2.18$, and $C_M = 1.14$.

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. It is obtained as the difference between the input total and condensation heat fluxes.

2.4 Other Removal Mechanisms

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

3.0 Validation of Removal Mechanisms

The aerosol processes discussed above are well established and have been confirmed in many separate effects experiments, which are discussed in standard references [4-6]. 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 [7]. 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 20-50% over a wide range of particle sizes [6]. The temperature gradient at the wall, which drives this phenomenon, can be approximated by the temperature difference between the bulk gas and the wall divided by an appropriate length scale obtained from heat transfer correlations. Alternatively, if 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, as indicated above.

4.0 STARNAUA

STARNAUA [3] is a Polestar-proprietary revised version of the mechanistic aerosol computer code NAUAHYGROS [2], which in turn is an enhanced version of NAUA-mod 4 [8]. These codes have been used successfully for many years to simulate aerosol behavior in containments. The containment geometry is specified by the user. STARNUA assumes that the containment is a single compartment in which the atmosphere and the aerosol are well mixed; there are no spatial dependencies in the

calculation. The user provides geometric data such as the containment volume and the surface areas for settling and diffusive depositions (including diffusiophoresis and thermophoresis). In addition, certain thermal hydraulic data must be input as a function of time. These include the gas temperature, wall temperature, steam injection rate, and volumetric leak rate as functions of time. For some calculational options additional or alternative input thermal hydraulic data may be used. In addition, the source aerosol is assumed to have a lognormal size distribution; the geometric mean radius and geometric standard deviation are user input (see below). As mentioned previously, STARNAUA models aerosol removal by sedimentation, diffusiophoresis, and thermophoresis. Brownian and gravitational agglomeration of particles are fully modeled. Turbulent agglomeration and diffusion, and the effects of steam condensation on hygroscopic particles are not modeled; as has been noted, this results in conservative removal coefficients.

STARNAUA models the depletion of airborne aerosols and calculates the mass of aerosol that is leaked to the environment. Aerosol removal coefficients are then calculated to yield the leaked mass, given the aerosol source rates in Section 6.

STARNAUA has been validated against the original NAUA - mod 4 and against NAUAHYGROS. The validation against NAUA is for the case of no steam condensation on particles or on the wall. The validation against NAUAHYGROS was performed for both dry (i.e., no condensation) and wet cases. These validations are described in full detail in reference [3]. NAUAHYGROS itself has been validated against the LACE experiments [7], in which thermophoresis was negligible. In addition, the thermophoresis model which is incorporated into STARNAUA has been validated, as mentioned above.

The validation of NAUAHYGROS (and therefore of STARNAUA) against the LACE experiments LA-2, LA-4, and LA-6 [7] is described in detail in reference [2]. It should be emphasized again that calculations that do not properly account for steam condensation on the particles and diffusiophoresis fail quite badly in predicting the aerosol deposition behavior in these experiments. For example, the calculated plated aerosol mass is too low by a factor of 60 compared with the measured value if diffusiophoresis is not included. (Thermophoresis was not significant in these tests). On the other hand, these effects might not be as important in other situations, depending on the thermal hydraulic conditions; as has been noted, steam condensation on the particles was neglected in the AP600 calculations.

5.0 Containment Geometry and Aerosol Source Parameters

5.1 Containment Geometry

The containment is assumed to be a cylinder with a volume of $47,930 \text{ m}^3$. The horizontal surface area for aerosol deposition by sedimentation is 4160 m^2 . This includes projecting areas such as decks in addition to the floor area. The total surface

are for Brownian diffusive plateout of aerosols is 7040 m^2 . (Since Brownian diffusion is small compared to diffusiophoresis and thermophoresis, the results are not sensitive to this choice.)

5.2 Source Size Distribution.

The aerosol source size distribution is assumed to be lognormal, with a geometric mean radius of $0.22 \text{ }\mu\text{m}$ 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 [9]. The sensitivity of leaked aerosol masses and lambdas to these values is small.

5.3 Aerosol release fractions

Core inventories of fission product and inert (structural and control) aerosol species at accident initiation are taken from reference [10]. The fission product inventories are shown in Table 1. These are based on ORIGEN calculations (scaled to a 600 MW(e) reactor) at the end of life after three 2-year cycles. Fractional releases to the containment of the fission products are those specified in NUREG-1465 [1], except for the low volatility species (Sr, Ba, Ce, and La). For these, the recommended values of Hobbins and Osetek [11] are used. Table 2 shows the fractional releases in the gap and early in-vessel phases. Since there is reflood in the reference accident sequence, no late releases were considered.

It should be noted that the values for the fission products in Tables 1 and 2 refer to individual species, not to groups. For example, reference [11] gives the early in-vessel release fraction for the Te group as 0.05, therefore this value was also used for Sb, which is a member of that group.

Table 1.Fission Product Core Inventories

Element	Core inventory, g
Cs	2.2 E5
I	1.8 E4
Te	3.8 E4
Ba	1.2 E5
Sr	7.1 E4
Ce	2.1 E5
La	9.7 E4
Ru	1.9 E5
Sb	2.3 E3

Table 2. Release Fractions*

	Gap release	Early in-vessel release
Cs	0.05	0.25
I	0.05	0.35
Te	-	0.05
Ba	-	0.004**
Sr	-	0.004**
Ce	-	0.0001**
La	-	0.0001**
Ru	-	0.0025
Sb	-	0.05

* From reference [1], except as noted.

** From reference [11].

5.4 Inert Aerosol Species

The inert species include SnO_2 , UO_2 , Cd, Ag, and Zr. They act as surrogates for all non-fission product species. The ratio of the total mass of inert species to fission product species was assumed to be 3:1. This value and the partitioning of the total inert mass among its constituents are consistent with results from degraded fuel experiments [10].

6.0 Aerosol Release Timing and Rates

Aerosol release timing is in accordance with NRC specifications for a PWR, as given in reference [1]. Aerosol release takes place in two phases, a gap release lasting for 1800 seconds, followed by an early in-vessel release of 1.3 hours (4680 sec) duration. During each phase the aerosols are assumed to be released at a constant rate given for each species by the values in Table 3. These rates were obtained for each species by combining its core inventory, release fraction, and the times of release.

Only Cs and I are released during the gap release phase. During the in-vessel release phase the other fission product and inert species are released as well.

Table 3. Aerosol Release Rates

	Gap release period, 0- 1800 sec, g/s	In-vessel release period, 1800-6480 sec, g/s
CsOH	6.3017	11.6643
CsI	1.0236	2.7559
Te	-	0.405983
BaO	-	0.114513
SrO	-	0.071765
CeO ₂	-	5.51194 E-03
La ₂ O ₃	-	2.43075 E-03
Ru	-	0.101496
Sb	-	0.024573
SnO ₂	-	24.2703
UO ₂	-	2.17942
Cd	-	21.5552
Ag	-	5.43086
Zr	-	2.69140

7.0 Containment Thermal Hydraulic Data

The thermal hydraulic parameters required for the STARNAUA aerosol removal calculation are the containment leak rate (volume percent per day), the containment gas temperature, the containment pressure, the steam condensation rate on the wall, the steam mole fraction, and the total heat transfer rate; all as functions of time. The AP600 specific parameters were obtained using MAAP4 [12] for the 3BE severe accident sequence (medium LOCA with failure to inject water from the refueling water storage tank into the reactor vessel).

8.0 Summary

Lambda values of 0.63 hr^{-1} for the first two hours and 0.81 hr^{-1} for the time period of 2 to 24 hours were determined with the use of parameters that have been selected to accurately model the environment that would be expected to exist as a result of a LOCA with concurrent core melt.

Sensitivity studies indicate that reasonable variations in source aerosol size, mass ratio of inert materials to fission products in the aerosols, timing of release, and sedimentation area do not have a significant effect on aerosol removal rate.

Additionally, these lambda values conservatively neglect steam condensation on the airborne particles, turbulent diffusion, and turbulent agglomeration. Finally, the source aerosol size assumed in this work is conservatively small. For example, the aerosol size used here is at the low end of the mass mean aerosol size range of 1.5 to 5.5 μm used in NUREG/CR-5966 [13]. Selection of smaller aerosol size would underestimate sedimentation.

Thus, the calculated lambdas are reasonably conservative and robust, and are considered to be appropriate for use in the evaluation of design basis LOCA radiological consequences.

References:

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