UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

July 29, 2021

MEMORANDUM TO: Kevin Hsueh, Chief
Radiation Protection and Consequence Branch
Division of Risk Assessment
Office of Nuclear Reactor Regulation

FROM: Elijah Dickson, Reactor Scientist
Radiation Protection and Consequence Branch
Division of Risk Assessment
Office of Nuclear Reactor Regulation

Elijah Dickson Signed by Dickson, Elijah on 07/29/21

SUBJECT: TECHNICAL BASIS FOR DRAFT RG 1.183 REVISION 1 (2021) RE-EVALUATED AEB-98-03 SETTLING VELOCITY METHOD, THE MULTI-GROUP METHOD, AND THE NUMERICAL INTEGRATION METHOD

The purpose of this memorandum is to document the technical basis for recommended updates to existing staff analyses related to design-basis loss-of-coolant accident (DBLOCA), main steam isolation value (MSIV) leakage pathway described in the staff assessment entitled, *Assessment of Radiological Consequences for the Perry Pilot Plant Application using the Revised (NUREG-1465) Source Term,* (AEB-98-03).[1] AEB-98-03 has been utilized for more than 20 years when implementing 10 CFR 50.67, *Accident source term*, through Regulatory Guide (RG) 1.183, Rev. 0, *Alternative Radiological Source Terms for Evaluating Design Basis Accidents at Nuclear Power Reactors,* (USNRC, 2000) which does not have an aerosol particle deposition model for main steam lines (MSLs). Since the initial Perry alternative source term (AST) review, the staff has approved full implementation of the AST at a majority of the boiling water reactor (BWR) nuclear power plants utilizing some form of the MSIV leakage pathway MSL aerosol deposition model described in AEB-98-03. Therefore, in conjunction with efforts to update RG 1.183 Rev. 0, the staff re-evaluated the AEB 98-03 analysis as well as incorporate lessons learned from several dozen license amendments utilizing the AST.

Following multiple operating reactor license amendment requests to revise their accident source term to implement an AST under 50.67, the U.S. Nuclear Regulatory Commission (NRC) staff published Regulatory Issues Summary 2006-04, *NRC Regulatory Issue Summary 2006-04, Experience with Implementation of Alternative Source Terms*. (NRC, 2006).

Enclosures:
As Stated

CONTACT: Elijah Dickson, NRR/DRA/ARCB Shawn Campbell, RES/DSA/FSCB

[1] See ADAMS Accession Number ML011230531

The purpose was to discuss the more frequent and significant issues encountered by the NRC staff during its review of AST submittals and to provide information for licensees to consider when developing submittals for implementation of an AST. A frequent point of contention between licensees and the NRC staff was the deposition of particulate iodine in the MSLs in BWRs. For calculating an aerosol settling velocity in the MSL piping of BWRs, the staff reaffirmed the modeling approach in AEB 98-03 but emphasized the AEB 98-03 analysis was based on the parameters of a particular plant and, therefore, the removal rate constant is specific to that plant. Any licensee who choose to reference these AEB 98-03 assumptions would need to provide appropriate justification that the assumptions are applicable to their particular facility design.

Upon further review of staff safety evaluations approving ASTs, two primary issues were identified. The first issue was that assumed aerosol particle size distribution in the vicinity of the MSIV is, in general, different from that in the containment. This difference is dependent on plant design, such as piping volumes. Thus, the aerosol deposition velocity assumed by the licensee needed to be adequately justified for their particular facility. The second issue was the use of a single median settling velocity which does not account for the removal of heavier and larger particles settling quicker than the lighter and smaller particles through each successive MSL volume. This aerosol particle behavior leads to the conclusion that the choice of an effective settling velocity in any volume should account for the distribution of particle sizes in that volume.

In response to the concerns raised in RIS 2006-04, licensees proposed a number of modeling changes from those assumed in AEB 98-03, such as utilizing a slower settling velocity and in some cases using the so-called “20-group method.” The 20-group method simulates the varied population of particulates in a given MSL volume, as opposed to a single median value, to account for the uneven settling of “easier-to-remove particles” versus “difficult-to-remove particles.” In effect, the modeling approach successively shifts “weight” from the easier-to-remove particles when entering the piping, to the difficult-to-remove particles as flow moves through the MSL.

With the renewed effort to update RG 1.183, the staff has decided to address issues described in RIS 2006-04 by:

- Re-evaluating the AEB 98-03 aerosol settling velocity technical basis to address known parameter modeling errors.

- Evaluating the 20-group method, herein referred to as the “multi-group method,” to address the AEB 98-03 use of a single median settling velocity which does not account for the removal of heavier and larger particles settling quicker than the lighter and smaller particles through each successive MSL volume.

- Including an additional method using numerical integration to compute MSL aerosol settling velocities and subsequence removal coefficients.

The Office of Nuclear Reactor Regulation (NRR), Division of Risk Assessment (DRA), Radiation Protection and Consequence Branch (ARCB), requested through an Informal Assistance Request (IAR) that the Office of Research (RES) independently review and provide recommendations for improvements of the AEB 98-03 aerosol settling velocity analysis. In response to the IAR, found in ADAMS Accession Package Number ML21078A155, RES provided recommended aerosol settling velocity physics parameters to those applied in AEB-98-03. Attachment 1 provides additional background on AEB-98-03 as well as a summary of the

IAR recommendations. Attachment 2 provides a review of the multi-group method which utilizes recommendations found in Attachment 1. Attachment 3 provides an independent technique for computing effective settling velocities using numerical integration which also utilizes recommendations found in Attachment 1. Attachment 4 provides the MATLAB script used to review the multi-group method and perform a variety of case-studies.

The following attachments are included with this memo:

Attachment 1: Re-Evaluation of AEB 98-03's Aerosol Parameters.

Attachment 2: Analytical Technique to Compute Effective Settling Velocities using the Multi-group Method and Sample Calculation

Attachment 3: Analytical Technique for Compute Effective Settling Velocities using Numerical Integration Method and Sample Calculation.

Attachment 4: MATLAB Script for AEB 98-03 Re-Evaluation and Multi-Group Method
The examples within the attachments are not regulatory positions.

SUBJECT: TECHNICAL BASIS FOR DRAFT RG 1.183 REVISION 1 (2021) RE-EVALUATED AEB-98-03 SETTLING VELOCITY METHOD, THE MULTI-GROUP METHOD, AND THE NUMERICAL INTEGRATION METHOD DATED:

DISTRIBUTION:
PUBLIC

EDickson SCampbell HEsmaili

ADAMS Accession No.: ML21141A006 NRR-106

OFFICE	RES/DSA/FSCB	NRR/DRA/ARCB	RES/DSA/FSCB	NRR/DRA/ARCB
NAME	SCampbell	EDickson	HEsmaili	KHsueh
DATE	7/29/2021	7/29/2021	7/29/2021	7/30/2021

OFFICIAL RECORD COPY

RE-EVALUATION OF AEB 98-03'S AEROSOL PARAMETERS.

Shawn Campbell, Mike Salay, James Corson

BACKGROUND

This re-evaluation of the staff report, *Assessment of Radiological Consequences for the Perry Pilot Plant Application Using the Revised (NUREG-1465) Source Term,* (AEB 98-03), focuses on its method of utilizing the Stokes settling velocity equation to estimate aerosol deposition within main steam line (MSL) piping. The intent is to develop a defensible simplified aerosol removal calculation starting with a representative size distribution for adoption into future regulatory guidance which would constitute a significant improvement over the single settling velocity approach of AEB-98-03.

The staff report, AEB 98-03, provides the current technical basis of modeling of aerosol settling velocity and deposition within the MSLs. These models were developed for the initial implementation of an AST under 10 CFR 50.67 for the Perry Nuclear Power Plant. This work was a first attempt to estimate possible release behavior. The analysis does involve a known non-conservatism in that it omitted the smaller tails of the size distribution, which spanned sizes that had long been understood to be minimally susceptible to removal processes and become increasingly relevant in time. Therefore, licensees who had subsequently adopted the AST which referenced as precedence AEB 98-03 as an acceptable method, needed to incorporate various resolutions to issues discussed in Regulatory Issues Summary 2006-04, U.S. Nuclear Regulatory Commission (*NRC) Regulatory Issue Summary 2006-04, Experience with Implementation of Alternative Source Terms (ASTs)*.

First, a discussion is provided related to issues associated with the AEB 98-03 settling velocity methodology. Next, a re-evaluation of the AEB 98-03 aerosol settling velocity technical basis was performed.

AEB 98-03 Analysis of Main Steam Line Aerosol Distributions

The AEB 98-03 analysis involved two relevant major assumptions: (1) that the radionuclide source term concentration matched that in containment as evaluated using the NUREG-1465, *Accident Source Terms for Light-Water Nuclear Power Plants (NUREG-1465)*, accident source term; and, (2) the use of an aerosol settling rate based on characteristics of size, density, and shape-factor distributions. The use of the containment aerosol concentration was a necessity given that this was the only information available without the considerable time involved in evaluating the aerosol distribution with a code that mechanistically evaluates aerosol behavior for the steam lines. Although AEB-98-03 used density and shape factor distributions that represented the understanding of the time, the size (diameter) distribution did not completely capture the distribution as described in the source material. AEB 98-03 uses a distribution for volume equivalent diameter of 1.5-5.5 μm as the probability distribution. This distribution is described as "For diameter, Reference 8 gives a range of 1.5 to 5.5 μm with a uniform distribution." [Reference 8 refers to Powers and Burson, "*A Simplified Model of Aerosol Removal By Containment Sprays," NUREG/CR-5966* (USNRC, 1993), also referred to as the Spray Decontamination Report] This is a misinterpretation of the distribution in NUREG/CR-5966 which does not consider the aerosol size distribution to be 1.5 to 5.5 μm.

Enclosure 1

The report considers the volume-equivalent diameter distribution of 1.5 to 5.5 μm to represent the [mass] mean of possible lognormal aerosol size distributions with the distribution widths characterized by the geometric standard deviation. Reference 8 of AEB 98-03 cites other analyses for the size distribution.

NUREG/CR-5966 provided two sets of volume-equivalent probability of size distributions, one for non-sprayed aerosols in containment and another for sprayed aerosols in containments. Both unsprayed and sprayed distributions involved the assumption of lognormal aerosol size distributions. The report considered the means of the non-sprayed aerosol volume equivalent diameter distributions to range uniformly from 1.5 to 5.5 μm and the geometric standard deviation to range uniformly from 1.6 to 3.7. The report considered the means of sprayed volume equivalent diameter distributions to range uniformly from 0.15 to 0.65 μm and the geometric standard deviation to be correlated with the mean and to range from 1.1 to 1.6.

NUREG/CR-5966 based the sprayed distribution on results from calculations of spray models involving the relevant removal mechanisms based on an initial aerosol size distribution. Note that the spray removal mechanisms have greater influence on the post-sprayed size distribution than the original size distribution. Powers based the original volume equivalent diameter distribution on the result of several calculations using the Source Term Code Package (STCP) code, the predecessor to the MELCOR code. The NAUA (Bunz, 1983) module is the sectional aerosol code for STCP to compute aerosol behavior in light water reactor core melt accidents. This code evaluates aerosol size changes in the same manner that MAEROS module does for the CONTAIN and MELCOR codes. Some in the nuclear industry have since adopted and enhanced the NAUA code.

A few years after the Spray Decontamination Report was published, the “Natural Processes Report” was published, *A Simplified Model of Aerosol Removal by Natural Processes in Reactor Containments*, NUREG/CR-6189, Powers, et al (USNRC, 1996). This report used a code similar to MAEROS in MELCOR. The authors studied condensation and other growth processes for expected chemical species of both radioactive and non-radioactive substances being released from a degrading core using the proposed specification of source term to containment. Parameters varied in the uncertainty analysis in the removal analysis include reactor and scenario properties along with various aerosol growth and removal uncertainties. The focus and main product of this report was a simplified removal coefficient model for natural processes in containment. The authors provided representative particle sizes but not size distributions. The provided effective particle size (presumably volume equivalent diameter) for a specific BWR scenario ranged approximately from 1.75-5.5 μm, similar to the mean size the authors used in NUREG/CR-5966 a few years earlier (and similar to the AEB-98-03 distribution).

The AEB-98-03 size distribution ultimately represents the mean of aerosol size distributions from multiple calculations using the STCP code, the predecessor to the MELCOR code, and involves uncertainty analysis using uncertainty methods from a study called Quantitative Uncertainty Estimation for the Source Term (QUEST) reported by Lipinski (1985). In other words, the AEB-98-03 size distribution was based on mechanistic calculations. Observations of the PHÉBUS -FP and other integral experiment aerosols (involving radionuclide release from fuel in representative chemical combinations and conditions) indicates that aerosol size distributions are smaller than previously assumed as in this report.

Even though the NUREG/CR-6189 Natural Processes report analysis showed a similar representative volume-equivalent-size distribution for a specific BWR calculation as the mean volume-equivalent size reported in the NUREG/CR-5966 Spray Decontamination report, the analyses used somewhat different approaches. This suggests that using the probability distribution for the mean of the volume equivalent size might be appropriate for evaluating releases from the MSIV leakage pathway. Subsequent analyses show that the entire size distribution must be considered to capture the major trends in release behavior.

The main impact of the simplification of AEB-98-03 using the mass mean diameter rather than the whole distribution is that the lower tails of the size distribution that govern longer-term behavior are not captured correctly. Furthermore, in addition to losing these tails, AEB-98-03 reduced the results to a single representative deposition velocity (hence the multi-group method was developed). This does not capture the change in settling velocity as easier-to-remove particles are removed. The AEB-98-03 settling velocity distribution was greater than that of the source material after some removal and did not account for the change in settling velocity as mass was lost from the size distribution over time. The combined effects result in a substantial overprediction of the settling velocity as the size distribution changes by removal mechanisms.

Aerodynamic Diameter and Settling Rate

The parameter that most correlates the settling velocity or removal rate is the aerodynamic diameter. Friedlander (2000) defines aerodynamic diameter as "the diameter of a hypothetical sphere of unit density with the same Stokes number (or settling velocity) of the particle in question." The Stokes equation indicates both the settling behavior and the rate of deviation from flow as it accelerates (for example, flow curving around a bend or obstacle, and thus whether the particle is likely to collide with the wall or the other obstacle).

Size distributions are obtained from impactor measurements from integral experiments involving degradation and radionuclide release from fuel. These impactors provide the mass-averaged aerodynamic diameter at the sampling location and time within measurement uncertainty. The distributions could differ if a sample was taken at different locations or times during the experiment.

The mass-weighted aerodynamic diameter directly relates to the mass-weighted settling velocity distribution once local fluid parameters (e.g., density, viscosity) are specified. When considering settling as the sole removal mechanism, an initial aerodynamic size distribution uniquely specifies not only the settling-velocity distribution for given fluid conditions but, for a given geometry with a well-mixed assumption, uniquely specifies the evolution of the size and settling velocity distributions. In other words, there exists one, and only one, removal coefficient evolution history for a given aerodynamic diameter mass distribution, when considering settling as the sole removal mechanism, neglecting growth mechanisms, and using the well mixed assumption for given geometry and fluid conditions. The current AEB-98-03 model considers settling as the sole removal mechanism and does not consider growth. It only considers a single monodisperse (single size) aerosol at a time.

The other aerosol parameters, density and shape, affect other removal and growth mechanisms but are not needed to evaluate settling rates once the aerodynamic distribution is known. To capture idealized long-term removal behavior, it may be useful to evaluate other removal mechanisms to determine whether removal rates stabilize but is out of scope of this re-analysis. Otherwise the predicted settling velocity and the resultant removal coefficient continue to decrease assuming a constant shape and neglecting the increase in slip for submicron particle sizes.

In 2009, Allelein, et al. (2009) published the State-of-the-Art Report on Nuclear Aerosols, referred to as the SOAR study which was sponsored by the Nuclear Energy Agency (NEA), Committee on the Safety of Nuclear Installations (CSNI). The theoretical, experimental and modelling studies presented in this SOAR summarize the status and current understanding of a wide range of nuclear aerosol topics. Pertinent to the re-evaluation of AEB 98-03 is that the SOAR reviewed aerosol characteristics from prototypical experiments (i.e., those producing aerosols from over-heated irradiated fuel) in order to identify common features and typical variations. As described in the SOAR, "the most significant advance on the experimental side is the availability of integral experiments in the PHÉBUS facility on fission product and structural material release and transport. These tests demonstrate the complex inter-linkage between different phenomena and have refined our understanding of nuclear aerosols, particularly in the circuit, where we are now able to refer to measured particle sizes and compositions." Among several objectives, the SOAR assesses the status of existing experimental data and analytical capabilities required for predicting aerosol source terms for light water reactor accidents. The SOAR states most of the radioactive material that can escape from a nuclear power plant during a severe reactor accident will do so in the form of aerosols ranging in size from 0.01 μm to 20 μm. The SOAR explains that the "number density of aerosol particles in a gas phase can be huge - exceeding $10^{13}/m^3$." It is quite impossible to predict aerosol behavior by calculating the dynamics of individual particles. Instead, aerosols must be considered in a collective sense and the aerosol is taken to have some continuous distribution of particle sizes. Considering the complexities of aerosol physics subject to particle growth by agglomeration and gravitational deposition onto surfaces, the aerodynamic diameter size distribution within various locations of the nuclear system can be approximated by a lognormal distribution.

Approach to updating AEB 98-03 Physics Parameters

The approach for re-evaluating the AEB 98-03 physics parameters is to use the aerodynamic diameter size distribution obtained directly from integral experiments as an initial size/settling-velocity distribution that is operated on by different removal processes (e.g. spray removal and/or sedimentation). Since it directly matches data it is similarly easy to verify that the settling rate matches the source. Appendix 1 of the SOAR (Allelein, 2009) provides a summary of experimental observations from integral experiments involving irradiated fuel to infer characteristics of aerosols under light water reactor severe accident conditions.

For aerosols in the reactor coolant system (RCS), the SOAR states:

> *As for size, it is difficult on the basis of the information reviewed to conclude on a typical size; perhaps a near-lognormal distribution with an AMMD not exceeding 1 μm and a standard deviation of around 2 would seem reasonable in the hot leg.*

As concluded in Section 9,

> *[O]n size and structure, information is less reliable but it would seem realistic for aerosols in the hot leg to comprise a near-lognormal population of particles with AMMD around 1 μm or less and standard deviation around 2.0.*

For aerosols in containment, the SOAR report states:

> *The aerosol size distributions were fairly lognormal with an average size (AMMD) in FPT0 of 2.4 μm at the end of the 5-hour bundle-degradation phase growing to 3.5 μm before stabilizing at 3.35 μm; aerosol size in FPT1 was slightly larger at*

between 3.5 and 4.0 μm. Geometric-mean diameter (d_{50}) of particles in FPT1 was seen to be between 0.5 and 0.65 μm… In both tests the geometric standard deviation of the lognormal distribution was fairly constant at a value of around 2.0.

It should be kept in mind that, although the PHÉBUS-FP experiments involve the degradation of real irradiated fuel and release of radionuclides from the bundle through a model RCS system to a model containment, differences exist between these experiments and prototypic accident conditions: The PHÉBUS-FP experiments involved only half a bundle rather than a whole core so the degradation and release could progress differently; the scenario parameters were constrained for equipment calibration and facility safety; some RCS temperatures were controlled to better identify deposition behavior and speciation; system pressures were limited below those possible in actual accidents; power and volume were scaled by 1/500 relative to the corresponding reactor; and, piping lengths were shorter and surface to volume ratios differ from typical light water reactor nuclear reactors. Many of these parameters can affect how the aerosol size distribution evolves.

Since settling behavior primarily depends on the measured aerodynamic diameter and not the individual aerosol parameters, one can evaluate settling from the aerodynamic diameter distribution without knowing the specific parameter (shape factor, density, volume equivalent diameter) distributions. These parameter distributions largely capture the bulk of depletion behavior for larger (>~1 μm) sizes. Therefore, for the purposes of this re-evaluation of AEB 98-03, the aerodynamic diameter will be used in the computation of the aerosol settling velocity and that the aerosol size distribution would be based, in part, on the SOAR recommendations which specify a log-normal distribution with an AMMD of either 1.0 μm (for aerosols originating from the RCS) or 3.0 μm (for those from containment) with a geometric standard deviation of 2.0 in either case.

<u>Re-evaluation of the Parameters and Equations used in AEB 98-03</u>

In AEB 98-03, the expression for the settling velocity, u_s, (m/sec) of an aerosol in a pipe is:

$$u_s = \frac{\rho d_e^2 g C_s(d_e)}{18\mu\kappa}, \qquad \text{Equation A1}$$

where:

ρ = aerosol density
d_e = aerosol equivalent diameter
g = gravitational acceleration
$C_s(d_e)$ = Cunningham slip factor
μ = viscosity
κ = shape factor

The values for the aerosol density, diameter, and shape factor have some uncertainty during the maximum hypothetical accident during the in-vessel phase. The three constants are gravitational acceleration, Cunningham slip factor, and viscosity which are not disputed. For the uncertain parameters, AEB 98-03 describes a Monte Carlo analysis to compute a settling velocity distribution representing all particle sizes as a function of this equation. The values of

each uncertain parameter were randomly sampled from their respective distributions, plugged into the settling velocity equation, to yield a distribution of settling velocities.
By utilizing the aerodynamic diameter, the settling velocity can be calculated without knowing the specific aerosol parameter distributions (shape factor, density, volume equivalent diameter). This evaluation utilizes the size/settling velocity distribution directly from integral experiments involving degraded nuclear fuel as a defensible and simple alterative and negates the need to assume an aerosol density and shape distribution.

The settling velocity given by Equation A1 can be re-written in terms of the aerodynamic diameter, d_a to be:

$$u_s = \frac{\rho_0 \cdot d_a^2 \cdot g \cdot C_s(d_a)}{18\mu}, \qquad \text{Equation A2}$$

where:

ρ_0 = aerosol unit density = 1.0 g/cm^3
d_a = aerosol aerodynamic diameter
$C_s(d_a)$ = Cunningham slip factor as a function of d_a
μ = viscosity

Table A1 provides aerosol parameters for the re-evaluated AEB 98-03 aerosol deposition velocity calculation.

Table A1: Updated AEB 98-03 aerosol parameters

Parameter	Distribution
Aerosol density	N/A
Aerosol diameter[a]	Log-normal dist with σ = 2.0 and μ = 1.0 AMMD for RCS μ = 3.0 AMMD for Containment
Shape factor	N/A
Cunningham slip factor	1, fixed value
viscosity	1.93x10^{-5} Pa-sec, fixed value

a) Source: Allelein, et. al, (2009)

<u>Employing the Recommended Size Distribution</u>:

The equation for a normalized number distribution ($n(d_a)$) of particles of aerodynamic diameter (d_a) is given (Williams, 91) by:

$$n(d_a) = \frac{1}{d_a\sqrt{2\pi}\ln(\sigma_g)} Exp\left[-\frac{\ln\left(\frac{d_a}{d_g}\right)^2}{2\ln(\sigma_g)^2}\right], \qquad \text{Equation A3}$$

where:

σ_g=geometric standard deviation
d_g=geometric mean (which, for a log-normal distribution, is the same as the median diameter)

According to the Hatch-Choate equations, the aerodynamic mass median diameter (AMMD) is related to the median diameter (d_g) by the relation:

$$\mathrm{d_g} = AMMD\ Exp[-3\ln{(\sigma_g)}^2], \qquad \text{Equation A4}$$

Hence, an AMMD of 1.0 μm and σ_g of 2.0 μm corresponds to a geometric mean of $d_g = 0.237\ \mu m$ and an AMMD of 3.0 μm and σ_g of 2.0 corresponds to a geometric mean of $d_g = 0.710\ \mu m$.

The probability density functions for an aerodynamic diameter of 1 and 3 is given in Figure A1. Since it is difficult to grasp how a relatively large AMMD corresponds to a relatively small geometric mean, the aerosol *mass* cumulative density function (on the order of diameter cubed) is given in Figure A2. Note that the 50th percentile corresponds to the aerodynamic diameters of 1 and 3 for the RCS and Containment distributions, respectively.

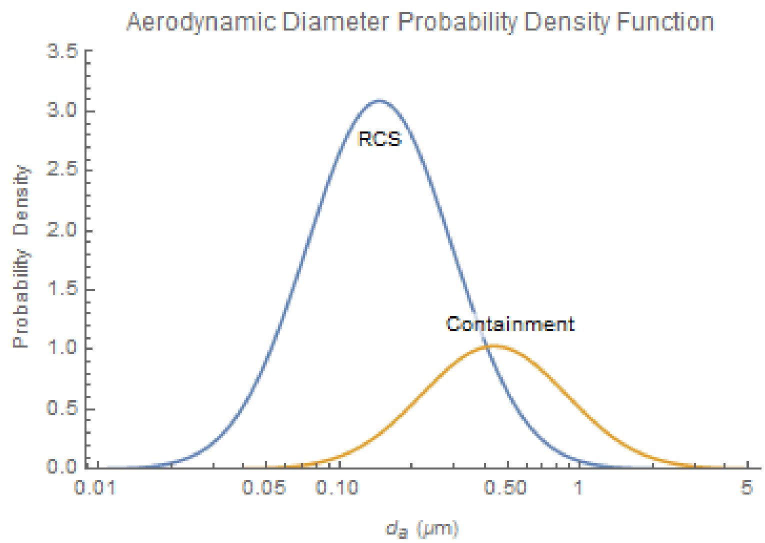

Figure A1: Updated AEB 98-03 Aerosol Diameter Probability Density Function

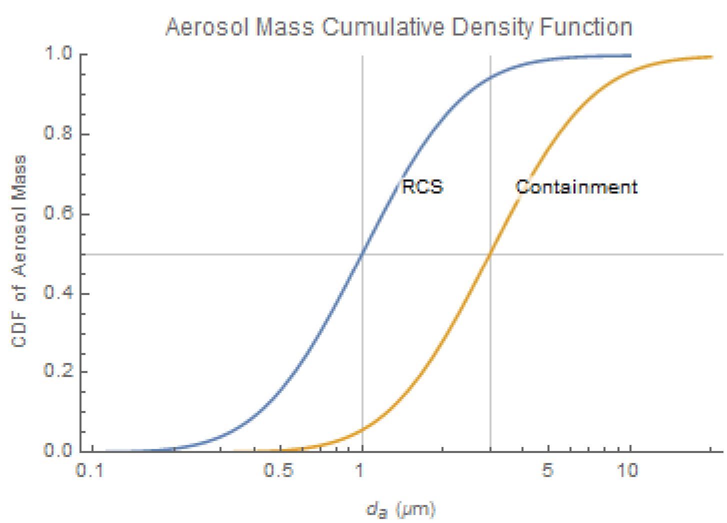

Figure A2: Updated AEB 98-03 Aerosol Mass Cumulative Density Function

For comparison to AEB 98-03 parameters, a Monte Carlo sampling of the density, shape and aerosol diameter distributions described in AEB 98-03 was performed and a distribution for the particle diameter was constructed. Figure 3 compares this distribution to the RCS and Containment distributions.

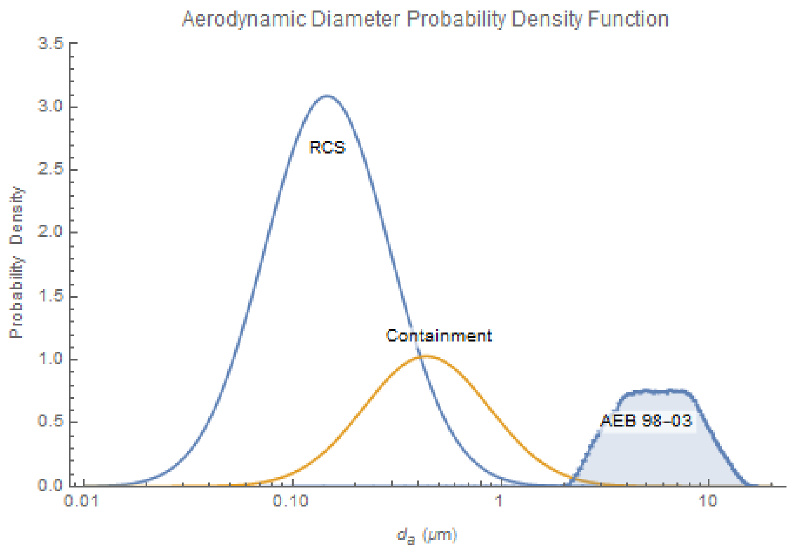

Figure A3: Comparison of the new aerosol diameter distributions to that used in AEB 98-03[2]

The settling velocity number distribution, $n(u)$, can be calculated using Equations A2 and A3 and the property that $n(u) = \frac{n(d_a)}{|u'(d_a)|}$ for a function, u, that is continuous and monotonic. This gives the following for the velocity distribution function

$$n(u) = \frac{1}{2u\sqrt{2\pi}\ln(\sigma_g)} Exp[-\ln\left(\frac{\sqrt{\frac{18\,\mu\,u}{(\rho_0 g C)}}}{d_g}\right)^2 / (2\ln(\sigma_g)^2)] \qquad \text{Equation A4}$$

Figure A4 gives the probability distribution of settling velocities for RCS aerosols and Figure A5 provides the same for containment aerosols. Using the settling velocity distribution, the percentiles for the settling velocity can be calculated and fed into the multi-group calculation described in Attachment 2 below.

[2] No attempt was made to normalize the AEB 98-03 distribution and is provided only for comparison to the other two distributions.

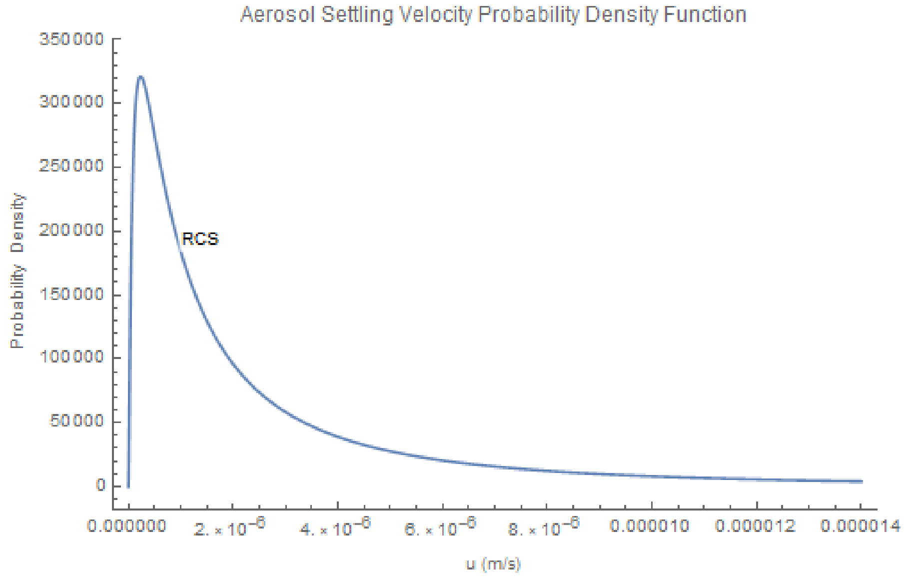

Figure A4: Settling Velocity Distribution for AMMD = 1.0 μm

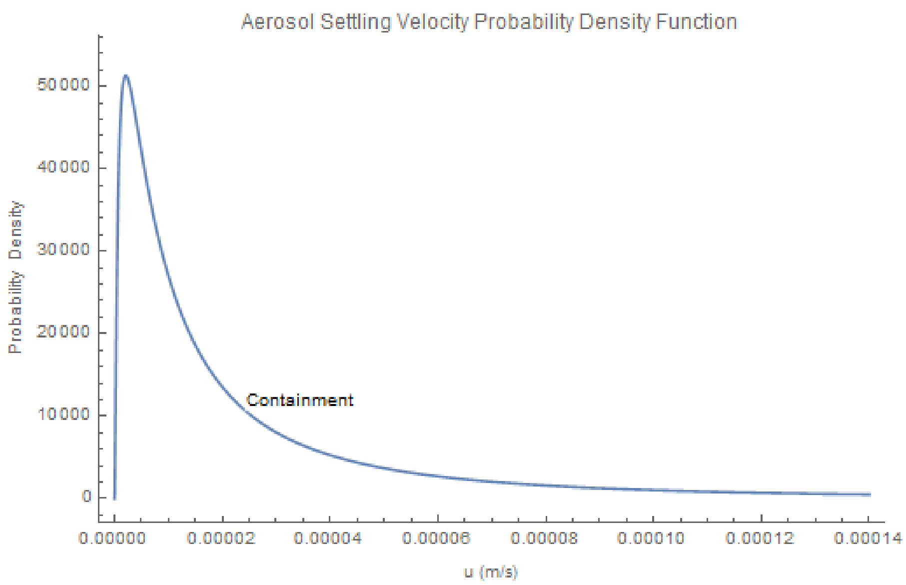

Figure A5: Settling Velocity Distribution for AMMD = 3.0 μm

A sample of the two velocity distributions above was taken for 10^5 trials and the respective percentiles of the distribution were computed. Results are given in Table A2. When compared to the results presented in AEB 98-03, Table A-1, *Results of Monte Carlo analysis for settling velocity in the MSL,* the updated settling velocities are generally 98.8% lower (or two orders of magnitude) which indicates aerosol particles remain suspended for longer periods of time within each of MSL volumes.

Table A2: Updated AEB 98-03 Results of Monte Carlo analysis for settling velocity in the MSL.

Percentile	1 AMMD			3 AMMD	
	Settling Velocity (m/sec)	Settling Velocity (ft/hr)		Settling Velocity (m/sec)	Settling Velocity (ft/hr)
'1st	6.34E-08	7.49E-04		5.71E-07	6.74E-03
'3rd	1.17E-07	1.39E-03		1.06E-06	1.25E-02
'10th	2.66E-07	3.15E-03		2.40E-06	2.83E-02
'20th	4.93E-07	5.82E-03		4.44E-06	5.24E-02
'30th	7.68E-07	9.07E-03		6.91E-06	8.16E-02
'40th	1.11E-06	1.31E-02		9.99E-06	1.18E-01
'50th	1.58E-06	1.87E-02		1.42E-05	1.68E-01
'60th	2.25E-06	2.65E-02		2.02E-05	2.39E-01
'70th	3.28E-06	3.87E-02		2.95E-05	3.48E-01
'80th	5.05E-06	5.96E-02		4.54E-05	5.37E-01
'90th	9.23E-06	1.09E-01		8.30E-05	9.81E-01
'100th	6.04E-04	7.14E+00		5.44E-03	6.42E+01

Summary and Conclusions of Recommendations

In forming an aerosol size distribution, the original AEB-98-03 sampled from a distribution for the density, shape and diameter. The settling velocities were then computed based upon this sample. The recommendation going forward is to use an aerodynamic diameter distribution taken directly from the PHÉBUS experiments as described in the SOAR. This approach is straightforward since it directly matches data and does not require assumptions on the aerosol shape or density. The SOAR describes a log-normal distribution of the particles with standard deviation of 2 and an AMMD of ~1.0 μm for RCS aerosols and of ~3.0 μm for containment aerosols. The velocity distribution can be directly calculated from these two distributions and used to create the groups need for the multi-group numerical integration methods.

Enclosure 1 References

NRC. (1999). *Assessment of Radiological Consequences for the Perry Pilot Plant Application Using the Revised (NUREG-1465) Source Term,* (AEB 98-03). ADAMS Accession Number ML011230531

Allelein, H.-J. A. (2009). *Technical Report NEA/CSNI/R(2009)5, State-of-the-Art Report on Nuclear Aerosols, NEA/CSNI/R(2009)5*. Nuclear Energy Agency / Committee on the Safety of Nuclear Installations (NEA/CSNI).

Friedlander, S. (2000). *Smoke, Dust, and Haze: Fundamentals of Aerosol Dynamics, Second Edition.* New York: Oxford University Press.

Gelbard, F., & Andrews, N. (2017). *A note on Aerosol Removal by Gravitational Settling in a Horizontal Steam Pipe (SAND2017-2651*). Albuquerque: Sandia National Laboratories.

NRC. (1993). *A Simplified Model of Aerosol Removal by Containment Sprays, NUREG/CR-5966.* Washington: Nuclear Regulatory Commission.

Bunz, H., Kayro, M., Schock, W., *NAUA-Mod 4: A Code for Calculating Aerosol Behavior in LWR Core Melt Accidents (KfK-3553)*. Kernforschungszentrum Karlsruhe Germany

NRC. (1996). *A Simplified Model of Aerosol Removal by Natural Processes in Reactor Containments*, NUREG/CR-6189. Washington: Nuclear Regulatory Commission.

Lipinski, R. J., et al.. *Uncertainty in Radiological Release Under Specific LWR Accident Conditions, SAND84-0410*. Sandia National Laboratories. Albuquerque.

Friedlander. (2000). *Smoke, Dust, and Haze: Fundamentals of Aerosol Dynamics, Second Edition.* Oxford University Press. New York.

NRC. (2006). *NRC Regulatory Issue Summary 2006-04, Experience with Implementation of Alternative Source Terms March, 7, 2006 (RIS 2006-04)*. Washington: Nuclear Regulatory Commission.

Powers, D. (2005). *Aerosol Deposition by Gravitational Settling in Piping Around the Main Steamline Isolation Valves*. Albuquerque: Sandia National Laboratories.

USNRC. (2000). Regulatory Guide 1.183, "*Alternative Radiological Source Terms for Evaluating Design Basis Accidents at Nuclear Power Reactors*". Washington: US Nuclear Regulatory Commission.

Williams, M.M.R. (1991). *Aerosol Science Theory and Practice*, New York: Pergamon Press.

ANALYTICAL TECHNIQUE TO COMPUTE EFFECTIVE SETTLING VELOCITIES USING THE MULTI-GROUP METHOD AND SAMPLE CALCULATION

Elijah Dickson

BACKGROUND

The multi-group methodology utilizes Monte Carlo methods to model a simple first order compartmental analysis which utilizes plant-specific flow rates and removal constants to describe the aerosol transfer between compartments and elimination of aerosol concentration due to gravitational settling within a compartment. Monte Carlo integration is a numerical technique which relies on random sampling to approximate the result. The multi-group method described here was originally developed by Dr. Aleem Boatright and Paul Reichert in support of a license amendment request for the Limerick Generating Station, Units 1 and 2, to re-analyze the loss-of-coolant accident using an alternative source term (AST).[3] When combing this method with the Stokes settling velocity equation utilizing the aerodynamic diameter distributions recommend by Allelein (Allelein, 2009), the multi-group method simulates the varied population of aerosol particulates having uneven settling velocities between the heavier and larger particles versus the lighter and smaller particles in a given MSL volume. The purpose of the multi-group method is to address U.S. Nuclear Regulatory Commission (NRC) staff concerns regarding AEB 98-03's use of a single median settling velocity which does not account for the removal of heavier and larger particles settling quicker than the lighter and smaller particles through each successive MSL volume.

By implementing the multi-group method, the analyst can model the distribution of aerosol particles and subsequent settling velocities as a semi-continuous, probability-weighted multi-group step function for each MSL volume. As the aerosol particles move from one volume to another, the distribution of particles is re-computed and compared to the initial distribution. This process successively shifts "weight" from the easier-to-remove particles when entering the piping to the difficult-to-remove particles as flow moves through the MSL. When the aerosol particles finally exit the system to the environment, the re-calculated settling velocity distribution indicates a more likely chance of "seeing" difficult-to-remove particles than was the case when entering the system.

The final result of the multi-group method is a set of filter efficiencies, called "total effective aerosol removal efficiencies" (TEAREs), and equivalent removal coefficients, λ (hr^{-1}), that are suitable for assessing design-basis accident radiological consequences.

Impact of Discretizing

The multi-group method selectively discretizes a settling velocity dataset into a number of uniform group sizes. The degree in which the TEAREs, and corresponding λ (hr^{-1}), converge is a direct function of the number of groups specified. A case study was performed to analyze how the number of groups impacts the computed results. The purpose was to understand what a sufficient number of groups would be to produce suitable results.

[3] See NRC Staff Safety Evaluation ADAMS Accession Number ML062210214

A series of five calculations were performed by varying the number of selected uniformly sized groups from 2 to 200,000. For the purposes of this example, the selected aerosol distribution is based on recommendations from Allelein, et al. (2009) with a AMMD of $3.0\ \mu m$ and geometric standard deviation, σ_g, of 2.0 which corresponds to a geometric mean of $d_g = 0.710\ \mu m$. Figure 6 presents the impact on computed removal lambda for each MSL volume as a function of discretizing the settling velocity dataset into a varying number of groups. This analysis indicates computed results are excessively high with 2 groups but rapidly decrease as more groups are modeled. The results begin to converge after 2000 groups with little difference up to 200,000 groups. Additionally, better resolution is seen between the changing settling velocity distribution for consecutive piping segments as more groups are modeled. For example, when using 20 groups, little difference is computed between the “MSL-B Inboard” (blue bar) and the “MSL-B Outboard” (orange bar); indicating little change in settling velocities. However, when modeling 2000 groups, or more, the changing settling velocity between consecutive piping segments becomes apparent. This impact on settling velocities between piping segments agrees with findings agreement from Gaunt, et al. (2008), *Analysis of Main Steam Isolation Valve Leakage in Design Basis Accidents Using MELCOR 1.8.6 and RADTRAD*. This report presents the findings of a transient mechanistic analysis which accounts for both growth and removal processes along with evaluation of parameters that affect these processes. Therefore, it would be advisable to when utilizing the multi-group method to discretize the settling velocity dataset into at least 2000 groups.

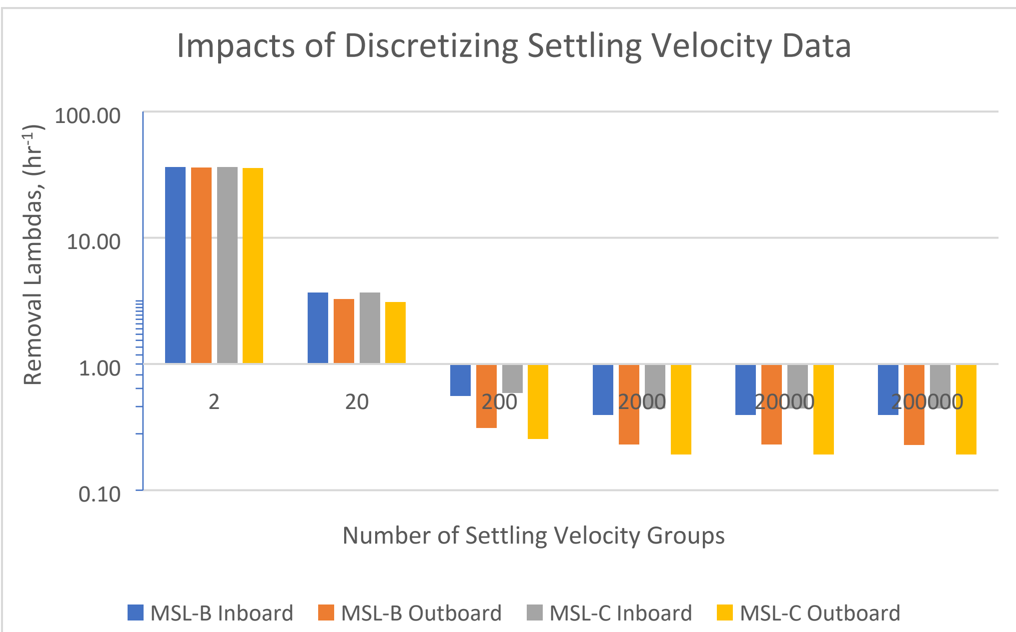

Figure 6: Impacts of Discretizing Settling Velocity Data

<u>Multi-Group Method</u>

Based on the NRC staff’s evaluation described above, the staff proposes the following guidance on use of a multi-group method to adequately model aerosol settling phenomena in MSLs. The multi-group method should include the following assumptions and steps to estimate removal coefficients:

1. Develop a settling velocity dataset of at least 10^5 data-points utilizing the above Attachment 1 modified Stokes settling velocity equation and AMMD distribution recommended by Allelein (2009).

2. Discretize the settling velocity dataset into at least 2000 equal-width groups. Assign relative probabilities for each group by dividing the number of data points within each bin by the sample size (e.g., 10,000 trials) to determine the group probabilities. Identify the mid-point of each group to represent the settling velocity for that group.

3. Compute for each group, aerosol filter efficiency using the following method. By rearranging Equations 2 and 3 from AEB 98-034, the filter efficiency, η_{filt}, is computed by utilize the group settling velocity, settling area, volumetric flow rate, and volume of the well-mixed region being modeled as follows:

$$\eta_{filt} = 1 - \frac{C_{out}}{C_{in}} = 1 - \frac{1}{1 + \frac{\lambda * V}{Q}} = 1 - \frac{1}{1 + \frac{u_s * A}{Q}} \quad \text{Equation 1}$$

   where:

   η_{filt} = removal, or filter efficiency;
   u_s = settling velocity (ft/hr);
   A = settling area (ft^2);
   C_{out} = outgoing concentration of nuclides in the pipe segment volume;
   C_{in} = initial concentration of nuclides in the pipe segment volume;
   Q = volumetric flow rate into pipe segment volume (ft^3/hr); and,
   λ = equivalent removal coefficient (hr^{-1}).

   Account for the effect of the changing settling velocity distribution in the downstream volumes by adjusting the downstream volume aerosol removal efficiencies by multiplying by the prior volume aerosol filter removal efficiency.

4. Compute the TEAREs and equivalent λ (hr^{-1}) for a credited volume by the following method. Compute the probability-weight aerosol filter efficiency by multiplying the aerosol filter efficiency by the group probability from Step 1. Then sum all the probability weighted aerosol removal efficiencies to obtain the TEARE. By solving for, λ, in Equation 2, the removal coefficients λ (hr^{-1}), are computed to yield:

$$\lambda = \frac{-\eta_{filt} * Q}{(\eta_{filt} - 1) * V} \quad \text{Equation 3}$$

   where:

   ηfilt = TEARE
   Q = volumetric flow rate into credited volume
   V = well-mixed pipe free volume

<u>Multi-Group Example Calculation</u>

The following example calculation demonstrates the multi-group method using plant-specific design information; however, plant-specific design information does not form the basis of the methodology. As such, the following discussion defines the boundary conditions of the calculation.

The “MSIV failed” line means that the inboard MSIV in one of the shortest MSL fails to close and remains open during the accident, which instantly extends the well mixed volume boundary from the reactor pressure vessel nozzle to the outboard MSIV. This MSIV failure complies with a single active component failure requirement that results in the most limiting radiological consequences (RG 1.183 Rev. 0, Section 5.1.2). All MSLs in the MSIV leakage release pathways are seismically designed and supported to withstand the Safe Shutdown Earthquake (SSE) and thereby comply with the RG 1.183, Appendix A, Section 6.5 requirement. As the MSLs remain intact, the horizontal pipe surface area is credited for the aerosol deposition and volume for dilution in the MSL upstream of the inboard MSIV that failed to close. All four MSL headers are Seismic Class I and QA Category I from the reactor pressure vessel nozzle to the seismic boundary break at the turbine stop valve. Therefore, they are qualified to withstand the SSE which complies with the RG 1.183, Appendix A, Section 6.5 requirement to be credited for aerosol deposition. Deposition credit in the outboard section of the MSL (between the outboard MSIV and the turbine stop valve) is determined in the same manner as the inboard section. Figure 7 provides a conceptual model of the MISV leakage pathway to the environment.

Table 3 provides the modeling parameters for the MSIV leakage pathway model. A total of 270 standard cubic feet per hour (scfh) MSIV leakage is assumed to occur in the following manner:

- MSL with failed MSIV – MSL “B” flow of 135 scfh (Pathway 8 in Figure 7):
    - Horizontal piping surface area and volume of the MSL upstream of outboard MSIV are credited for aerosol deposition. One well-mixed volume (V1) is between the reactor pressure vessel nozzle and outboard MSIV.
    - Horizontal piping surface area and volume of the MSL between the outboard MSIV and turbine stop valve are credited for aerosol deposition. A second well-mixed volume or node (V2) is between the outboard MSIV and TSV.
    - No credit is taken for a holdup time in the MSIV failed MSL.

- Intact MSL - Second shortest MSL (MSL “C”) (Pathway 11 in Figure 7):
    - Horizontal piping surface area and volume of the MSL between the RPV Nozzle and inboard MSIV are credited for aerosol deposition. One well-mixed volume (V3) is modeled between the reactor pressure vessel nozzle and inboard MSIV.
    - Horizontal piping surface area and volume of the MSL between the inboard MSIV and turbine stop valve are credited for aerosol deposition. A second well-mixed volume (V4) represents the volume between the inboard MSIV and turbine stop valve.
    - No credit is taken for a holdup time in the intact MSLs.

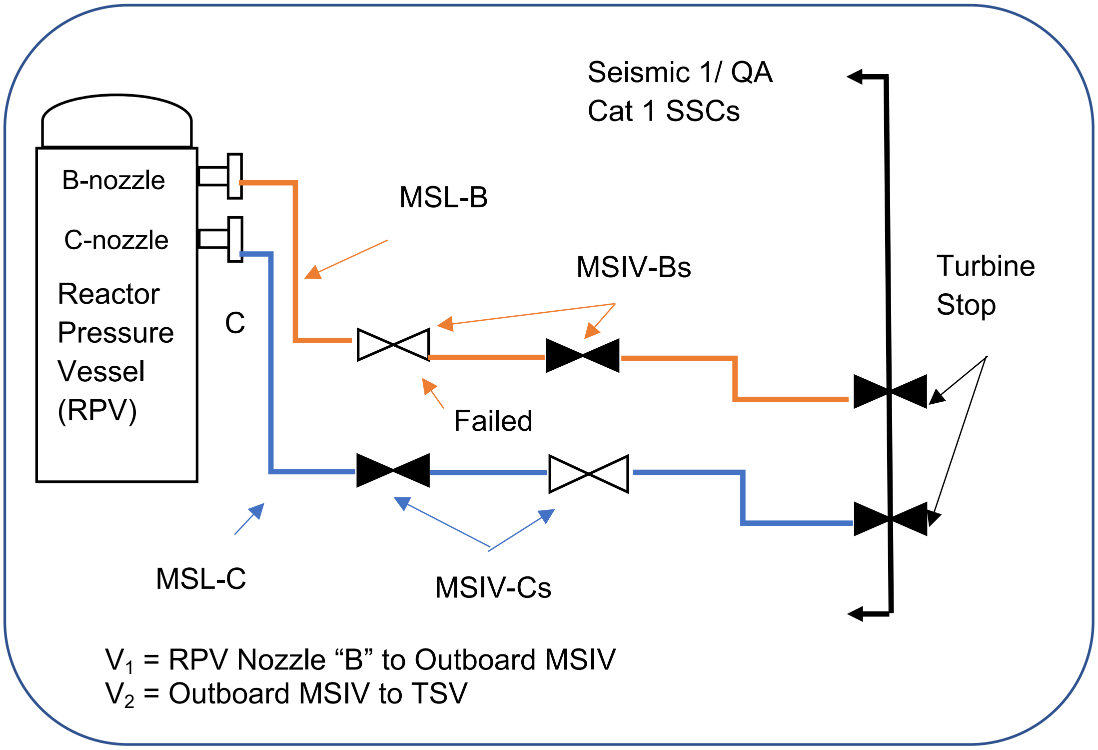

Figure 7: Conceptual MSIV Leakage Model

Table 3: MSIV Leakage Model Parameters

MSL	Parameter	Inboard	Outboard
MSL-B	Horizontal (ft^2)	250.94	770.4
	Horizontal (ft^3)	111.47	342
	Flow rate (ft^3/hr)	49.48	135.00
MSL-C	Horizontal (ft^2)	159.72	861.62
	Horizontal (ft^3)	70.95	382.52
	Flow rate (ft^3/hr)	49.48	135.00

For the sake of brevity, all reported results are presented for MSL-B. However, the MATLAB script found in Appendix 4 performs calculations and produces the applicable figures and results for both the MSL-B and MSL-C.

EXAMPLE CALCULATION
WITH RE-EVALUATED AEB 98-03 AND MULTI GROUP METHOD

This example calculation derives input parameters for iodine aerosol deposition within the main steam line (MSL) which satisfy regulatory issues described in Regulatory Issues Summary 2006-04, *NRC Regulatory Issue Summary 2006-04, Experience with Implementation of Alternative Source Terms*. Specifically, issues related to:

1. The AEB 98-03 settling velocity calculation where an updated model utilizes well-established aerosol physics parameters to re-compute a representative aerosol settling velocity distribution.

2. The AEB 98-03 use of a single median settling velocity for sequential down-stream MSLs where a probabilistically method has been developed which simulates the varied population of aerosol particulates having uneven settling velocities between the heavier and larger particles versus the lighter and smaller particles in a given MSL volume.

A step-by-step calculation is provided:

Step 1a: Define the Settling Velocity Distribution:

The AEB 98-03 model of aerosol settling in horizontal main steam piping occurs as a result of particles settling due to their "Stokes settling velocity," u_s (m/sec), expressed in AEB 98-03 as:

$$u_s = \frac{\rho d_e^2 g C_s}{18\mu\kappa}, \qquad \text{Equation 1}$$

where:

ρ = aerosol density
d_e = aerosol diameter
g = gravitational acceleration
C_s = Cunningham slip factor as a function of d_e
μ = viscosity
κ = shape factor

It is appropriate to utilize the size/settling velocity distribution directly from integral experiments involving degraded nuclear fuel as a defensible and simple alterative and negates the need to assume an aerosol density and shape distribution. Therefore, by utilizing the aerodynamic mass median diameter, the settling velocity can be calculated without knowing the specific aerosol parameter distributions (shape factor, density, volume equivalent diameter). As such, the settling velocity given by Equation 1 can be re-written in terms of the aerodynamic diameter, d_a to be:

$$u_s = \frac{\rho_0 \cdot d_a^2 \cdot g \cdot C_s(d_a)}{18\mu}, \qquad \text{Equation 2}$$

EXAMPLE CALCULATION
WITH RE-EVALUATED AEB 98-03 AND MULTI GROUP METHOD (Continued)

where:

σ_g=geometric standard deviation
d_g=geometric mean (which, for a log-normal distribution, is the same as the median diameter)

According to the Hatch-Choate equations, the aerodynamic mass median diameter (AMMD) is related to the median diameter (d_g) by the relation:

$$\mathrm{d_g} = AMMD\ Exp[-3\ln(\sigma_g)^2], \qquad \text{Equation 4}$$

Hence, an AMMD of $3.0\ \mu m$ and σ_g of 2.0 corresponds to a geometric mean of $d_g = 0.710\ \mu m$.

Regulations pertaining to radiological consequence analyses and regulatory practices support the use of the in-containment source term where is it "a*ssumed to result in substantial meltdown of the core with subsequent release into the containment."* Technical Report, "State-of-the-Art Report on Nuclear Aerosols," (SOAR), (Allelein, 2009) interpreted the aerosol behavior in the PHEBUS-FP experiments, describing the aerosol distributions in terms of AMMD. The SOAR recommends an in-containment aerosols distribution to be log-normal with an AMMD of 3.0 μm with a geometric standard deviation of 2.0.

Table 1 gives the updated AEB 98-03 aerosol parameters where values for the aerosol density and shape factor are not included since they are intrinsic to the aerodynamic diameter.

Table 1: Re-evaluated AEB 98-03 aerosol deposition velocity parameters

Parameter	Distribution
Aerosol density	N/A
Aerosol diameter[a]	Log-normal dist with μ = 3.0 AMMD and σ = 2.0
Shape factor	N/A
Cunningham slip factor	1, fixed value
viscosity	$1.93\text{x}10^{-5}$ Pa-sec, fixed value

a) Source: (Allelein, 2009)

<u>Step 1b: Develop a Settling Velocity Dataset by Sampling the Settling Velocity Distribution</u>:

Utilizing Equation 2 and the Parameters in Table 1, a random sampling of 1E5 trials from the aerosol diameter distribution is appropriate to develop the settling velocity distribution dataset.

EXAMPLE CALCULATION
WITH RE-EVALUATED ABE 98-03 AND MULTI GROUP METHOD (Continued)

Step 2: Utilizing the Multi-group Method:

The purpose of utilizing the multi-group method is to address NRC staff concerns discussed in RIS 2006-04 regarding AEB 98-03's use of a single median settling velocity which does not account for the removal of heavier and larger particles settling quicker than the lighter and smaller particles through each successive MSL volume. The multi-group methodology probabilistically simulates the varied population of aerosol particulates having uneven settling velocities between the heavier and larger particles versus the lighter and smaller particles in a given MSL volume.

Step 2a: Discretize the Settling Velocity Dataset and Assign Relative Probabilities

Discretize the settling velocity data set into at least 2000 equal-width groups and assign relative probabilities to each group. Next, identify the center point for each group to represent the settling velocity for that group.

Step 2b – Compute Group Aerosol Particulate Removal Efficiencies

For each settling velocity group, AEB 98-03 Equations 2 and 3 are utilized to compute removal efficiencies, λ_s, or "filter efficiencies," η_{filt}, for each inboard and outboard MSL volume. For the outboard removal efficiency, remember to account for the changing settling velocity distribution by also multiplying by the inboard removal efficiency. The calculations are as follows:

$$\lambda_s = \frac{u_s * A}{V}$$ (AEB 98-03 Equation 2) Equation 5

where:

u_s = settling velocity
A = settling area of well-mixed pipe segment
V = volume of well-mixed pipe segment

and,

$$C = C_{in}\frac{1}{1 + \frac{\lambda_s * V}{Q}}$$ (AEB 98-03 Equation 3) Equation 6

where:

C = concentration of nuclides in the pipe segment volume
λ_s = settling velocity
V = volume of well-mixed pipe segment
Q = volumetric flow rate into pipe segment volume

EXAMPLE CALCULATION
WITH RE-EVALUATED ABE 98-03 AND MULTI GROUP METHOD (Continued)

By rearranging Equations 2 and 3, the filter efficiencies, η_{filt}, are computed by utilize the settling velocity, settling area, volumetric flow rate, and volume of the well-mixed region being modeled then finally subtracting by 1 to convert to a filter efficiencies, η_{filt}, as follows:

$$\eta_{filt} = 1 - \frac{C}{C_{in}} = 1 - \frac{1}{1 + \frac{\lambda_s * V}{Q}} = 1 - \frac{1}{1 + \frac{u_s * A}{Q}}$$ Equation 7

where:

η_{filt} = removal, or filter efficiency
u_s = settling velocity (ft/hr)
A = settling area (ft^2)
C_{out} = outgoing concentration of nuclides in the pipe segment volume
C_{in} = initial concentration of nuclides in the pipe segment volume
Q = volumetric flow rate into pipe segment volume

Solving for λ yields:

$$\lambda = \frac{-\eta_{filt} * Q}{(\eta_{filt} - 1) * V} .$$ Equation 8

Table 3 provides the plant-specific MSL design parameters.

Step 2c – Compute Probability Weighted Aerosol Removal Efficiencies

For each group, compute “Probability Weighted Aerosol Removal Efficiencies” by multiplying each group aerosol removal efficiency by the group probability from Step 2a.

Step 2d - Compute Total Effective Aerosol Removal Efficiencies (TEAREs)

Compute “Total Effective Aerosol Removal Efficiencies (TEARs) and lambdas for each inboard and outboard control volume. The TEARE is computed by summing all of the “Probability Weighted Aerosol Removal Efficiencies.” Apply Equation 8 to compute corresponding lambda, λ_s, with the applicable plant-specific parameters.

Example Calculation:

Table 3 provides an example of results of computing results for a 2000-group analysis with an assumed AMMD of 3 µm with a geometric standard deviation of 2. The table’s footnotes provide a key for how each column it calculated.

To check the model, utilize the following example plant parameters in Table 4 and compare them to the results in Table 5.

EXAMPLE CALCULATION
WITH RE-EVALUATED ABE 98-03 AND MULTI GROUP METHOD (Continued)

Table 3: Example Calculation of Multi-group Methods Steps 2b, 2c, and 2d

Step 2a					Step 2b		Step 2c and 2d	
2000-Groups				Settling Velocity Group (ft/hr.) (B)	Aerosol Removal Eff., ηfilt		Prob. Weighted Aerosol Removal Eff.	
Settling Velocity Group	Lower Bound Percent of SV data (L_b)	Upper Bound Percent of SV data (U_b)	Probability of Bin (C)		MSL-B Inboard (D)	MSL-B Outboard (E)	MSL-B Inboard (C*D)	MSL-B Outboard (C*E)
1	0.00%	0.05%	11.66%	1.61E-02	7.55%	0.69%	0.88%	0.08%
2	0.05%	0.10%	12.65%	4.83E-02	19.68%	5.15%	2.5%	0.65%
3	0.10%	0.15%	10.09%	8.05E-02	28.99%	11.76%	2.9%	1.2%
4	0.15%	0.20%	7.96%	1.13E-01	36.37%	18.96%	2.9%	1.5%
5	0.20%	0.25%	6.30%	1.45E-01	42.36%	25.94%	2.8%	1.6%
…	…	…	…	…	…	…	…	…
2000	1	1	0.00%	6.44E+01	100%	100%	0%	0%
						Sum =	47%	37%

D = (1-(1/(1+(B*250.94)/49.48)))

E = (1-(1/(1+(B*D*770.40)/135)))

Table 4: Example Parameters for Multi-Group MSIV Leakage Model

MSL	Parameter	Inboard	Outboard
MSL-B	Horizontal (ft^2)	250.94	770.4
	Horizontal (ft^3)	111.47	342
	Flow rate (ft^3/hr)	49.48	135.00
MSL-C	Horizontal (ft^2)	159.72	861.62
	Horizontal (ft^3)	70.95	382.52
	Flow rate (ft^3/hr)	49.48	135.00

Table 5: Example Results for Multi-Group MISV Leakage Model

Removal Parameter	MSL-B Penetration		MSL-C Penetration	
	Inboard	Outboard	Inboard	Outboard
η_{filt} (TEAREs)	47%	37%	39%	35%
λ_s (hr^{-1})	0.40	0.23	0.45	0.19

Attachment 2 References

Allelein, H.-J. A. (2009). *Technical Report NEA/CSNI/R(2009)5, State-of-the-Art Report on Nuclear Aerosols, NEA/CSNI/R(2009)5*. Nuclear Energy Agency / Committee on the Safety of Nuclear Installations (NEA/CSNI).

Friedlander, S. (2000). *Smoke, Dust, and Haze: Fundamentals of Aerosol Dynamics, Second Edition.* New York: Oxford University Press.

Gelbard, F., & Andrews, N. (2017). *A note on Aerosol Removal by Gravitational Settling in a Horizontal Steam Pipe (SAND2017-2651*). Albuquerque: Sandia National Laboratories.

NRC. (2006). *NRC Regulatory Issue Summary 2006-04, Experience with Implementation of Alternate Source Terms March, 7, 2006 (RIS 2006-04)*. Washington: Nuclear Regulatory Commission.

Powers, D. (2005). *Aerosol Deposition by Gravitational Settling in Piping Around the Main Steamline Isolation Valves*. Albuquerque: Sandia National Laboratories.

USNRC. (2000). Regulatory Guide 1.183, "*Alternative Radiological Source Terms for Evaluating Design Basis Accidents at Nuclear Power Reactors*". Washington: US Nuclear Regulatory Commission.

Williams, M.M.R. (1991). *Aerosol Science Theory and Practice*, New York: Pergamon Press.

Gaunt, R., Randel, T., Salay, M., & Kalinich, D. (2008). *Analysis of Main Steam Isolation Valve Leakage in Design Basis Accidents Using MELCOR 1.8.6 and RADTRAD, SAND 2008-6601.* Albuquerque: Sandia National Laboratories,.

ANALYTICAL TECHNIQUE FOR COMPUTE EFFECTIVE SETTLING VELOCITIES USING NUMERICAL INTEGRATION METHOD AND SAMPLE CALCULATION

James Corson

This method uses numerical integration to compute the respective removal coefficients to address U.S. Nuclear Regulatory Commission (NRC) staff concerns discussed in RIS 2006-04 regarding the AEB 98-03 parameters for aerosol density and aerosol diameter as well as the use of a single median settling velocity.

As discussed in Attachment 1, the equation for a normalized number distribution, ($n(d_a)$) of particles of aerodynamic diameter (d_a) is given by Williams in (1991) as:

$$n(d_a) = \frac{1}{d_a\sqrt{2\pi}\ln(\sigma_g)} Exp\left[-\frac{\ln\left(\frac{d_a}{d_g}\right)^2}{2\ln(\sigma_g)^2}\right], \qquad \text{Equation A3-1}$$

where:

σ_g= geometric standard deviation
d_g= geometric mean (which, for a log-normal distribution, is the same as the median diameter)

According to the Hatch-Choate equations, the AMMD is related to the median diameter (d_g), in meters, is by the relation:

$$\mathrm{d_g} = AMMD\ Exp[-3\ln(\sigma_g)^2], \qquad \text{Equation A3-2}$$

Hence, an AMMD of 1.0 μm and σ_g of 2.0 μm corresponds to a geometric mean of $d_g = 0.237\ \mu m$ and an AMMD of 3.0 μm and σ_g of 2.0 corresponds to a geometric mean of $d_g = 0.710\ \mu m$.

To directly integrate the settling velocity distribution, first discretize the range of particle diameters, d_a, from 1E-9 to 1E-3 microns in to 150 groups. For each group, apply Equations A3-1 and A3-2 to compute the normalized number distribution, ($n(d_a)$).

For each aerosol diameter size, apply Equation A6 to compute the concentration leaving the inboard volume as:

$$c_{inb,\,out}(d_a)\mathrm{d}d_a = \frac{c_{inb,in}(d_a)}{1+\frac{u_s(d_a)*A_{inb}}{Q_{inb}}}\mathrm{d}d_a = C_{inb,in}^{tot}\frac{n(d_a)}{1+\frac{u_s(d_a)*A_{inb}}{Q_{inb}}}\mathrm{d}(d_a) \qquad \text{Equation A3-3}$$

Here, $c_{inb,\,out}(d_a)\mathrm{d}d_a$ and $c_{inb,\,out}(d_a)\mathrm{d}d_a$ are the concentrations of aerosols entering and leaving the inboard volume with diameter d_a about a differential size $\mathrm{d}d_a$, and $C_{inb,in}^{tot}$ is the total aerosol concentration entering the inboard volume. Similarly, the concentration of aerosols with diameter d_a leaving the outboard volume is:

$$c_{outb,\,out}(d_a)\mathrm{d}d_a = \frac{c_{inb,out}(d_a)}{1+\frac{u_s(d_a)*A_{outb}}{Q_{outb}}}\mathrm{d}d_a = C_{inb,in}^{tot}\frac{n(d_a)}{\left[1+\frac{u_s(d_a)*A_{inb}}{Q_{inb}}\right]\left[1+\frac{u_s(d_a)*A_{outb}}{Q_{outb}}\right]}\mathrm{d}(d_a)$$

Equation A3-4

To determine the total concentrations of aerosols leaving the inboard and outboard volumes, integrate the above expressions over all diameters:

$$C_{inb,out}^{tot} = \int_0^{\infty} c_{inb,\,out}(d_a)\mathrm{d}d_a = C_{inb,in}^{tot}\int_0^{\infty}\frac{n(d_a)}{1+\frac{u_s(d_a)*A_{inb}}{Q_{inb}}}\mathrm{d}(d_a)$$

Equation A3-5

$$C_{outb,out}^{tot} = \int_0^{\infty} c_{outb,\,out}(d_a)\mathrm{d}d_a = C_{inb,in}^{tot}\int_0^{\infty}\frac{n(d_a)}{\left[1+\frac{u_s(d_a)*A_{inb}}{Q_{inb}}\right]\left[1+\frac{u_s(d_a)*A_{outb}}{Q_{outb}}\right]}\mathrm{d}(d_a)$$

Equation A3-6

EXAMPLE CALCULATION WITH NUMERICAL INTEGRATION

The discretized range of diameters should be from 1E-9 to 1E-3 m with a geometric factor (in this example, 1.1). Equations A3-1 and A3-2 are used to calculate the settling velocity, u_s, and number density, $n(d_a)$, of each diameter. Equation A3-6 is then used to calculate the concentration, C, of particles leaving the inboard and outboard MSL volumes and Equations A1-7 and A1-8 are used to calculate the filter efficiency, η_{filt}, and corresponding removal coefficients (hr^{-1})

Table 8 provides the updated AEB 98-03 aerosol parameters (from Table 1 above) as well as example plant-specific parameters (from Table 6 above) in the proper units to perform the calculation. The discrete calculated values given in Table 9. The table's footnotes provide a key for how each column it calculated.

Table 8: Parameters used in the example numerical solution

Parameter	Abbreviation	Value	Units
Re-evaluated AEB 98-03 aerosol deposition velocity parameters			
Aerodynamic Mass Median Diameter	AMMD	3.00E-06	m
Standard Deviation	σ	2	-
Geometric mean diameter	d_g	7.10E-07	m
geometric factor	gf	1.10	-
Viscosity	μ	1.93E-05	Pa*s
Density	ρ	1.00E+03	kg/m^3
Example Parameters for Multi-Group MSIV Leakage Model			
MSL-B inboard area	BIA	23.31	m^2
MSL-B inboard volume	BIV	3.16	m^3
MSL-B inboard flow rate	BIF	3.89E-04	m^3/s
MSL-B outboard area	BOA	71.57	m^2
MSL-B outboard volume	BOV	9.68	m^3
MSL-B outboard flow rate	BOF	1.06E-03	m^3/s

EXAMPLE CALCULATION WITH NUMERICAL INTEGRATION (Continued)

Table 9: Discrete values used for the numerical integration

d_a [m] (A)	$n(d_a)$ [1/m] (B)	u [m/s] (C)	Inboard C_{out} (D)	Outboard C_{out} (E)	Inboard η (F)	Outboard η (G)
1.00E-09	1.91E-11	2.82E-11	1.91E-11	1.91E-11	1.69E-06	1.90E-06
1.10E-09	6.32E-11	3.42E-11	6.32E-11	6.32E-11	2.05E-06	2.30E-06
1.21E-09	2.05E-10	4.13E-11	2.05E-10	2.05E-10	2.48E-06	2.79E-06
1.33E-09	6.55E-10	5.00E-11	6.55E-10	6.55E-10	3.00E-06	3.37E-06
1.46E-09	2.05E-09	6.05E-11	2.05E-09	2.05E-09	3.63E-06	4.08E-06
…			…			…
6.86E-04	3.71E-19	1.33E+01	4.66E-25	5.20E-31	1.00E+00	1.00E+00
7.55E-04	8.54E-20	1.61E+01	8.87E-26	8.18E-32	1.00E+00	1.00E+00
8.30E-04	1.93E-20	1.95E+01	1.66E-26	1.26E-32	1.00E+00	1.00E+00
9.13E-04	4.28E-21	2.35E+01	3.04E-27	1.91E-33	1.00E+00	1.00E+00
1.00E-03	9.32E-22	2.85E+01	5.46E-28	2.84E-34	1.00E+00	1.00E+00

B=1/(A*SQRT(2*PI())*LN(σ))*EXP(-1*(LN(A)-LN(d_g))^2/(2*(LN(σ))^2))
C = ρ*A^2*9.81/(18* μ)
D = B/(1+C*BIA/BIF)
E = D/(1+C*BOA/BOF)
F = 1-D/B
G = 1-E/D

An integration is then needed to compute the total concentrations and filter efficiencies. A simple trapezoidal method is used, taking the average of two inputs times the bin size. The final values for concentrations are then summed and the efficiencies are computed using equation 7. Table 9 gives the result of this integration.

EXAMPLE CALCULATION
WITH NUMERICAL INTEGRATION (Continued)

Table 10: Averaged values over each interval in the trapezoidal method and the results for the entire distribution.

	C_{in} (H)	Inboard C_{out} (I)	Outboard C_{out} (J)	Inboard η (K)	Outboard η (L)
	4.12E-21	4.12E-21	4.12E-21	1.96E-06	2.21E-06
	1.48E-20	1.48E-20	1.48E-20	2.38E-06	2.67E-06
	5.21E-20	5.21E-20	5.21E-20	2.87E-06	3.23E-06
	1.80E-19	1.80E-19	1.80E-19	3.47E-06	3.91E-06
	6.11E-19	6.11E-19	6.11E-19	4.20E-06	4.73E-06
…			…		…
	6.09E-23	8.94E-29	1.17E-34	1.00E+00	1.00E+00
	1.57E-23	1.90E-29	2.06E-35	1.00E+00	1.00E+00
	3.95E-24	3.97E-30	3.56E-36	1.00E+00	1.00E+00
	9.79E-25	8.13E-31	6.03E-37	1.00E+00	1.00E+00
	2.38E-25	1.64E-31	1.00E-37	1.00E+00	1.00E+00
Total	1.00E+00	5.30E-01	3.36E-01	4.71E-01	3.66E-01

$H = AVERAGE(B_{n-1},B_n)*(A_n-A_{n-1})$
$I = AVERAGE(D_{n-1},D_n)*(A_n-A_{n-1})$
$J = AVERAGE(E_{n-1},E_n)*(A_n-A_{n-1})$
$K = 1-I/H$
$L = 1-J/I$

Results from example, using the site-specific design parameters and AMMD = 3 microns, the inboard filter efficiency = 47%, outboard efficiency = 37%, inboard lambda = 0.40/hr, outboard lambda = 0.23/hr.

MATLAB SCRIPT FOR AEB 98-03 RE-EVALUATION AND MULTI-GROUP METHOD

```
% Title: Re-Analysis of AEB 98-03 DBA LOCA MSIV Leakage Pathway
% Description: This computer program is a re-analysis of the DBA LOCA MSIV
% Leakage Pathway.  This program was written with MATLAB Version R2015b
% with the Statistic and Machine learning Toolbox. This program was used
% for the calculations in Attachment 2. The program is divided
% into three parts:


%   1 - Reanalysis of AEB 98-03 using aerosol dist. by Allelein, et al,
%        the State-of-the-Art Report on Nuclear Aerosols,
%         NEA/CSNI/R(2009)5, (SOAR report)
%   2 - Implantation of the Multi-group Probabilistic Distribution Method
%   3 - Printing of various figures tables.

% ---------------------------------------------------------------
%  Reanalysis of AEB 98-03 Monte Carlo Settling Velocity Analysis
% ---------------------------------------------------------------

% --- Aerosol Deposition Velocity Parameters Ranges and Distributions ---
%
% aerosol_diameter = 1.0 AMMD, log-normal dist.: geometric mean = 0.237 um
%                     and geometric st. dev. 2.0
%                   OR
%                   3.0 AMMD, log-normal dist.: geometric mean = 0.710 um
%                     and geometric st. dev. 2.0
% aerosol_density = N/A
% shape_factor = N/A
% cunningham_slipping_factor = 1 (dimensionless) fixed
% viscosity = 1.93x10^-5 Pa-sec, (g/cm-sec), of 1.93x10^5 (g/cm-sec) fixed
% gravitational constant = 9.81 (m/sec^2), fixed
%
% --- Define Plant-specific Piping Nodes ---
MSLB_Area_In = 250.95; % squared feet
MSLB_Area_Out = 770.4; % squared feet
MSLB_Vol_In = 111.47;  % cubic feet
MSLB_Vol_Out = 342;    % cubed feet
MLSB_Flow_In = 49.48;  % cubic feet per hour
MLSB_Flow_Out = 135;   % cubic feet per hour

MSLC_Area_In = 159.72; % squared feet
MSLC_Area_Out = 861.62; % squared feet
MSLC_Vol_In = 70.95;   % cubic feet per hour
MSLC_Vol_Out = 382.52; % cubed feet
MLSC_Flow_In = 49.48;  % cubic feet per hour
MLSC_Flow_Out = 135;   % cubic feet per hour
% --- Notation ---
```

```
% AMMD = Aerodynamic mass median diameter
% BinPen = Bin Penetration
% EffPen = Effective Penetration
% MSL = main steam line (B-line or C-line)
% NRF = net removal efficiency
% RF = removal efficiency
% SV = settling velocity

% ------------------------------------
% --- Settling Velocity Calculation ---
% ------------------------------------

% --- Define Distributions ---
aerosol_density = 1;
shape_factor = 1;
aerosol_diameter_AMMD = 3.0;
aerosol_diameter_sigma_g = 2.0;
aerosol_diameter_Mean = aerosol_diameter_AMMD*exp(-
3*log(aerosol_diameter_sigma_g)^2);
aerosol_diameter = makedist('Lognormal','mu',log(aerosol_diameter_Mean),...
   'sigma',log(aerosol_diameter_sigma_g));

% --- Define Constants ---
cunningham_slipping_factor = 1;
viscosity = 1.93*10^-5;
gravitational_constant = 9.81;

% --- Define Other Modeling Parameters
Group_Number = 2000; % Number of Groups
Trial_Number = 1E5;  % Nuber of Trials

% --- Compute the Probability and Cumulative Density Functions ---
x = 0:0.01:5;
aerosol_diameter_pdf = pdf(aerosol_diameter,x);
aerosol_diameter_cdf = cdf(aerosol_diameter,x);

% --- Generate Random Number for Each Distribution ---
% Using 1E5 randomly generated numbers.
rng('default')
aerosol_diameter_randdist = random(aerosol_diameter, Trial_Number,1);

% --- Compute Settling Velocity ---
SV = ((aerosol_density.*aerosol_diameter_randdist.^2*...
gravitational_constant*cunningham_slipping_factor*1000*1e-6*1e-6)./(18*viscosity*...
shape_factor));

% --- Compute Settling Velocity Percentiles ---
one_percentile = prctile(SV,1);
third_percentile = prctile(SV,3);
tenth_percentile = prctile(SV,10);
```

```
twenty_percentile = prctile(SV,20);
thirty_percentile = prctile(SV,30);
forty_percentile = prctile(SV,40);
fifty_percentile = prctile(SV,50);
sixty_percentile = prctile(SV,60);
seventy_percentile = prctile(SV,70);
eighty_percentile = prctile(SV,80);
ninty_percentile = prctile(SV,90);
onehundred_percentile = prctile(SV,100);

% -------------------------------------
% --- Multi-Group Method Calculation ---
% -------------------------------------

% --- Define Groups ---
Low_Bin = linspace(0,1-(1./Group_Number),Group_Number)';
Upper_Bin = linspace(1./Group_Number,1,Group_Number)';
Bin_Counts = histcounts(SV,Group_Number)';
Bin_Probs = Bin_Counts ./ Trial_Number;

% --- Define Upper Bound Settling Velocity of each bin ---
SV_min = min(SV);
SV_max = max(SV);
SV_delta = SV_max - SV_min;

% Convert Settling units from (m/s) to (ft/hr)
Convert = 3.29*3600;

LowBin_SV = SV_max .* Low_Bin .* Convert;
UpperBin_SV = SV_max .* Upper_Bin .* Convert;
MidBin_SV = LowBin_SV + ((UpperBin_SV - LowBin_SV) ./2);

SelectedBin_SV = MidBin_SV;

% --- Compute Removal Efficiency for each group ---
%
% Utilize Equation 4 (from Tect Bases Memo) which is derived from
% Equation 2 and 3 (from AEB 98-03) the aerosol particulate removal
% efficiencies are computed utilizing the settling velocity,
% settling area, volumetric flow rate, and volume of the well-mixed
% region being modeled.
%
MSLB_In_BinRE = 1 - (1 ./ (1 +((SelectedBin_SV...
   .* MSLB_Area_In) ./ MLSB_Flow_In)));
MSLB_Out_BinRE = 1 - (1 ./ (1 +((MSLB_In_BinRE .*SelectedBin_SV...
   .* MSLB_Area_Out) ./ MLSB_Flow_Out)));
MSLB_In_BinRE_ProbWeighted = MSLB_In_BinRE .* Bin_Probs;
MSLB_Out_BinRE_ProbWeighted = MSLB_Out_BinRE .* Bin_Probs;
MSLB_In_FilterEff = sum(MSLB_In_BinRE_ProbWeighted);
MSLB_Out_FilterEff = sum(MSLB_Out_BinRE_ProbWeighted);
MSLB_In_Lambda = (-MSLB_In_FilterEff*MLSB_Flow_In) ./...
```

```
   ((MSLB_In_FilterEff - 1) * MSLB_Vol_In);
MSLB_Out_Lambda = (-MSLB_Out_FilterEff*MLSB_Flow_Out) ./...
   ((MSLB_Out_FilterEff - 1) * MSLB_Vol_Out);

MSLB_BinNRF = Bin_Probs .*...
  (1- MSLB_Out_BinRE).*(1 - MSLB_In_BinRE);

MSLC_In_BinRE = 1 - (1 ./ (1 +((SelectedBin_SV...
   .* MSLC_Area_In) ./ MLSC_Flow_In)));
MSLC_Out_BinRE = 1 - (1 ./ (1 +((MSLC_In_BinRE .*SelectedBin_SV...
   .* MSLC_Area_Out) ./ MLSC_Flow_Out)));
MSLC_In_BinRE_ProbWeighted = MSLC_In_BinRE .* Bin_Probs;
MSLC_Out_BinRE_ProbWeighted = MSLC_Out_BinRE .* Bin_Probs;
MSLC_In_FilterEff = sum(MSLC_In_BinRE_ProbWeighted);
MSLC_Out_FilterEff = sum(MSLC_Out_BinRE_ProbWeighted);
MSLC_In_Lambda = (-MSLC_In_FilterEff*MLSC_Flow_In) ./...
   ((MSLC_In_FilterEff - 1) * MSLC_Vol_In);
MSLC_Out_Lambda = (-MSLC_Out_FilterEff*MLSC_Flow_Out) ./...
   ((MSLC_Out_FilterEff - 1) * MSLC_Vol_Out);

MSLC_BinNRF = Bin_Probs .*...
   (1- MSLC_Out_BinRE).*(1 - MSLC_In_BinRE);

% --- Compute Total Effective Aerosol Removal Efficiency (TEARE) ---

% --- Effective Aerosol Efficiency ---
% MSLB_In_BinPen = 1- MSLB_In_BinRE;
% MSLB_Out_BinPen = 1- MSLB_Out_BinRE;
%
% MSLC_In_BinPen = 1- MSLC_In_BinRE;
% MSLC_Out_BinPen = 1- MSLC_Out_BinRE;
%
% MSLB_In_EffPen = sum(MSLB_In_BinPen .* Bin_Probs);
% MSLB_Out_EffPen = sum(MSLB_Out_BinPen .* Bin_Probs);
%
% MSLC_In_EffPen = sum(MSLC_In_BinPen .* Bin_Probs);
% MSLC_Out_EffPen = sum(MSLC_Out_BinPen .* Bin_Probs);

% -----------------------------------------------------------
% Generate Plots, Figures, Tables
% -----------------------------------------------------------

% --- Plot the Cumulative Density Functions ---
figure(1);
semilogx(x,aerosol_diameter_pdf,'r','LineWidth',2)
  title('Aerosol Diameter Probability Density Function')
  legend('3.0 AMMD, Log-normal dist.: geometric mean = 0.710 \mum, GSD = 2.0')
  xlabel('Diameter, (\mum)')
  ylabel('Density of Probability')

figure(2);
```

```
plot(x,aerosol_diameter_cdf,'r','LineWidth',2)
  title('Aerosol Diameter Cumulative Distribution')
  legend('3.0 AMMD, Log-normal dist.: geometric mean = 0.710 \mum, GSD = 2.0')
  xlabel('Diameter, (\mum)')
  ylabel('Cumulative Distribution')

 % --- Plot Settling Velocity Histogram ---
figure(3)
histogram(SV,2500)
xlim([0, 1E-5])
title('Settling Velocity Histogram')
  xlabel('Settling Velocity (m/s)')
  ylabel('Number of Results')

% --- Print Percentile Matrix ---
Percentile = {'1st Percentile'; '3rd Percentile'; '10th Percentile';...
    '20th Percentile'; '30th Percentile'; '40th Percentile';...
    '50th Percentile'; '60th Percentile'; '70th Percentile';...
    '80th Percentile'; '90th Percentile'; '100th Percentile'};

% --- Percentile Vector (m/s)
SV_mpers = [one_percentile; third_percentile; tenth_percentile;...
 twenty_percentile; thirty_percentile; forty_percentile;...
 fifty_percentile; sixty_percentile; seventy_percentile;...
 eighty_percentile; ninty_percentile; onehundred_percentile];

% --- Percentile Vector (ft/hr)
SV_ftperhr = (SV_mpers*11811);

SV_PercentileTable = table(Percentile, SV_mpers, SV_ftperhr);

% Print Table 3, Removal Efficiencies and Net Release Fractions

MSLB_RFandNRF = table(Low_Bin,Upper_Bin,Bin_Probs,SelectedBin_SV,...
   MSLB_In_BinRE, MSLB_Out_BinRE, MSLB_In_BinRE_ProbWeighted,...
     MSLB_Out_BinRE_ProbWeighted);

MSLC_RFandNRF = table(Low_Bin,Upper_Bin,Bin_Probs,SelectedBin_SV,...
   MSLC_In_BinRE, MSLC_Out_BinRE, MSLC_In_BinRE_ProbWeighted,...
     MSLC_Out_BinRE_ProbWeighted);

%  Print Table 5, TEAREs and Lambdas results

MSLBC_FilEffs = table(MSLB_In_FilterEff, MSLB_Out_FilterEff,...
   MSLC_In_FilterEff, MSLC_Out_FilterEff);

MSLBC_Lambdas  = table(MSLB_In_Lambda, MSLB_Out_Lambda,...
   MSLC_In_Lambda, MSLC_Out_Lambda);
```