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A Note on Aerosol Removal by Gravitational Settling in a Horizontal Steam Pipe

Fred Gelbard and Nathan Andrews

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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A Note on Aerosol Removal by Gravitational Settling in a Horizontal Steam Pipe

Fred Gelbard & Nathan Andrews
Advanced Nuclear Fuel Technology and Structural and Thermal Analysis
&
Severe Accident Analysis
Sandia National Laboratories
PO Box 5800
Albuquerque, New Mexico 87185-MS0747

ABSTRACT

This work determines the decontamination factors for an aerosol laden gas flowing slowly through a horizontal pipe. These factors are obtained for two models; a well-mixed pipe interior and plug flow through the pipe. The decontamination factor (DF) is given analytically as a function of particle size and time for both models. Plots of the DF for a specific steam pipe geometry are also given.

ACKNOWLEDGEMENTS

The authors thanks Randall Gauntt for requesting a quick analysis of the effects of gravitational settling in a horizontal pipe.

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NOMENCLATURE

AMMD = aerodynamic mass median diameter (μm)

C = aerosol mass concentration (kg/m^3)

C_{in} = inlet aerosol mass concentration (kg/m^3)

C_c = Cunningham slip correction factor

d_p = aerosol particle diameter (m)

g = gravitational constant (9.81 m/s^2)

GSD = geometric standard deviation

K = agglomeration coefficient (m^3/s)

Kn = Knudsen number of aerosol particle ($2\lambda/d_p$)

k_B = Boltzmann's constant (1.38×10^{-23} J/K)

L = pipe length (5 m)

m = steam molecule mass ($0.018/6.02 \times 10^{23} = 3 \times 10^{-26}$ kg)

N = aerosol particle number concentration (m^{-3})

P = ambient pressure (1.01325×10^5 Pa)

Q = volumetric flow rate through pipe (4×10^{-4} m^3/s)

R = pipe radius (0.254 m = 10 inches)

Re_g = Reynolds number for gas flow ($2Rv_g\rho_g/\eta$)

Re_p = Reynolds number for spherical aerosol particle settling ($d_p v_s \rho_g/\eta$)

T = absolute temperature (373 K)

t = time (s)

V = pipe volume (m)

v_g = average gas velocity (2.0×10^{-3} m/s)

v_s = aerosol particle settling velocity (m/s)

η = gas viscosity (12.6×10^{-6} kg/m/s)

λ = gas mean free path (m)

ρ_g = gas density (0.588 kg/m^3)

ρ_p = particle material density (4500 kg/m^3, corresponding to CsI)

τ_a = characteristic time scale for aerosol agglomeration (s)

τ_g = characteristic time scale for gas flow (L/v_g = 2500 s)

τ_s = characteristic time scale for particle settling (s)

1 FLOW FEATURES OF THE PROBLEM

The pipe is modeled as a horizontal hollow cylinder with a length of 5 m and a radius of 0.254 m, with a volumetric gas flow rate of 4×10^{-4} m^3/s, as given to the author. A scaled drawing is given below in

Figure 1-1.

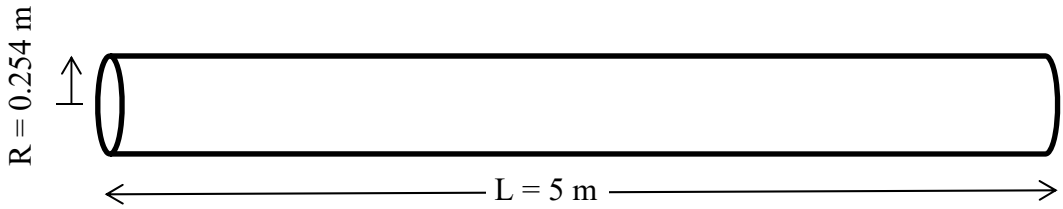

Figure 1-1. Scaled drawing of horizontal steam pipe.

For incompressible isothermal flow, the average gas velocity is given by,

$$v_g = \frac{Q}{\pi R^2} = \frac{4\times10^{-4}}{\pi(0.254)^2} = 2.0\times10^{-3}\,\mathrm{m/s}. \quad (1.1)$$

For the gas properties, the author was asked to take those for steam at 373 K and 1 atmosphere pressure. Thus, ρ_g = gas density (0.586 kg/m^3), and η = gas viscosity (12.6×10^{-6} kg/m/s). Hence the Reynolds number is,

$$Re_g = 2Rv_g\rho_g/\eta = 2(0.254)(2\times10^{-3})(0.588)/12.6\times10^{-6} = 47. \quad (1.2)$$

This low Reynolds number indicates that the flow is laminar. In the future, aerosol dynamics can be computed within a laminar velocity profile. However, for the analysis in this work the flow will be considered to be either well-mixed or plug flow.

The characteristic time scale for gas flow is,

$$\tau_g = L/v_g = 5/(2.0\times10^{-3}) = 2500\ \mathrm{s} = 42\ \mathrm{minutes}. \quad (1.3)$$

2 AEROSOL PROCESS TIME SCALES

The aerosol processes to consider are gravitational settling, agglomeration, and steam condensation on hygroscopic CsI particles. Condensational particle growth would result in larger particles that settle faster. Similarly, agglomeration would also result in larger particles that settle faster. For this conservative analysis, condensation and agglomeration will be neglected but may be included later if so requested. (A calculation was performed with MAEROS that incorporated flow, settling and agglomeration. This calculation did show the increase in aerosol removal by agglomeration compared to the results in this note.)

Processes are significant when the aerosol process time scale is shorter than the time scale for gas flow through the pipe. A discussion of these time scales is given in this section, and a summary of the aerosol time scales is given below in Table 2-1 and Figure 2-1.

Table 2-1. Characteristic time scales♦

Symbol	Process	Expression	Range (s)
τ_g	gas flow	L/v_g	2500
τ_a	aerosol agglomeration (monodisperse)	$\frac{3}{4k_B T N_o}$	4.4×10^{-1} – 4.4×10^{7}
τ_s	aerosol particle settling	R/v_s	10 – 3×10^{4}

♦L = 5 m, R = 0.254 m, T = 373 K.

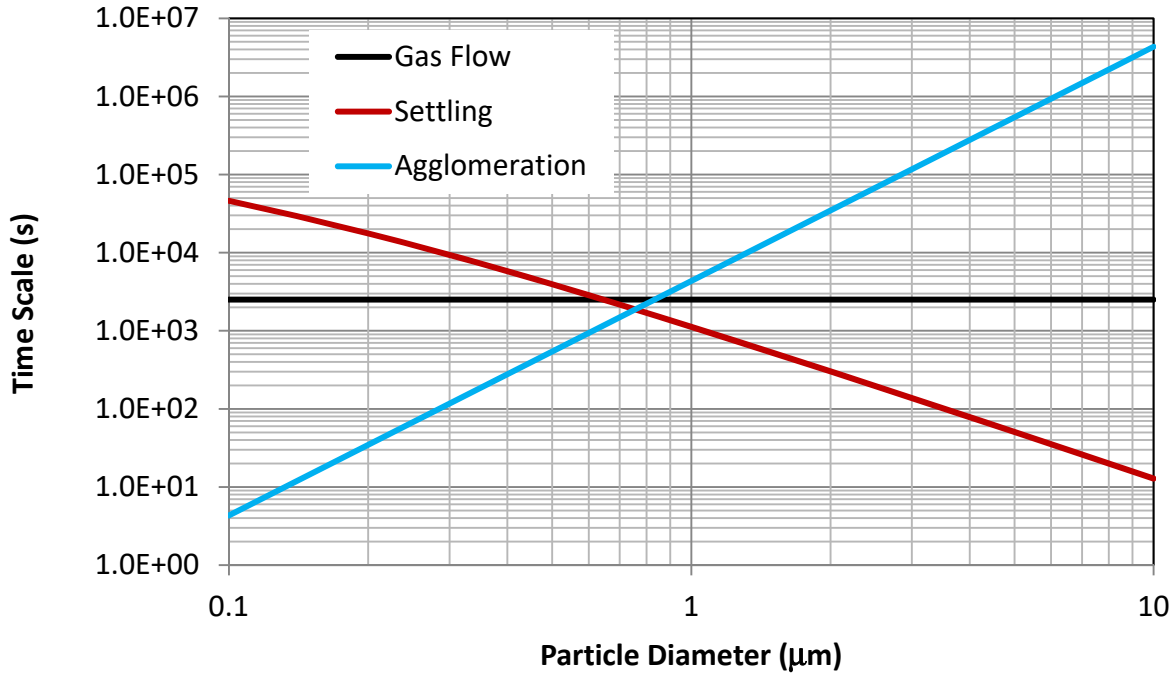

Figure 2-1. Comparison of time scales. Aerosol process time scales much shorter than the gas flow time scale can be expected to significantly alter the aerosol concentration or size distribution by the time the aerosol has exited the pipe.

2.1 Aerosol Particle Gravitational Settling

The settling velocity of a sphere falling with a particle Reynolds number less than 0.2, in an isothermal stagnant gas is given by [Kulkarni et al., 2011; Friedlander, 2000; Hinds 1999],

$$v_s = \frac{(\rho_p - \rho_g) g d_p^2 C_c}{18\eta}. \tag{2.1}$$

The Cunningham correction factor for noncontinuum effects is given by,

$$C_c = 1 + Kn[1.255 + 0.4\exp(-1.1/Kn)], \tag{2.2}$$

where the Knudsen number Kn, is defined in the nomenclature section above. To determine Kn, the gas mean free path is determined from,

$$\lambda = \frac{\eta}{P}\sqrt{\frac{\pi k_B T}{2m}}. \tag{2.3}$$

For steam at T = 373 K and P = 1.01×10^5 Pa, the gas viscosity is $\eta = 12.6\times10^{-6}$ kg/m/s. Thus the gas mean free path is given by,

$$\lambda = \frac{12.6\times10^{-6}}{1.01\times10^{5}}\sqrt{\frac{\pi(1.38\times10^{-23})(373)}{2(0.018/6.02\times10^{23})}} = 6.4\times10^{-8}\,\text{m} = 0.064\,\mu\text{m}. \qquad (2.4)$$

A plot of the settling velocity for particles with a density of 4500 kg/m^3 (corresponding to CsI), settling in steam at 373 K is given in Figure 2-2. As a check that the Reynolds number is less than 0.2, consider the maximum settling velocity of 0.02 m/s for a 10 μm diameter CsI particle. The Reynolds number for the particle is given by,

$$\text{Re}_p = \frac{d_p v_s \rho_g}{\eta} = \frac{10^{-5}(0.02)(0.588)}{12.6\times10^{-6}} = 9\times10^{-3}. \qquad (2.5)$$

Because the Reynolds number is less than 0.2, the expression given by Eq. (2.1) is valid.

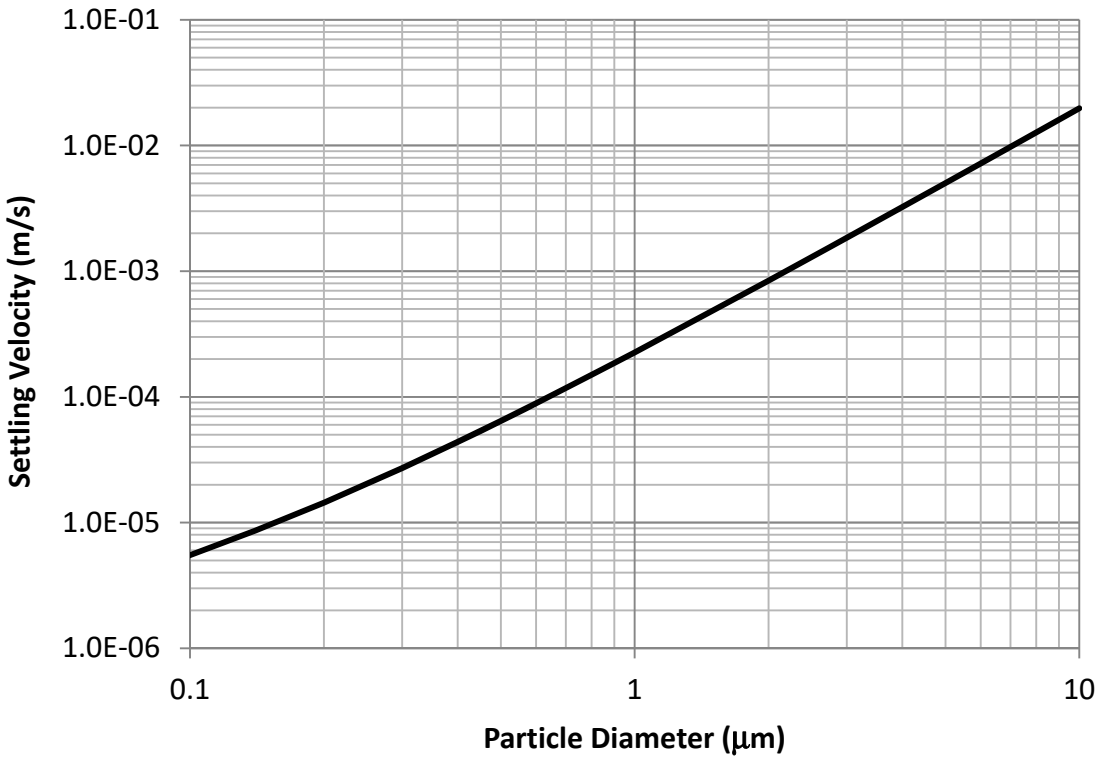

Figure 2-2. Aerosol particle settling velocity in stagnant steam at 373 K with a particle material density of 4500 kg/m^3.

Thus the time scale to traverse one pipe radius is given by R/v_s and is plotted in Figure 2-1.

Notice that for particles much less than about 0.6 μm diameter, the settling time scale is too long compared to the gas flow time scale. Thus for these small particle settling is not an important removal process.

2.2 Aerosol Agglomeration

Aerosol agglomeration is a nonlinear process that is dependent on the particle number concentration. For monodisperse aerosols this time scale is given by [Friedlander, 2000],

$$\tau_a = \frac{3\eta}{4k_B TN}. \tag{2.6}$$

As particles agglomerate, the number concentration will decrease, and thus increase the time scale for agglomeration. The initial number concentration was not provided. Instead, this can be estimated from the range in aerosol mass concentration coming into the pipe and the range of particle diameter.

For aerosol mass concentration ranging from 10^{-2} to 10^{-4} kg/m^3, and particle diameters ranging from 0.1 to 10 μm, the number concentration is given by

$$N = \frac{6M}{\pi\rho d_p^3} \tag{2.7}$$

Thus the maximum number concentration is given for the smallest particles in the pipe and the highest mass concentration. The highest number concentration is,

$$N_{max} = \frac{6M}{\pi\rho d_p^3} = \frac{6(10^{-2})}{\pi(4500)(10^{-7})^3} = 4.2\times10^{15}\,\mathrm{m}^{-3} \tag{2.8}$$

$$N_{min} = \frac{6M}{\pi\rho d_p^3} = \frac{6(10^{-4})}{\pi(4500)(10^{-5})^3} = 4.2\times10^{7}\,\mathrm{m}^{-3} \tag{2.9}$$

Therefore, the shortest agglomeration time scale is

$$\tau_a = \frac{3\eta}{4k_B TN} = \frac{3(12.6\times10^{-6})}{4(1.38\times10^{-23})(373)(4.2\times10^{15})} = 4.4\times10^{-1}\,\text{s}. \qquad (2.10)$$

For convenience, we consider an aerosol mass concentration of 10^{-3} kg/m^3 in Figure 2-1. For particles much less than one micrometer in diameter, agglomeration is expected to be significant because the time scale for agglomeration of these particles is much less than the gas flow time scale.

3 WELL-MIXED AEROSOL SETTLING IN PIPE

As a first approximation, the volume in the pipe is assumed to be spatially homogeneous. The area for settling is the projected bottom area of the pipe given by 2RL. For constant volumetric gas flow through the pipe, the aerosol mass concentration in the pipe, which is also the exit concentration, is given by,

$$\frac{dC}{dt} = C_{in}\frac{Q}{V} - C\frac{Q}{V} - v_s\frac{2RL}{V}C, \tag{3.1}$$

where

Q = volumetric gas flow rate into and out of the pipe,

C = aerosol mass concentration inside and exiting the pipe,

C_{in} = inlet aerosol mass concentration, and

V = pipe volume ($\pi R^2 L$).

Initially we assume the most conservative case that $C = C_{in}$ at t = 0. The solution with this initial condition is,

$$\frac{C}{C_{in}} = \exp\left[-\frac{(2RLv_s + Q)t}{V}\right] + \frac{Q}{Q + 2RLv_s}\left\{1 - \exp\left[-\frac{(2RLv_s + Q)t}{V}\right]\right\}. \tag{3.2}$$

The decontamination factor is defined as C_{in}/C. From the previous equation,

$$DF = \frac{C_{in}}{C} = \frac{\exp\left[\frac{(2RLv_s + Q)t}{V}\right]}{1 + \frac{Q}{Q + 2RLv_s}\left\{\exp\left[\frac{(2RLv_s + Q)t}{V}\right] - 1\right\}}. \tag{3.3}$$

For long times such that,

$$\frac{Q}{Q + 2RLv_s}\exp\left[\frac{(2RLv_s + Q)t}{V}\right] >> 1, \tag{3.4}$$

the DF reduces to,

$$DF = \frac{Q + 2RLv_s}{Q}. \tag{3.5}$$

This asymptotic limit is approached regardless of the initial conditions at t = 0, and may also be determined by setting the derivative of C with respect to time to zero in Eq. (3.1). A plot of the decontamination factor as a function of time is given in Figure 3-1. Notice from this figure that after about 600 seconds (10 minutes), the asymptotic limit is attained for particles larger than 5 μm diameter.

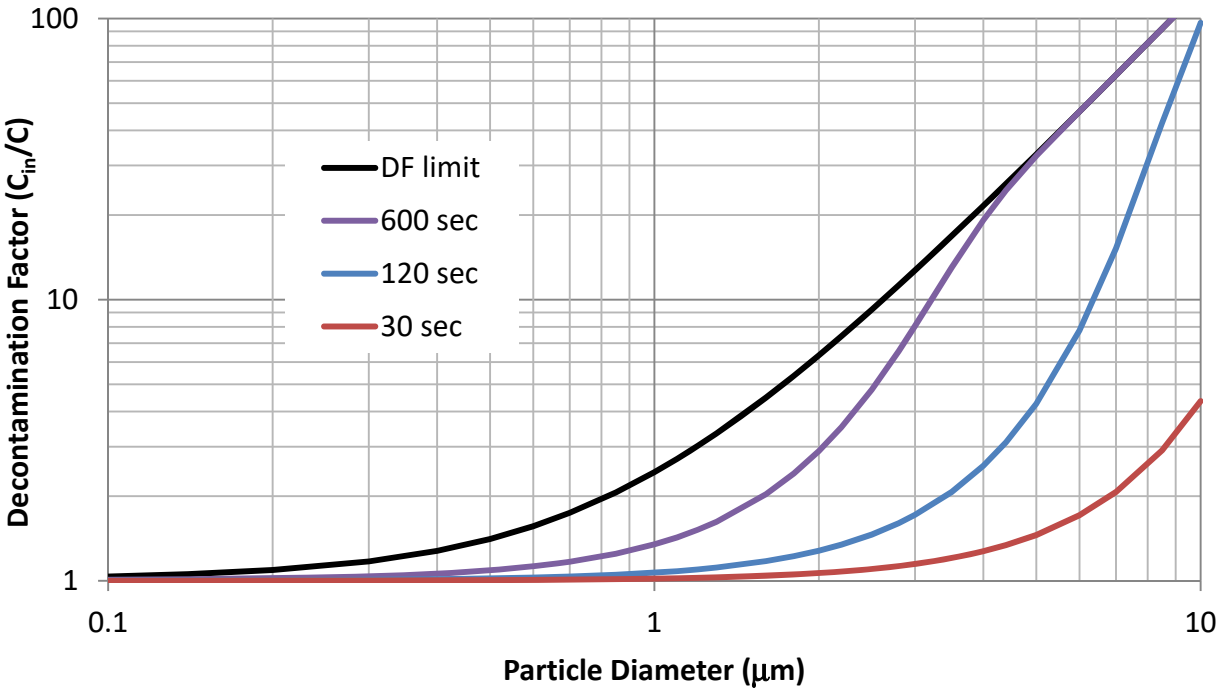

Figure 3-1. Decontamination factor for a well-mixed pipe with a constant flow rate and aerosol undergoing gravitational settling.

4 SIMULTANEOUS ONE-DIMENSIONAL FLOW AND AEROSOL SETTLING IN PIPE

A more accurate model as used in MELCOR is to divide the pipe into a series of contiguous homogeneous control volumes. For this analysis, we can take the limit as the control volume shrinks to zero and an infinite number of control volumes are used so that we obtain a continuous variation in aerosol concentration along the length of the pipe. Thus we will avoid discretization errors that introduce numerical diffusion.

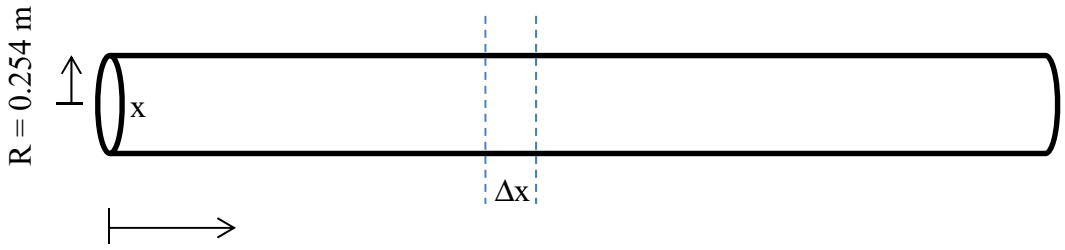

Figure 4-1. Differential aerosol mass balance for a one-dimensional model.

Consider a differential slice of pipe of length Δx as shown in

Figure 4-1. The aerosol mass in the slice is the volume of the slice times the aerosol concentration. The volume of the differential slice is $\pi R^2 \Delta x$. For gas flowing in the positive x-direction, the aerosol mass flow rate into the slice is $v_g C$ times the cross-sectional area of the pipe evaluated at x. Similarly, the aerosol mass flow rate leaving the slice is $v_g C \pi R^2$ evaluated at $x+\Delta x$. The aerosol mass rate settling out over the projected bottom area of the slice is $2R\Delta x v_s C$. Thus the aerosol mass balance is given by,

$$\frac{\partial}{\partial t}\left[\pi R^2 \Delta x C\right] = \left[v_g \pi R^2 C\right]_x - \left[v_g \pi R^2 C\right]_{x+\Delta x} - 2R\Delta x v_s C . \tag{4.1}$$

Dividing Eq. (4.1) by Δx and taking the limit as $\Delta x \rightarrow 0$ results in,

$$\frac{\partial C}{\partial t} + v_g \frac{\partial C}{\partial x} + \frac{2 v_s}{\pi R} C = 0 \tag{4.2}$$

The initial and boundary conditions are,

$$C = C_{in} \quad \text{for all x at t = 0 ,} \tag{4.3}$$

and

$$C = C_{in} \quad \text{for all t at x = 0.} \tag{4.4}$$

Eq. (4.2) is a hyperbolic partial differential equation with constant coefficients, which is readily solvable by the Method of Characteristics. The solution is given in two parts as follows,

$$C = \begin{cases} C_{in} \exp\left(-\dfrac{2v_s t}{\pi R} \right) & \text{for} \quad t \le \dfrac{x}{v_g} \\ \\ C_{in} \exp\left(-\dfrac{2v_s x}{\pi R v_g} \right) & \text{for} \quad t \ge \dfrac{x}{v_g} \end{cases} . \tag{4.5}$$

The decontamination factor for aerosol exiting the pipe at x = L is therefore given by,

$$DF = \frac{C_{in}}{C(x = L)} = \begin{cases} \exp\left(\dfrac{2v_s t}{\pi R} \right) & \text{for} \quad t \le \dfrac{L}{v_g} \\ \\ \exp\left(\dfrac{2v_s L}{\pi R v_g} \right) & \text{for} \quad t \ge \dfrac{L}{v_g} \end{cases} . \tag{4.6}$$

The DF is plotted below in Figure 4-2. The DF attains a constant steady state value for times greater than the time scale for flow through the pipe. Comparing Figure 3-1 and Figure 4-2, we see that the DF is significantly smaller for a gas that is well-mixed within the pipe, than when a sharp front results from a plug flow model. These two models provide the limiting cases that may be used in MELCOR. A single control volume for a well-mixed model would result in the DF given in Figure 3-1, or the limit of essentially an infinite number of control volumes given in Figure 4-2.

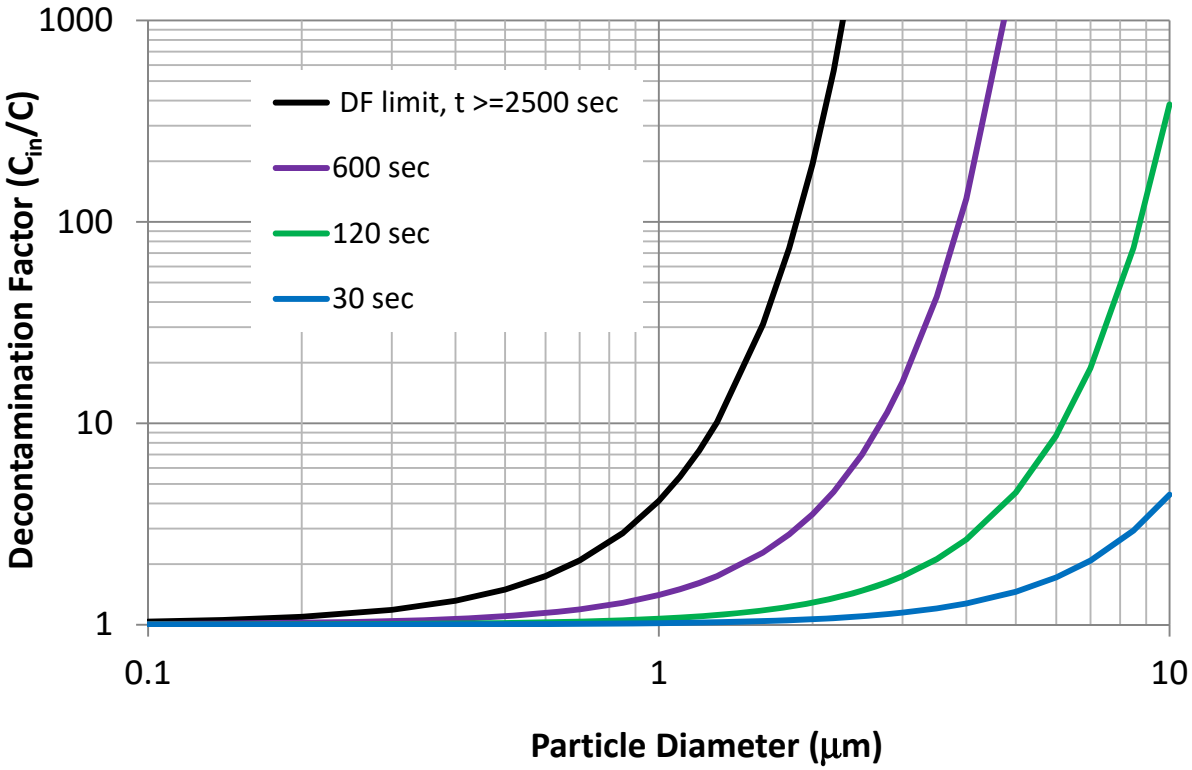

Figure 4-2. DF for plug flow aerosol settling.

5 APPLICATION OF DECONTAMINATION FACTOR TO DIFFERENT AEROSOL CONCENTRATION

5.1 Plotting Aerosol Concentration from the State-of-the-Art Report on Nuclear Aerosols and AEB-98-03

Normalized aerosol concentration in a nuclear reactor system can be expressed as a lognormal distribution following the recommendations set forth in the "State-of-the-Art Report on Nuclear Aerosols", which state a range of Aerosol Mass Median Diameter (AMMD) from 1.0 to 2.0 μm and a geometric standard deviation (GSD) of 2.0. [Allelein et al, 2009] The normalized concentration of aerosols for this lognormal distribution is shown in Equation (5.1).

$$n(D) = \frac{1}{\sqrt{2\pi}\ln(GSD)D}\exp\left[-\frac{\ln\left(\frac{D}{D_g}\right)}{2\ln^2(GSD)}\right] \tag{5.1}$$

Where:
$n(D) =$ Number Concentration of Aerosol Particles, #/m^3/μm
Geometric Number Median Diameter $(D_g) = 0.237$ μm and 0.473 μm
Geometric Standard Deviation $(GSD) = 2.0$
Aerodynamic Mass Median Diameter $(AMMD) = 1.0$ μm and 2.0 μm

To convert from AMMD for D_g, Equation (5.2) can be used:

$$AMMD = D_g\exp\left[3\ln^2(GSD)\right] \tag{5.2}$$

The aerosol concentration used in "Assessment of radiological consequences for the Perry pilot plant application using the revised (NUREG-1465) source term," issued as technical report AEB-98-03, is uniform between equivalent aerosol diameters between 1.5 and 5.5 μm. To convert this this to an aerodynamic diameter, the density of the aerosol particles was taken to be 4.5 g/cc with a shape factor of 1.5 ($\chi = 1.5$), to maintain consistency with the decontamination factors previously calculated, [Schaperow, 1998]. Conversion to an aerodynamic diameter can be performed per Equation (5.3) [Hinds, 1999].

$$D_a = D_e\sqrt{\frac{\rho_p}{\rho_0\chi}} = D_e\sqrt{\frac{4.5}{1.5}} = 1.73D_e \tag{5.3}$$

A normalized probability density function (PDF) of the aerosol mass distribution can be seen in Figure 5-1 for lognormal distributions found in the "State-of-the-Art Report on Nuclear

Aerosols", and the uniform distribution found in AEB-98-03, [Allelein et al., 2009; Schaperow, 1998]. A cumulative distribution function (CDF) can be seen in Figure 5-2.

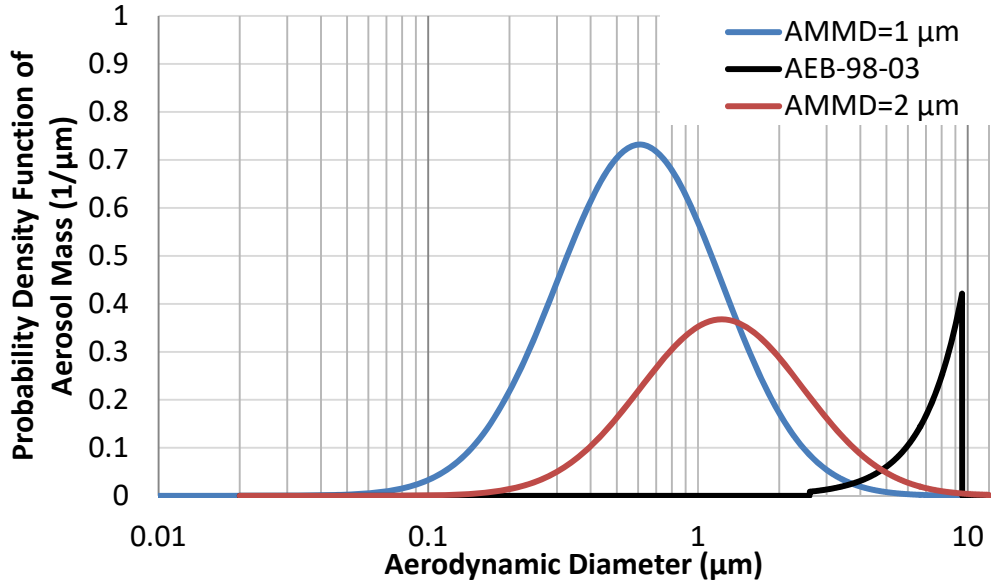

Figure 5-1. PDF of initial aerosol concentration, showing two separate concentrations based on the State-of-the-Art Report on Nuclear Aerosols [Allelein et al, 2009], and one based on the AEB-98-03 distribution [Schaperow, 1998].

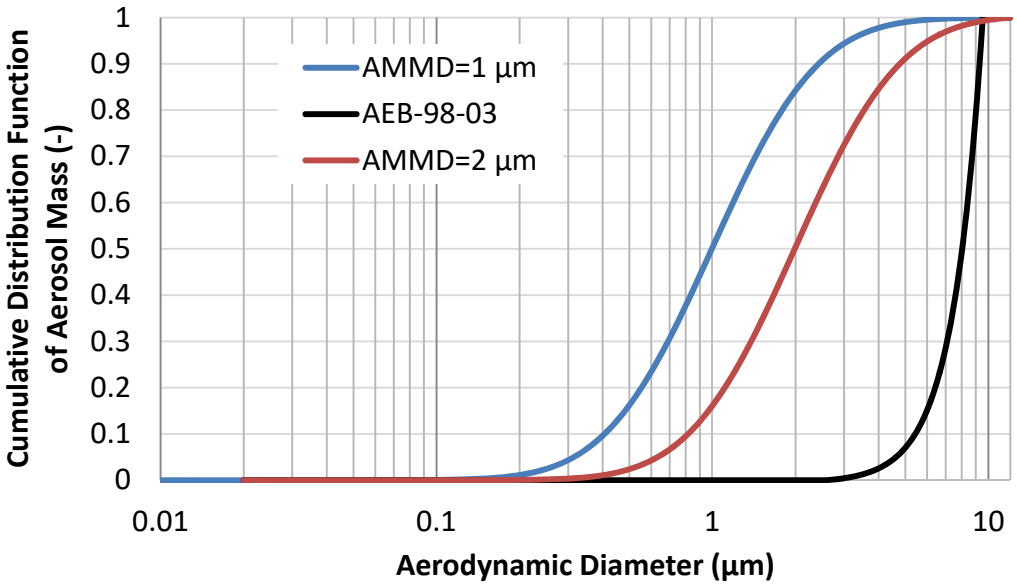

Figure 5-2. CDF of initial aerosol concentration, showing two separate concentrations based on the State-of-the-Art Report on Nuclear Aerosols [Allelein et al, 2009], and one based on the AEB-98-03 distribution [Schaperow, 1998].

5.2 Applying Well Mixed Pipe Decontamination Factors to Initial Concentrations

The previously calculated DF limit for a well-mixed pipe, found in Figure 3-1, was applied to the three separate aerosol distributions detailed in Section 5.1.

$$m_{final}(D) = \frac{m_{initial}(D)}{DF(D)} \tag{5.3}$$

Where:

$m_{initial}(D)$ = Initial Mass of Aerosol Particles

$m_{final}(D)$ = Final Mass of Aerosol Particles

This assumption is the most appropriate and is currently the one used in the severe accident analysis code MELCOR. Upon applying the diameter-dependent final aerosol concentrations were calculated for all three distributions. The final DF-scaled distribution can be seen in Figure 5-3 and 5-4.

Both of the initial AMMD mass distributions are normalized to 1.0, whereas the final values are based on this number multiplied by the decontamination factor. It can be seen that the overall decontamination factor is much higher for the AEB-98-03 distribution than the Allelein et al., 2009 distributions. This is because the aerosol diameters in AEB-98-03 are much higher, and thus lead to more decontamination.

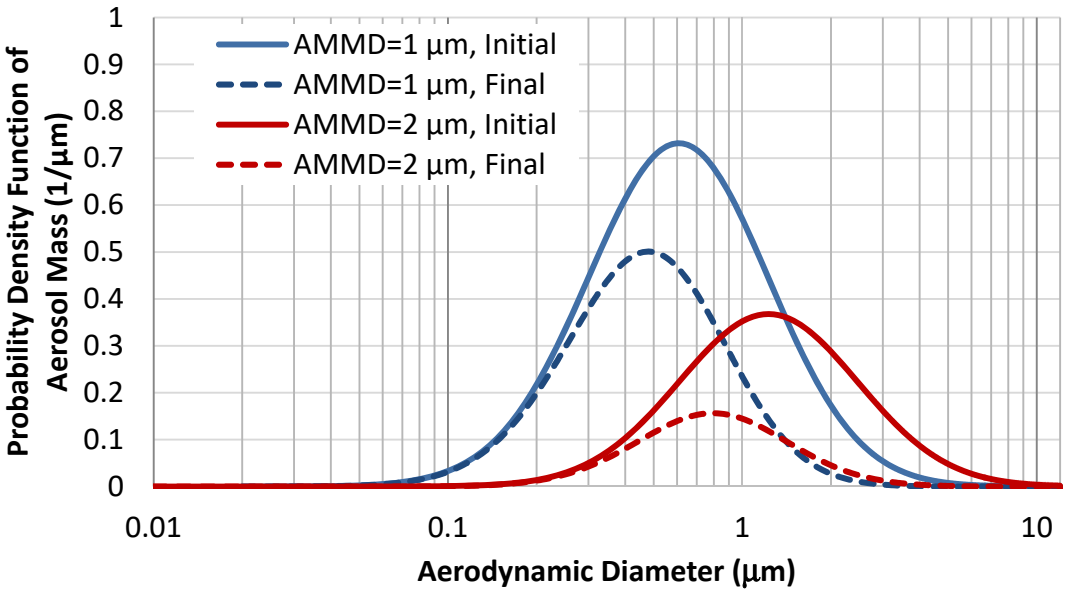

Figure 5-3. Impact of the decontamination factor limit applied to two separate distributions .from the State-of-the-Art Report on Nuclear Aerosols [Allelein et al, 2009]. Both the initial and final concentration for both distributions is shown.

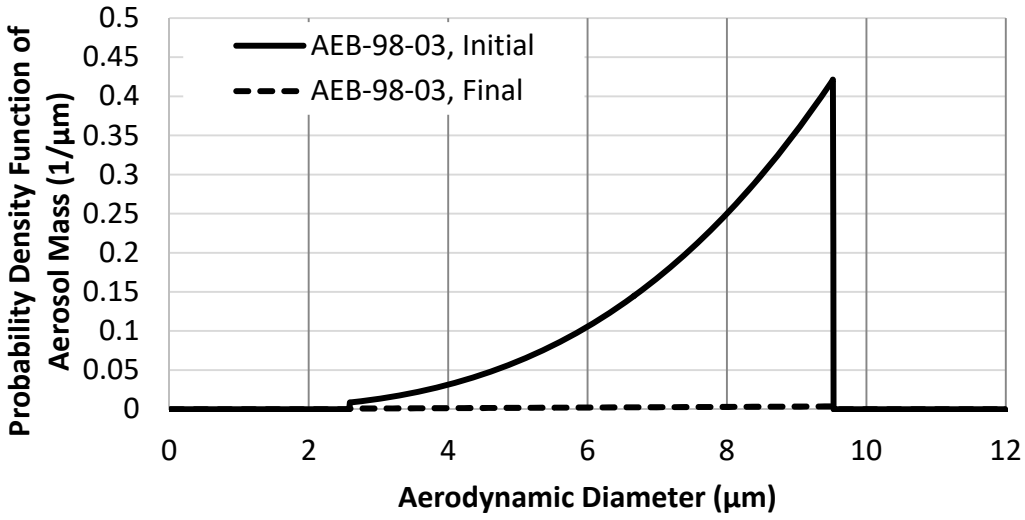

Figure 5-4. Impact of the decontamination factor limit applied to the AEB-98-03 uniform distribution [Schaperow, 1998].

5.3 Overall Decontamination Factors for Different Distributions and Modeling Parameters

The maximum DF, using the DF limits from Figure 3-1 and Figure 4-2, for the three size distributions is shown in Table 5-1. Two separate calculations of the DF as a function of aerosol size are shown, a well-mixed pipe and a pipe with plug flow. The decontamination factors were calculated based on the change in total aerosol mass in the pipe.

It can be seen that the "well mixed" assumption results in a lower DF. This methodology is applied in MELCOR. It should be noted that the Max DF for AMMD = 1 μm and a well-mixed pipe is essentially the same as the value calculated by MELCOR within the old MSIV report. It can clearly be seen that the overall DF for the uniform AEB-98-03 distribution is much higher that obtained when using the State-of-the-Art distributions.

Table 5-1. Determination of Maximum DF from various aerosol size distributions and decontamination factor distributions, DF is based on aerosol mass

Distribution	AMMD = 1.0 μm GSD = 2.0		AMMD = 2.0 μm GSD = 2.0		Uniform AEB-98-03	
Pipe Parameter	Well Mixed	Plug Flow	Well Mixed	Plug Flow	Well Mixed	Plug Flow
Maximum DF by Aerosol Mass	2.3	3.2	4.6	9.7	63.2	3.9×10^6

The State-of-the-Art distributions are the most accurate and the "well-mixed" pipe is the most realistic assumption. This leads an overall estimated DF for the MSIV piping between 2.3 and 4.6.

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