SANDIA REPORT
SAND2021-13183
October 2021

Sandia National Laboratories

Update to the Finite Cloud Dose Correction Factors in MACCS

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ABSTRACT

In WASH-1400, external exposure from the finite radioactive cloud (cloudshine) is calculated by assuming that the cloud is semi-infinite, the concentration of radioactive material is uniform, and by using a correction factor to account for these approximations. This correction factor is originally based upon formulations by Healy and depends on the effective size of the plume and the distance from the plume center to the receptor. The range of the finite cloud dose correction factor table from WASH-1400 developed using Healy formulations can be exceeded in certain situations. When the range of the table is exceeded, no extrapolation is performed; rather interpolation at the edge of the table is performed per WASH-1400. The tabulated values of these finite cloud dose correction factors from WASH-1400 and the interpolation at the edge of the table have been used in MACCS since its creation. An expanded table of finite cloud dose correction factors is one way to reduce the need of using interpolation at the edge of the table. The generation of an expanded finite cloud dose correction factor table for future use in MACCS is documented in this report.

This work was sponsored by the U.S. NRC's Office of Nuclear Regulatory Research under contract number 31310020F0032.

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ACRONYMS AND DEFINITIONS

Abbreviation	Definition
AERMOD	American Meteorological Society / Environmental Protection Agency Regulatory Model
ARCON96	Atmospheric Relative Concentrations in Building Wakes
ATD	Atmospheric Transport and Dispersion
CFD	Computational Fluid Dynamics
X/Q	Normalized, ground-level, time-integrated air concentration
DOE	Department of Energy
LWR	Light Water Reactor
MACCS	MELCOR Accident Consequence Code System
NRC	Nuclear Regulatory Commission
PAVAN	Program for the Meteorological Evaluation of Non-Routine Releases from Nuclear Power Stations
QUIC	Quick Urban and Industrial Complex

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1. INTRODUCTION

The Reactor Safety Study [1] presented the first comprehensive probabilistic risk assessment of hypothetical nuclear power plant accidents. This report is also commonly referred to as WASH-1400. In WASH-1400, external exposure from the finite radioactive cloud (cloudshine) is calculated by assuming that the cloud is semi-infinite, the concentration of radioactive material is uniform, and by using a correction factor to account for these approximations. This correction factor is originally based upon formulations by Healy [2] and depends on the effective size of the plume and the distance from the plume center to the receptor. The tabulated values of these finite cloud dose correction factors from WASH-1400 [1] are shown in Table 1-1 and have been used in MACCS since its creation.

Table 1-1. Finite cloud dose correction factors from WASH-1400* [1]

Effective Plume Size, $\sqrt{\sigma_y \sigma_z}$ [m]	Distance to Cloud Center Relative to the Effective Plume Size, $\frac{\sqrt{y^2+z^2}}{\sqrt{\sigma_y \sigma_z}}$ [unitless]					
	0	1	2	3	4	5
3	0.020	0.018	0.011	0.007	0.005	0.004
10	0.074	0.060	0.036	0.020	0.015	0.011
20	0.150	0.120	0.065	0.035	0.024	0.016
30	0.220	0.170	0.088	0.046	0.029	0.017
50	0.350	0.250	0.130	0.054	0.028	0.013
100	0.560	0.380	0.150	0.045	0.016	0.004
200	0.760	0.511	0.150	0.024	0.004	0.001
400	0.899	0.600	0.140	0.014	0.001	0.001
1,000	0.951	0.600	0.130	0.011	0.001	0.001

*From WASH-1400 [1] Table VI 8-1 with correction of a typographic error.

As shown in Table 1-1, the tabulated values of the finite cloud dose correction factors are a function of effective plume size and distance to cloud center relative to the effective plume size. They are also rounded to the nearest thousandth, with a minimum value of 0.001. The maximum effective plume size in the table is 1,000 m and the maximum distance to cloud center is five times the effective plume size. When the range of the table is exceeded, no extrapolation is performed; rather interpolation at the edge of the table is performed per WASH-1400 [1]. The table edge interpolation aligns with the MACCS implementation of the finite cloud dose correction factors.

Analyses with unstable weather conditions can exceed an effective plume size of 1,000 m at distances of 10 km or greater. Analyses near the release location (< 1 km) at altitude and/or including buoyancy and small plume sizes can exceed a relative distance to the cloud center of five times the effective plume size. Using the interpolation at the edge of the table can overestimate the cloudshine doses calculated for these conditions. This overestimation could potentially skew analyses. An expanded table of finite cloud dose correction factors is one way to reduce the need of using interpolation at the edge of the table for these types of analyses, reducing the possibility of skewing analysis results. The objective of this report is to document the generation of an expanded finite cloud dose correction factor table for future use in MACCS.

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2. WASH-1400 VALUES

Formulations of the finite cloud dose correction factors were presented by Healy [2] in 1968. The formulations were presented again by Healy [3] in 1984 with minor differences in the presentation, figures and discussion, but no differences in the equations used. The formulations were derived using the coordinate system reproduced in Figure 2-1, by considering the dose rate to a receptor on the ground at point $(x_1, y_1, 0)$ and at time t from a spherical cloud with a radius of r, released at height h and moving at an average velocity of $\bar{u}$ in the x-z plane. The derivation assumes perfect reflection at the ground plane, and therefore can be extended to clouds released at ground level or clouds that expand to and past ground level.

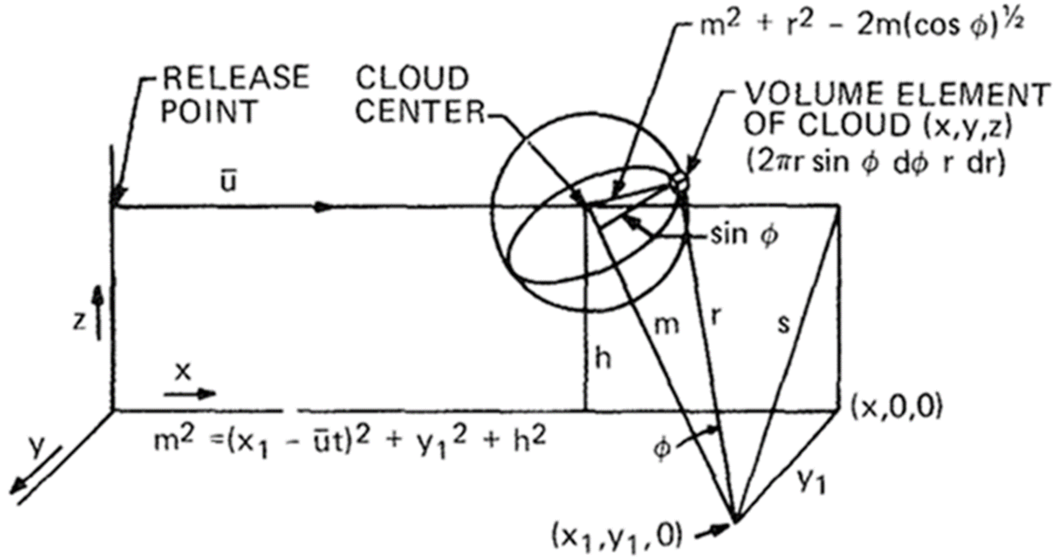

Figure 2-1. Coordinate system for finite cloud dose correction factor calculations (Figure 16.5 from Healy [3])

Using the coordinate system above, Healy [2][3] defines the following geometry factors of I_1 and I_2 as:

$$I_1 = \frac{\bar{u}}{4(2\pi)^{1/2}\mu\sigma_{av}} \int_0^\infty \int_0^\infty \frac{exp(-\mu r)}{mr} \left\{ exp\left[\frac{-(m-r)^2}{2\sigma_{av}^2}\right] - exp\left[\frac{-(m+r)^2}{2\sigma_{av}^2}\right] \right\} dr\, dt \quad (2\text{-}1)$$

$$I_2 = \frac{\bar{u}}{4(2\pi)^{1/2}\mu\sigma_{av}} \int_0^\infty \int_0^\infty \frac{\mu\, exp(-\mu r)}{m} \left\{ exp\left[\frac{-(m-r)^2}{2\sigma_{av}^2}\right] - exp\left[\frac{-(m+r)^2}{2\sigma_{av}^2}\right] \right\} dr\, dt \quad (2\text{-}2)$$

where

$\bar{u}$ = the average velocity of the cloud in the x-z plane, m/s,
μ = the total absorption coefficient for air, m^{-1},
σ_{av} = the average size of the plume, $\sqrt{\sigma_y \sigma_z}$, m,
m = the distance from the receptor to center of the cloud, $\sqrt{(x_1 - \bar{u}t)^2 + y_1^2 + h^2}$, m,
r = the cloud radius, m,
t = the cloud travel time, s.

Using these geometric factors, Healy [2][3] gives the equation derived for the finite cloud dose correction factor ($FCDCF$) as follows:

$$FCDCF = 2.03\ \mu\ \mu_a \sigma_{av}^2 (I_1 + kI_2) \quad (2\text{-}3)$$

where

μ_a = the energy absorption coefficient for air, m^{-1},
k = $(\mu - \mu_a)/\mu_a$, unitless.

To provide illustrative results, Healy [2][3] assumes the cloud is composed of radionuclides emitting 0.7-MeV gamma photons, with $\mu = 9.7 \times 10^{-3}\ m^{-1}$ and $\mu_a = 3.8 \times 10^{-3}\ m^{-1}$. Healy [2][3] provides a figure showing $FCDCF$ results using equations (2-1), (2-2), and (2-3) and the properties of 0.7-MeV gamma photons, reproduced in Figure 2-2. Values of $FCDCF$ are shown on a log-based scale for the cloud center (y = 0) and at various distances from the center of the cloud in units of plume size (measured by standard deviations, e.g. y = σ, y = 2σ, etc.) for various plume sizes on a log-based scale in Figure 2-2.

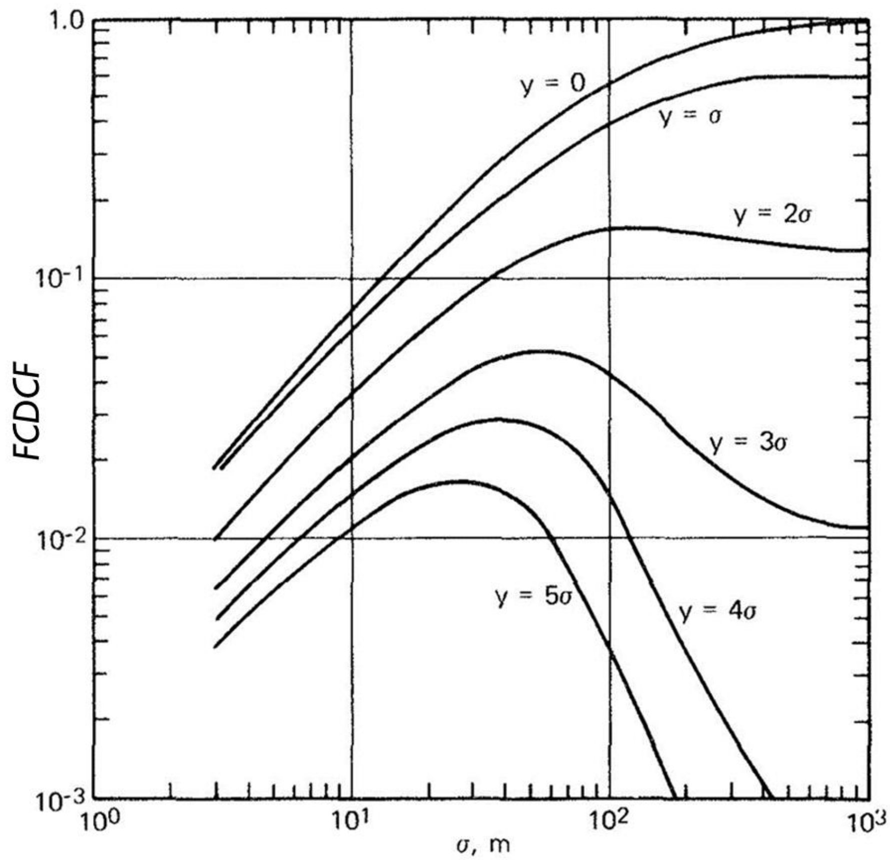

Figure 2-2. Ratio of gamma dose in a finite cloud to the gamma dose to an infinite cloud for 0.7-MeV gamma rays (Figure 16.10 from Healy [3])

One of the trends shown in Figure 2-2 is increasing $FCDCF$ values with increasing plume size for the cloud center (y = 0) and one effective plume size away from the center (y = σ). The other four curves reach a maximum between an effective plume size of 20 m to 200 m and then decrease. The y = 0, y = σ, y = 2σ, and y = 3σ curves appear to plateau near a 1,000 m effective plume size. A plateau is not shown for the y = 4σ and y = 5σ curves, most likely due to the lower bound of 0.001 in the figure. Another trend shown is that the $FCDCF$ values decrease with increasing relative distance to the cloud center at all effective plume sizes.

Healy [2][3] noted that as the effective plume size increases to ~1,000 m or larger, the $FCDCF$ value is "reasonably described by using the Gaussian function". The values from the Gaussian function for each relative distance in Table 1-1 are shown in Table 2-1. These values are within 10% of the values for the largest effective plume sizes (1,000 m) in Table 1-1, except for y = 4σ and y = 5σ, since they are fixed to the 0.001 lower bound.

Table 2-1. Gaussian function versus sigma

Number of σ from Center	Gaussian Function
0	1.0E+00
1	6.1E-01
2	1.4E-01
3	1.1E-02
4	3.4E-04
5	3.7E-06

For use in WASH-1400 [1], the values of $FCDCF$ were extracted from the 1968 version of Figure 2-2 (Figure 7.14 from Healy [2]) at the six relative distances to the cloud center (y = 0, y = σ, y = 2σ, y = 3σ, y = 4σ, and y = 5σ) shown in the figure and at nine selected plume sizes (3 m, 10 m, 20 m, 30 m, 50 m, 100 m, 200 m, 400 m and 1,000 m) as shown in Table 1-1. A graphical comparison of the $FCDCF$ values in Table 1-1 with Figure 2-2 is shown in Figure 2-3. As seen in Figure 2-3, the extracted data points used in WASH-1400 (Table 1-1) follow the curves in the figure with minor deviations at some locations.

The values of $FCDCF$ in Table 1-1 were rounded to the nearest thousandth, with a lower bound value of 0.001 in WASH-1400 [1]. The maximum effective plume size in the table is 1,000 m and the largest relative distance to the cloud center is five times the effective plume size. The $FCDCF$ values in Table 1-1 have been used in MACCS calculations up through version 4.0. Both limits can be exceeded in MACCS calculations.

An example of exceeding the effective plume size limit of Table 1-1 would be for MACCS calculations with unstable atmospheric conditions. Unstable atmospheric conditions enhance mixing, which increases both the horizontal and vertical dispersion of the plumes and can result in effective plume sizes larger than 1,000 m at distances as close as 10 km from the release location. Calculations with neutral or stable atmospheric conditions can also exceed effective plume sizes larger than 1,000 m, but at further distances downwind.

Releases at elevation in MACCS calculations can have receptors beyond the maximum relative distance to cloud center limit of Table 1-1 (five times the effective plume size). Near the release location and during reduced mixing/dispersion, the plume effective size can be small relative to the height of the center of the cloud. Accounting for the additional off-center distance for some receptors can result in relative distances to the cloud center greater than the limit of Table 1-1 (five times the effective plume size). The relative distance decreases as the plume increases in effective size.

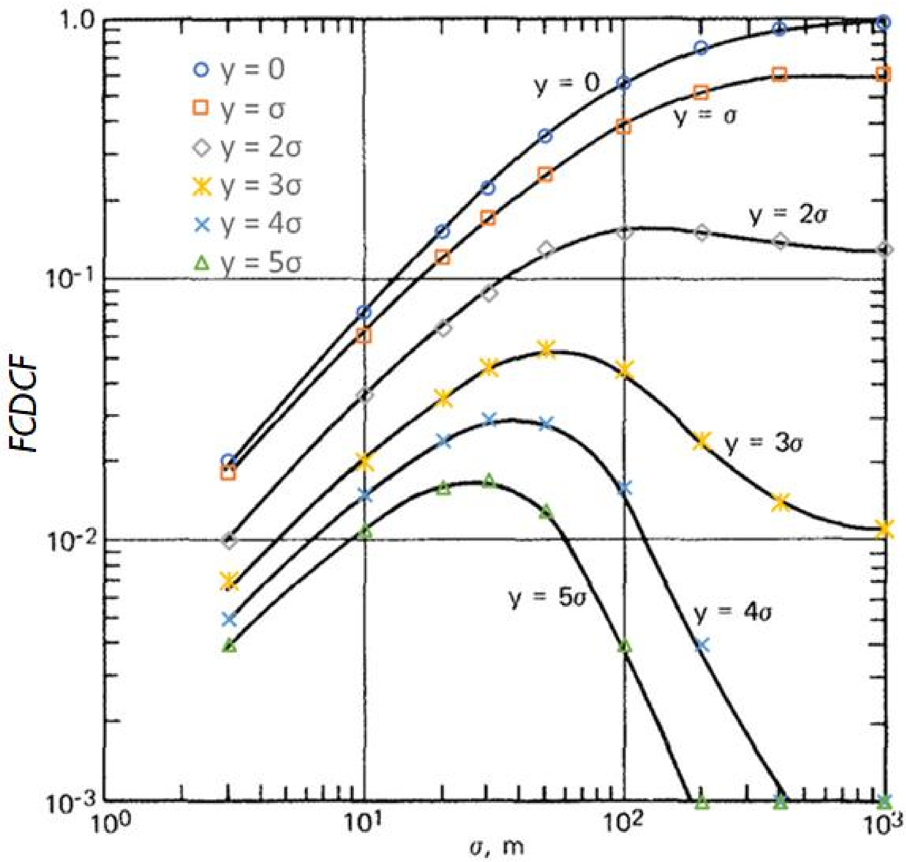

Figure 2-3. Comparison of $FCDCF$ values between Table 1-1 and Figure 2-2

When the bounds of Table 1-1 are exceeded, the recommendation in WASH-1400 [1] is to not extrapolate, but rather to interpolate at the edge of the table. This results in the following two conditions.

- When the effective plume size is greater than 1,000 m, the $FCDCF$ values for 1,000 m are used in the interpolation across relative distances to the cloud center.
- When the relative distance to the cloud center is greater than five times the effective plume size, the $FCDCF$ values for five times the effective plume size are used in the interpolation across effective plume size.

The combination of these two conditions and the values in Table 1-1 result in a maximum value for the $FCDCF$ of 0.951 and a minimum value of 0.001. This range of $FCDCF$ values may underestimate the cloudshine dose for effective plume sizes greater than 1,000 m and near the center of the cloud while overestimating the dose far from the cloud center. This underestimation and/or overestimation could potentially skew analyses from reality. An expanded table of finite cloud dose correction factors would reduce the possibility of using interpolation at the edge of the table during MACCS calculations, reducing the possibility of skewing analysis results.

3. EXPANDED TABLE GENERATION

To develop an expanded table of finite cloud dose correction factors, the formulations presented by Healy [2][3] were used and were structured into a Matlab® function format. The Matlab functions were used to determine the finite cloud dose correction factor for each combination of effective plume size and relative distance to the cloud center in the expanded table. The Matlab file used to generate the expanded table is repeated in Appendix A. Some of the specific implementation details used by Healy were not apparent in the original formulations. Hence, simplifications and assumptions were made while implementing the formulations into the Matlab function format and they are discussed below.

In the Healy formulations [2][3], values of $(I_1 + kI_2)$ are combined as a single term, I_T. For this analysis, the calculation of the total geometric factor (I_T) was implemented as a single Matlab function. This helped to simplify the calculation with the added benefit of reducing the computational time needed for each calculation. The I_T was defined by combining equations (2-1) and (2-2) with the definition of I_T as follows:

$$I_T = (I_1 + kI_2)$$

$$= \frac{\bar{u}}{4(2\pi)^{1/2}\mu\sigma_{av}} \int_0^{\infty}\int_0^{\infty} (1 + k\mu r)\frac{exp(-\mu r)}{mr}\left\{exp\left[\frac{-(m-r)^2}{2\sigma_{av}^2}\right] - exp\left[\frac{-(m+r)^2}{2\sigma_{av}^2}\right]\right\} dr\, dt \qquad (3\text{-}1)$$

The results of equation (3-1) is then used in equation (2-3) to determine the finite cloud dose correction factor. Apart from m, the variables inside the double integral are treated as constants, with respect to r and t, for each effective plume size and relative distance to the cloud center. The variable m was implemented as a Matlab function instead of a constant value as it varies with time.

As defined above in Figure 2-1, m is the total distance from the receptor to the cloud center.

$$m = \sqrt{(x_1 - \bar{u}t)^2 + y_1^2 + h^2} \qquad (3\text{-}2)$$

The three terms in equation (3-2) represent the downwind, crosswind and vertical distances between the receptor and cloud center, respectively. The downwind distance is a function of the receptor location. The receptor location was treated as on the ground (z=0) with the combination of the crosswind and vertical distances from the cloud assumed to be equal to the off-centerline distance. The off-centerline distance (s) is calculated by multiplying the relative distance to the cloud center ($\sqrt{y^2 + z^2}/\sqrt{\sigma_y\sigma_z}$) and the effective plume size ($\sqrt{\sigma_y\sigma_z}$).

The receptor downwind location is assumed to be at a distance applicable to the effective plume size. This assumption is based on the concept that smaller plume sizes are more applicable to close-in receptors, while larger plume sizes are more applicable to receptors further downwind. Approximations to the original Pasquill-Gifford dispersion curves expressed as power law fits have been provided by Eimutis and Konicek [4] in the form:

$$\sigma_y = A_y \cdot x^{B_y} + C_y \qquad (3\text{-}3)$$

$$\sigma_z = A_z \cdot x^{B_z} + C_z \qquad (3\text{-}4)$$

where

A_y, B_y, and C_y = the crosswind dispersion power law coefficients,
A_z, B_z, and C_z = the vertical dispersion power law coefficients.

Equations (3-3) and (3-4) were implemented into Matlab functions, along with the definition of the effective plume size. The combination of these functions is solved to determine the downwind distance that would correspond to the effective plume size and the downwind receptor location is then used in equation (3-2).

Eimutis and Konicek [4] provide dispersion coefficients for different atmospheric stability classes. During the initial evaluations of the expanded table, a sensitivity study of the $FCDCF$ values to the stability class specific dispersion coefficients was conducted and found that differences in the individual values were <10% for effective plume sizes greater than 20 m or relative distances to the cloud center less than 10σ between evaluations assuming neutral stability (Pasquill-Gifford stability class D) and stable conditions (Pasquill-Gifford stability class F). Larger differences (still <20%) were observed for the combination of small effective plume sizes (<20 m) and larger relative distances (>10σ). This indicates that the $FCDCF$ values are relatively insensitive to the assumption of stability class. The dispersion parameters for neutral stability (Pasquill-Gifford stability class D) were used in the expanded table generation.

The downwind distance in equation (3-2) is also a function of the cloud average velocity ($\bar{u}$). During the initial evaluations of the expanded table, a sensitivity study of the $FCDCF$ values to the value assumed for the cloud average velocity was conducted and found that differences in the individual values were <1% for effective plume sizes greater than 3 m or relative distances to the cloud center less than 20σ with the cloud average velocity ranging from 1 to 100 m/s. Larger differences (still <10%) were observed for the combination of small effective plume sizes (<3 m) and larger relative distances (>20 σ). This indicates that the $FCDCF$ values are relatively insensitive to the value used for the cloud average velocity.

The numerical integration scheme used in Matlab was not able to converge on a $FCDCF$ value with all variations of cloud average velocity or tolerance parameters at larger effective plume sizes (>1,000 m). Most of the $FCDCF$ values were generated assuming a cloud average velocity of 10 m/s and the tolerance parameters shown in Appendix A. $FCDCF$ values generated using other combinations of cloud average velocity and tolerance parameters were used when convergence was not achieved with the parameters above.

An expanded table of $FCDCF$ values was generated by using the Matlab functions and assumptions discussed above to determine the factor for each value of effective plume size and relative distance to the cloud centerline. The $FCDCF$ values are shown on a log-based scale in Figure 3-1 and in tabular form in Table 3-1. The expanded table has an increased resolution and range of effective plume sizes, with 25 discrete values between 1 m and 10,000 m and an increased range of relative distances to the cloud center, with 14 discrete values between 0 and 100 effective plume sizes. To align with the WASH-1400 values and accounting for the sensitivities discussed above, only two significant figures are reported in the table and a value of 1.0E-6 is used as a lower bound.

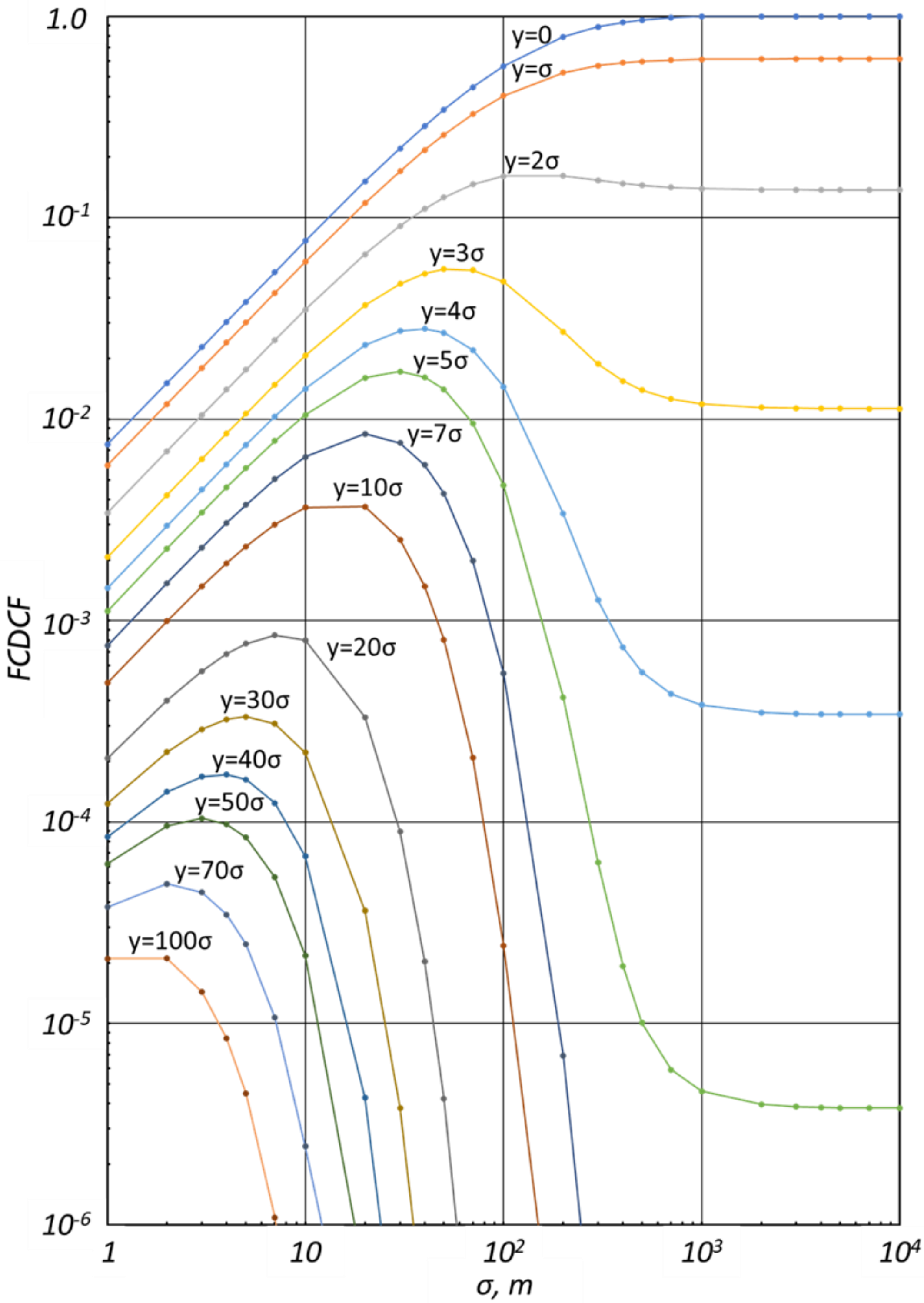

Figure 3-1. Finite cloud dose correction factors versus effective plume size for various relative distances to the cloud center

Table 3-1. Expanded table of finite cloud dose correction factors

Effective Plume Size, $\sqrt{\sigma_y \sigma_z}$ [m]	Distance to Cloud Center Relative to the Effective Plume Size, $\frac{\sqrt{y^2+z^2}}{\sqrt{\sigma_y \sigma_z}}$ [unitless]													
	0	**1**	**2**	**3**	**4**	**5**	**7**	**10**	**20**	**30**	**40**	**50**	**70**	**100**
1	7.5E-3	5.9E-3	3.4E-3	2.1E-3	1.4E-3	1.1E-3	7.5E-4	4.9E-4	2.1E-4	1.2E-4	8.4E-5	6.2E-5	3.8E-5	2.1E-5
2	1.5E-2	1.2E-2	6.9E-3	4.2E-3	3.0E-3	2.3E-3	1.5E-3	9.9E-4	4.0E-4	2.2E-4	1.4E-4	9.6E-5	4.9E-5	2.1E-5
3	2.3E-2	1.8E-2	1.0E-2	6.4E-3	4.5E-3	3.4E-3	2.3E-3	1.5E-3	5.6E-4	2.9E-4	1.7E-4	1.0E-4	4.5E-5	1.4E-5
4	3.0E-2	2.4E-2	1.4E-2	8.5E-3	6.0E-3	4.6E-3	3.1E-3	1.9E-3	6.8E-4	3.2E-4	1.7E-4	9.7E-5	3.5E-5	8.4E-6
5	3.8E-2	3.0E-2	1.8E-2	1.1E-2	7.5E-3	5.7E-3	3.8E-3	2.3E-3	7.7E-4	3.3E-4	1.6E-4	8.4E-5	2.5E-5	4.5E-6
7	5.4E-2	4.2E-2	2.5E-2	1.5E-2	1.0E-2	7.8E-3	5.0E-3	3.0E-3	8.4E-4	3.1E-4	1.2E-4	5.3E-5	1.1E-5	1.1E-6
10	7.7E-2	6.0E-2	3.5E-2	2.1E-2	1.4E-2	1.0E-2	6.5E-3	3.6E-3	8.0E-4	2.2E-4	6.7E-5	2.2E-5	2.5E-6	1.0E-6
20	1.5E-1	1.2E-1	6.6E-2	3.7E-2	2.3E-2	1.6E-2	8.5E-3	3.7E-3	3.3E-4	3.6E-5	4.3E-6	1.0E-6	1.0E-6	1.0E-6
30	2.2E-1	1.7E-1	9.1E-2	4.7E-2	2.7E-2	1.7E-2	7.6E-3	2.5E-3	9.0E-5	3.8E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6
40	2.9E-1	2.2E-1	1.1E-1	5.3E-2	2.8E-2	1.6E-2	5.9E-3	1.5E-3	2.0E-5	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6
50	3.4E-1	2.6E-1	1.3E-1	5.6E-2	2.7E-2	1.4E-2	4.3E-3	8.0E-4	4.2E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6
70	4.5E-1	3.3E-1	1.5E-1	5.5E-2	2.2E-2	9.5E-3	2.0E-3	2.1E-4	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6
100	5.7E-1	4.0E-1	1.6E-1	4.8E-2	1.4E-2	4.7E-3	5.5E-4	2.4E-5	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6
200	7.9E-1	5.3E-1	1.6E-1	2.7E-2	3.4E-3	4.1E-4	6.9E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6
300	8.9E-1	5.7E-1	1.5E-1	1.9E-2	1.3E-3	6.3E-5	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6
400	9.3E-1	5.9E-1	1.5E-1	1.5E-2	7.4E-4	1.9E-5	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6
500	9.6E-1	6.0E-1	1.4E-1	1.4E-2	5.5E-4	1.0E-5	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6
700	9.8E-1	6.1E-1	1.4E-1	1.3E-2	4.3E-4	5.9E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6
1,000	1.0E+0	6.1E-1	1.4E-1	1.2E-2	3.8E-4	4.6E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6
2,000	1.0E+0	6.1E-1	1.4E-1	1.1E-2	3.5E-4	4.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6
3,000	1.0E+0	6.2E-1	1.4E-1	1.1E-2	3.4E-4	3.9E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6
4,000	1.0E+0	6.2E-1	1.4E-1	1.1E-2	3.4E-4	3.8E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6
5,000	1.0E+0	6.2E-1	1.4E-1	1.1E-2	3.4E-4	3.8E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6
7,000	1.0E+0	6.2E-1	1.4E-1	1.1E-2	3.4E-4	3.8E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6
10,000	1.0E+0	6.2E-1	1.4E-1	1.1E-2	3.4E-4	3.8E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6	1.0E-6

A comparison between the $FCDCF$ values in Table 3-1 and the illustrative results provided by Healy [2][3], reproduced in Figure 2-2, was made to verify the implementation and is shown in Figure 3-2. As seen in Figure 3-2, the $FCDCF$ values in Table 3-1 follow the curves in the figure with minor deviations at some locations. The differences likely arise from the differences in assumptions and numerical integration. Furthermore, the values from the Gaussian function for each relative distance shown in Table 2-1 were compared with the $FCDCF$ values for the largest effective plume sizes (10,000 m) in Table 3-1. The Gaussian function values are within 3% of the $FCDCF$ values at 10,000 m in Table 3-1 for relative distances of 5σ or less. The values for 7σ or higher are limited by the 1.0E-6 lower bound and are not compared. Based on these comparisons, the Healy formulations for determining the finite cloud dose correction factors appear to be correctly implemented.

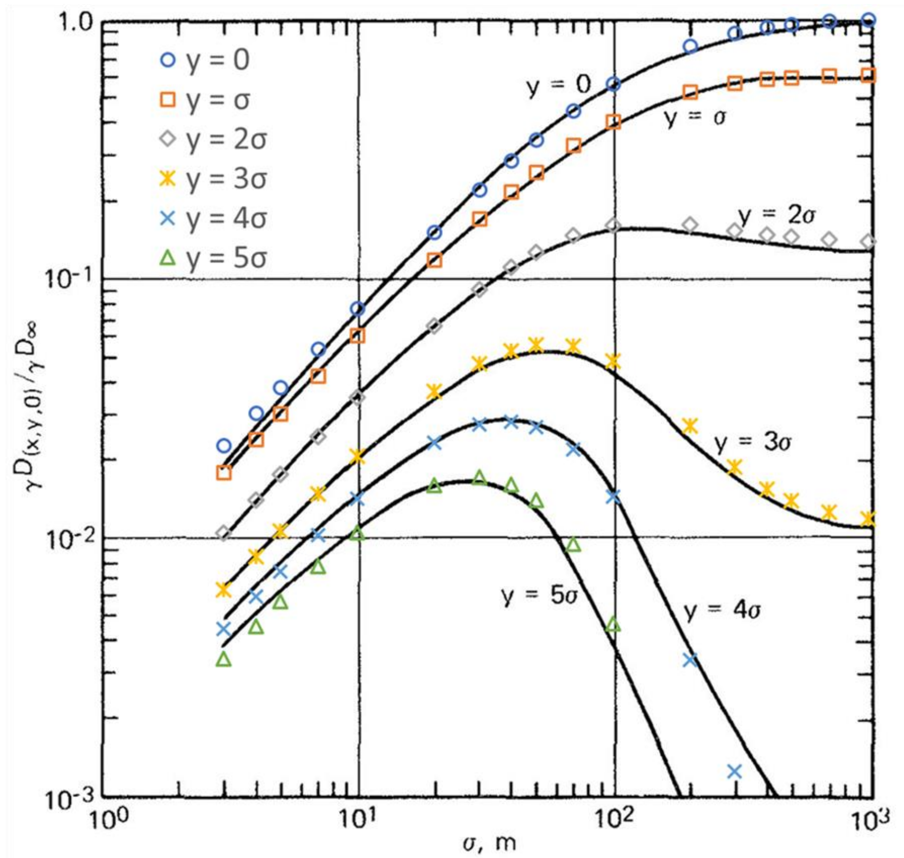

Figure 3-2. Comparison of $FCDCF$ values between Table 3-1 and Figure 2-2

When the bounds of Table 3-1 are exceeded, it is still recommended to not extrapolate, but rather to interpolate at the edge of the table. This results in the following two conditions.

- When the effective plume size is greater than 10,000 m, the $FCDCF$ values for 10,000 m are used in the interpolation across relative distances to the cloud center.
- When the relative distance to the cloud center is greater than 100 times the effective plume size, the $FCDCF$ values for 100 times the effective plume size are used in the interpolation across effective plume size.

The combination of these two conditions and the values in Table 3-1 result in a maximum value for the $FCDCF$ of 1.0 and a minimum value of 1.0E-6. As the curves in Figure 3-1 plateau at effective plume sizes of 10,000 m, the impact of interpolating at the edge of the table for larger effective plume sizes is expected to be negligible. This range of $FCDCF$ values may still overestimate the dose far from the cloud center due to the lower bound, but this is now three orders of magnitude lower than the value used in the WASH-1400 table (1.0E-6 versus 0.001). It is expected that using the expanded table of finite cloud dose correction factors will significantly reduce the possibility of using interpolation at the edge of the table during MACCS calculations and when the table edge interpolation is used, the effect on the cloudshine dose calculations would be negligible. This then reduces the possibility of skewing analysis results.

4. SUMMARY

In WASH-1400, external exposure from the finite radioactive cloud (cloudshine) is calculated by assuming that the cloud is semi-infinite, the concentration of radioactive material is uniform, and by using a correction factor to account for these approximations. This correction factor is originally based upon formulations by Healy [2] and depends on the effective size of the plume and the distance from the plume center to the receptor. The range of the table can be exceeded in certain situations. When the range of the table is exceeded, no extrapolation is performed; rather interpolation at the edge of the table is performed per WASH-1400 [1]. The tabulated values of these finite cloud dose correction factors from WASH-1400 [1] and the interpolation at the edge of the table have been used in MACCS since its creation.

The $FCDCF$ values combined with the range of the table from WASH-1400 may underestimate the cloudshine dose for effective plume sizes greater than 1,000 m and near the center of the cloud while overestimating the dose far from the cloud center. Hence, there is a potential to skew analyses from reality. An expanded table of finite cloud dose correction factors would reduce the possibility of using interpolation at the edge of the table during MACCS calculations, reducing the possibility of skewing analysis results.

An expanded table of finite cloud dose correction factors was developed using the formulations presented by Healy [2][3] and is provided in Table 3-1. The formulations were structured into a Matlab® function format and were used to determine the finite cloud dose correction factor for each combination of effective plume size and relative distance to the cloud center in the expanded table. It is expected that using the expanded table of finite cloud dose correction factors will significantly reduce the possibility of using interpolation at the edge of the table during MACCS calculations. When the table edge interpolation is used, the effect on the cloudshine dose calculations would be negligible, thus reducing the possibility of skewing analysis results.

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[1] U.S. Nuclear Regulatory Commission, "Reactor Safety Study: Appendix VI (NUREG-75/014; WASH-1400)," U.S. Nuclear Regulatory Commission, Washington, DC, 1975.

[2] Healy, J. W., "Radioactive Cloud Dose Calculations," Meteorology and Atomic Energy, D. Slade Editor, U.S. Atomic Energy Commission, Washington, DC, TID-24190, 1968.

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[4] E.C. Eimutis, M.G. Konicek, 1972, "Derivations of Continuous Functions for the Lateral and Vertical Atmospheric Dispersion Coefficients," **Atmospheric Environment 6**, 859-863.

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APPENDIX A. MATLAB FILE

Below is the Matlab® file used to generate the expanded table of finite cloud correction factors.

```
sig2 = [1.,2.,3.,4.,5.,7.,10.,20.,30.,40.,50.,70.,100.,200.,300.,400.,500.,700.,...
   1000.,2000.,3000.,4000.,5000.,7000.,10000.];
sf2 = [0.,1.,2.,3.,4.,5.,7.,10.,20.,30.,40.,50.,70.,100.];

results = zeros(25,14);
format shortE

for c = 1:14
   for r = 1:25
      results(r,c) = cldfactor(sig2(r),sf2(c));
   end
end
results

function y = cldfactor(sigma, sfac)
   mu = 9.7e-3;
   mua = 3.8e-3;
   k = (mu-mua)/mua;

   ubar = 10;

   function y = sigy(dist, c_y)
      y = c_y(1)*dist^c_y(2)+c_y(3);
   end

   function y = sigz(dist, c_z1, c_z2, c_z3)
      if dist <= 100
         y = c_z1(1)*dist^c_z1(2)+c_z1(3);
      elseif dist <= 1000
         y = c_z2(1)*dist^c_z2(2)+c_z2(3);
      else
         y = c_z3(1)*dist^c_z3(2)+c_z3(3);
      end
   end

   function y = dist_sol(dist, sig)
      Dy1 = [0.1471, 0.9031, 0]; %using D stability function for sigmaY (E&K)
      Dz1 = [0.079, 0.881, 0]; %using D stability function for sigmaZ <100 m (E&K)
      Dz2 = [0.222, 0.725, -1.70]; %using D stability function for sigmaZ 100-1000 m (E&K)
      Dz3 = [1.26, 0.516, -13.0]; %using D stability function for sigmaZ >1000 m (E&K)
      y = (sigy(dist, Dy1).*sigz(dist, Dz1, Dz2, Dz3)) - sig.^2;
   end

   fun_dist = @(dist) dist_sol(dist, sigma);
```

```
    x = fzero(fun_dist,[0,1e6*sigma]);

    s = sfac * sigma;

    m = @(t) ((ubar*t - x).^2 + s^2).^0.5;

    fun_IT = @(r,t) (1+k*mu.*r).*(exp(-mu.*r)./(m(t).*r).*...
        (exp(-((m(t)-r)/sigma).^2/2.)-exp(-((m(t)+r)/sigma).^2/2.)));

    double_IT = integral2(fun_IT,0,inf,0,inf,'AbsTol',0,'Reltol',1e-7);

    IT = ubar/(4.*(2.*pi)^0.5*mu*sigma)*double_IT;

    y = min(max(2.03*mu*mua*sigma^2*IT,0.),1.);
end
```

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