Comparative Analysis of Near-Field Atmospheric Dispersion Models for Nuclear Emergency Planning Zone Sizing

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1. Introduction

Emergency Planning Zones (EPZs) are predefined areas around nuclear power plants within which emergency preparedness and protective actions are planned to protect the public from accidental radioactive releases. For large light water reactors (LWRs), U.S. regulations have historically adopted a plume exposure pathway EPZ of about 10 miles and an ingestion pathway EPZ of about 50 miles, based on NUREG-0396 and associated Environmental Protection Agency (EPZ) Protective Action Guides (PAGs) [1, 2].

Advanced reactors, including Small Modular Reactors (SMRs) and non-LWRs, pursue reduced EPZ sizes by leveraging lower thermal power, enhanced safety features, and reduced source terms compared with existing large LWRs. Minimizing EPZs is important for siting flexibility near population centers, public acceptance of urban or semi-urban deployment, and improved project economics.

EPZ sizing requires the following sequential analyses: (1) event selection, (2) source term evaluation, (3) atmospheric dispersion assessment, and (4) dose assessment. From an EPZ reduction perspective, a more detailed assessment of near-field atmospheric dispersion is of particular importance.

This paper presents a comparative analysis of several near-field atmospheric dispersion models focusing on how model choice influences EPZ sizing. The study compares a basic Gaussian plume model, the Regulatory Guide (RG) 1.145-based model, and the Ramsdell and Fosmire (RAF) model, and evaluates their impact on calculated doses and resulting EPZ radii under generic assumptions.

2. Emergency Planning Zone Methodologies

NUREG-0396 established the technical basis for the current U.S. EPZ concept and recommended a 10-mile plume exposure pathway EPZ and a 50-mile ingestion pathway EPZ for large LWRs [1]. The sizing rationale considers a spectrum of accidents, including design-basis accidents (DBAs), “less-severe” severe accidents, and “more-severe” beyond-design-basis accidents, and identifies distances at which PAGs may be exceeded or early fatal health effects can be substantially reduced. For the plume exposure pathway, the early-phase EPA PAG for sheltering and evacuation is defined as an effective dose range of 1–5 rem (10–50 mSv) over four days, which forms the reference range for EPZ evaluations.

NUREG-0396 explicitly distinguishes between the plume exposure pathway and the ingestion exposure pathway. Historically, these considerations led to the generic 10-mile plume EPZ and 50-mile ingestion EPZ.

For SMRs and other new technologies, the NRC has promulgated 10 CFR 50.160 and issued RG 1.242 to provide a performance-based framework for EPZ sizing [3]. RG 1.242 generalizes the NUREG-0396 methodology and describes acceptable approaches for event selection, source term definition, meteorological input, and atmospheric transport and dispersion modeling, including the explicit requirement to identify an approach that accounts for near-field effects in atmospheric transport. For SMRs and non-LWRs, the NRC has concluded that a dedicated ingestion EPZ is not necessary because of improvements in logistics, monitoring, and understanding of the food chain, so only the plume exposure pathway EPZ is typically considered.

In this regulatory context, EPZ sizing for advanced reactors is shifting from fixed distances toward consequence-oriented criteria based on plant-specific severe accident analyses and probabilistic dose aggregation, as reflected in RG 1.242 appendices and industry guidance such as NEI 24-05 [4]. This shift increases the importance of realistically modeling atmospheric dispersion, particularly in the near field, because over-conservative dispersion assumptions may negate the safety benefits of smaller source terms when determining EPZ radii.

3. Near-Field Atmospheric Dispersion Models

3.1 Gaussian plume formulation

The representative atmospheric dispersion model is the Gaussian plume model. For a steady, ground-level release of activity Q (Bq/s) in homogeneous conditions, the time-averaged concentration $C(x, y, z)$ at a location with downwind distance x, crosswind offset y, and height z is typically expressed as

$$C(x,y,z) = \frac{Q}{2\pi u \sigma_y(x)\sigma_z(x)} * \exp(-\frac{y^2}{2\sigma_y(x)^2}) * [\exp\left(-\frac{z^2}{2\sigma_z(x)^2}\right)) + \exp\left(-\frac{(z+2H)^2}{2\sigma_z(x)^2}\right)],$$

where u is wind speed at reference height, $\sigma_y(x)$ and $\sigma_z(x)$ are horizontal and vertical dispersion parameters, and H is effective release height. Centerline concentrations and normalized air concentrations χ/Q are directly proportional to the combination $\frac{1}{u\sigma_y\sigma_z}$.

In the Gaussian framework, dispersion in the near field is controlled primarily by the parameterization of σ_y and σ_z, which are usually derived from empirical diffusion curves such as the Pasquill–Gifford relationships. Near-field enhancement or reduction of dispersion is implemented as a modification of σ_y and σ_z.

3.2 Near-field effects and correction approaches

Two of the most important phenomena in near-field atmospheric dispersion are plume meander and building wake effects [5].

- *Plume meander*: Under low wind speed and stable conditions, the plume centerline wanders in direction over the averaging interval, resulting in a broader lateral plume spread and increasing crosswind dispersion relative to Pasquill–Gifford expectations; this tends to reduce centerline concentrations.
- *Building wake*: Flow separation and turbulence in the downwind of buildings produce enhanced mixing within a wake cavity whose dimensions scale with building height and width; this can significantly increase σ_y and σ_z, again reducing centerline concentrations.

The representative near-field models considering the meander and building wake effects are RG 1.145-based model, and the Ramsdell and Fosmire (RAF) model

3.3 RG 1.145-based near-field model

RG 1.145 introduces equations for calculating normalized concentration χ/Q at the plume centerline considering plume meander and building wake [6].

Two equations include building wake effects: one adds an effective building cross-sectional area term $A/2$ to $2\pi\sigma_y\sigma_z$, while another imposes an upper limit on wake credit by capping the enhancement to a factor of three.

The third equation accounts for plume meander by replacing σ_y with $\sigma_{y,m} = M\sigma_y$, where the meander factor M depends on stability class and wind speed, with full credit at wind speeds below 2 m/s and diminishing credit up to 6 m/s.

MACCS implements an RG 1.145 meander model that combines building wake and meander terms through crosswind meander factors. The crosswind dispersion with meander, $\sigma_{y,m}(x)$, is defined as

$$\sigma_{y,m}(x) = \max\left[\min\left(f_{y,m1}, f_{y,m2}\right), f_{y,m3}\right]\sigma_y(x),$$

where $f_{y,m1}$ captures building-wake-induced mixing, $f_{y,m2}$ enforces an upper limit to that wake credit, and $f_{y,m3}$ is the RG 1.145 meander factor dependent on stability class and wind speed. The model assumes that enhanced meander is active over the first several hundred meters and then transitions back to standard Gaussian dispersion.

3.4 Ramsdell and Fosmire (RAF) model

The Ramsdell and Fosmire model was developed to represent low-wind plume meander and building-wake-enhanced dispersion using a more physically motivated, turbulence-based formulation [7]. In this approach, the standard Gaussian dispersion coefficients $\sigma_y(x)$ and $\sigma_z(x)$ are combined with additional low-wind and high-wind contributions to yield composite dispersion parameters $\Sigma(x)$:

$$\Sigma(x) = [\sigma_0(x)^2 + \Delta\sigma_1(x)^2 + \Delta\sigma_2(x)^2]^{1/2},$$

where the subscripts for lateral and vertical components are implicit. The additional terms are functions of turbulence intensity, time scales, and building cross-sectional area, and are parameterized separately for low-wind meander and high-wind wake effects. RAF parameters were tuned using a set of tracer experiments covering distances from about 6 m to 1200 m and a range of stability and wind conditions.

4. Comparative Analysis

4.1 Analysis framework and assumptions

To quantify the influence of near-field dispersion models on EPZ sizing, a comparative analysis was performed using MACCS [8]. The objective was to examine how different dispersion treatments affect dose–distance profiles and the EPZ radius for a fixed dose criterion relevant to EPZ sizing for advanced reactors.

The following generic assumptions were adopted for the EPZ evaluation:

- Plant and site representation: The analysis does not specify a particular reactor design or site; Most input parameters are based on a MACCS sample problem.
- Accident category and dose criterion: A DBA category release is assumed, and the EPZ sizing dose criterion is set to 0.01 Sv total effective dose equivalent (TEDE) over 96 hours under average meteorological conditions.
- Radionuclides: The analysis focuses on I-131 and Cs-137 as representative radionuclides important for EPZ and safety analyses. I-131 is dominant in early phase thyroid and whole-body dose, while Cs-137 contributes more to longer-term external exposure from ground deposition; the cases are treated as single-nuclide releases for analytical clarity.

- Release amount: For each nuclide, total release amounts (Q) were varied over a broad range from 10^{13} to 10^{17} Bq, representing a sensitivity analysis rather than a plant-specific source term. A one-hour release duration is assumed.
- Meteorology and dispersion coefficients: MACCS default example meteorological data were used, and dispersion coefficients were computed using the Eimutis–Konicek table data [9].
- Dose coefficients: Dose conversion factors were taken from FGR-13.

Table 1. Summary of Input Parameters and Assumptions for EPZ Evaluation

Parameter	Value / Description
Distance [km]	0.05-10
Radionuclides	I-131, Cs-137
Release amount [Bq]	10^{13}, 10^{14}, 10^{15}, 10^{16}, 10^{17}
Number of plumes	1
Plume duration [s]	3600
Meteorological dataset	MACCS example data
Dispersion coefficient	Eimutis-Konicek table data
Surface roughness [cm]	10
Building height/width [m]	50/50
Dose coefficient	FGR-13
Dispersion model	Basic, RG 1.145, RAF

For the basic model, a building-wake-based area source representation was used only at release point ($x = 0$), while the RG 1.145 and RAF models used point-source.

4.2 Dose–distance behavior and model comparison

For fixed source term and meteorology, the calculated dose at a given distance is proportional to the χ/Q, which in turn is strongly influenced by the crosswind and vertical dispersion parameters. Figures 1 and 2 present the dose-distance profiles for the three models, assuming a 10^{15} Bq release of I-131 and Cs-137, respectively.

Under the assumptions above, several consistent patterns emerge from the comparisons.

First, for a given release, I-131 cases produce higher TEDE values than Cs-137 cases in the 96-hour early phase because I-131 contributes strongly to inhalation and thyroid dose during the initial days following release, whereas Cs-137's dominant pathway is longer-term external exposure that is not fully expressed within 96 hours. Consequently, for the same Q, I-131 cases yield larger EPZ radii than Cs-137 cases under the 0.01 Sv/96 h TEDE criterion.

Second, the relative behavior of the three dispersion models with respect to distance can be summarized qualitatively as follows:

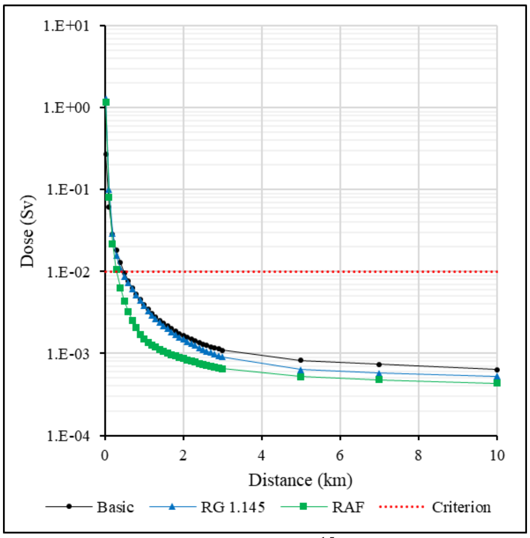

Fig. 1. Dose-distance profile for a 10^{15} Bq release of I-131

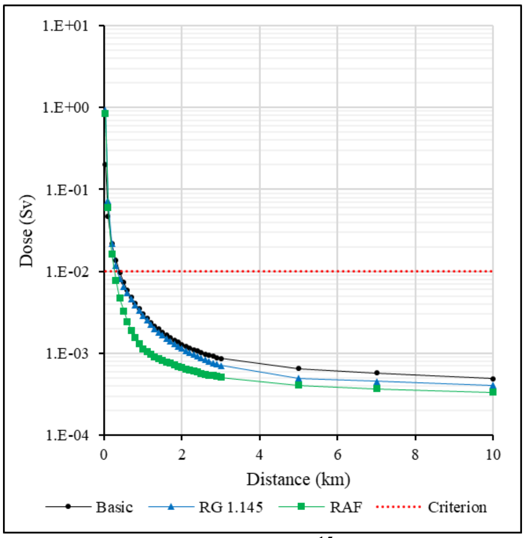

Fig. 2. Dose-distance profile for a 10^{15} Bq release of Cs-137

- In the very near field, the basic model yields lower doses than the RG 1.145 and RAF, because the building-wake implementation in MACCS represents the release as an area source with significant initial plume spread, which leads to lower centerline concentrations immediately downwind compared with a point-source assumption.
- At intermediate distances (hundreds of meters to a few kilometers), both RG 1.145 and RAF introduce enhanced dispersion via meander and building wake terms, usually producing larger σ_y and σ_z and therefore lower centerline concentrations than the basic Gaussian model.
- As distance increases, the differences among models diminish, because the correction terms of RG 1.145 and RAF reach saturation and become negligible at greater distances.

4.3 EPZ radius as a function of release amount

The EPZ radii were determined via simple linear interpolation to identify the distance where the 0.01 Sv/96 h TEDE criterion is met. However, because concentration and dose decrease exponentially with distance, the actual EPZ radii may be shorter than the interpolated values. Figures 3 and 4 present the estimated EPZ radii as a function of release amount for I-131 and Cs-137, respectively, across the three models. Table 2 presents the EPZ radii as a function of release magnitude for each model, along with the reduction ratios of the RG 1.145 and RAF models relative to the Basic model.

At lower release magnitudes, e.g., $Q \leq 10^{13}$ Bq, the 0.01 Sv criterion is not exceeded at any distance for most cases, implying an EPZ radius of zero. At the upper end of the examined range, $Q \geq 10^{17}$ Bq, the 0.01 Sv threshold is exceeded at or beyond 10 km, indicating that, for such large releases, an EPZ radius larger than 10 km would be required regardless of near-field model selection.

In intermediate ranges of Q, the ordering of EPZ radii is broadly consistent: excluding the very near-source distance where the basic model's area-source representation gives lower doses, the EPZ radius is largest for the basic Gaussian model, smaller for the RG 1.145 model, and smallest for the RAF model in most cases. This reflects the fact that both RG 1.145 and RAF introduce additional lateral and vertical dispersion in the near field, reducing doses; RAF, which incorporates both low-wind meander and high-wind building wake more comprehensively, tends to yield larger dispersion than RG 1.145 and thus smaller EPZ radii

Table 2. EPZ radii [km] as a function of release amount for different dispersion models

Nuclide	Model	Release amount (Bq)				
		10^{13}	10^{14}	10^{15}	10^{16}	10^{17}
I-131	Basic	0.000	0.086	0.491	3.738	>10
	RG 1.145	0.043	0.100	0.446	2.768	>10
	Reduction (%)	<0	-16%	9%	26%	-
	RAF	0.036	0.099	0.312	1.644	>10
	Reduction (%)	<0	-14%	36%	56%	-
Cs-137	Basic	0.000	0.074	0.393	2.559	>10
	RG 1.145	0.000	0.098	0.349	2.238	>10
	Reduction (%)	-	-31%	11%	13%	-
	RAF	0.000	0.096	0.274	1.159	>10
	Reduction (%)	-	-29%	30%	55%	-

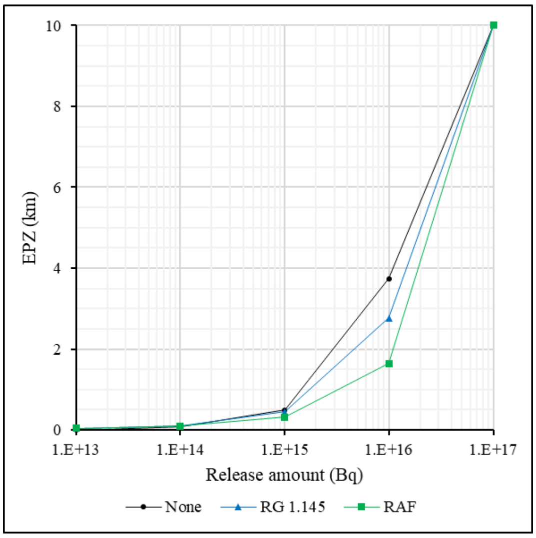

Fig. 3. EPZ radius as a function of I-131 release magnitude for different dispersion models

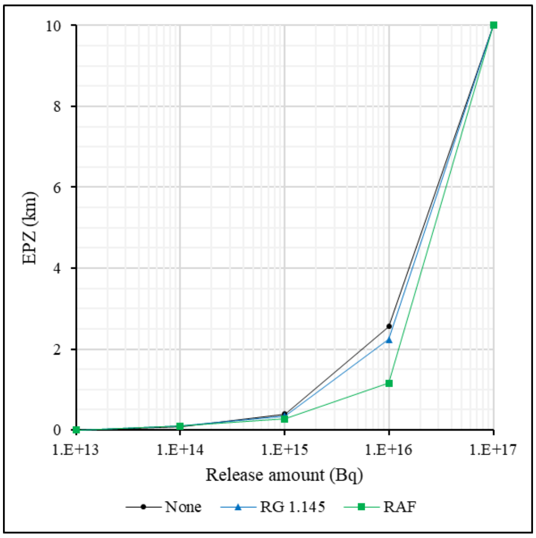

Fig. 4. EPZ radius as a function of Cs-137 release magnitude for different dispersion models

5. Conclusions

Advanced reactors, including SMRs and non-LWRs, seek to reduce EPZ sizes. In this context, near-field atmospheric dispersion modeling is important, because conservative assumptions may overestimate early-phase doses in the first few kilometers, thus limiting opportunities to reduce the EPZ radius despite inherently smaller source terms.

The comparative analysis using MACCS shows that, apart from specific very near-source effects related to building-wake area-source assumptions, the basic Gaussian model tends to yield higher doses and larger EPZ size than near-field models that account for plume meander and building wake effects. These findings suggest that explicitly modeling near-field meander and building-wake effects can help avoid overestimated dose predictions and support more realistic EPZ sizing for advanced reactors, consistent with the framework of 10 CFR 50.160 and RG 1.242.

Meanwhile, the present study relies on simplified source terms and generic meteorology; therefore, the presented EPZ values should be interpreted as illustrative, and the emphasis should be placed on the relative trends observed among dispersion models rather than on the absolute distances.

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