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A Sensitivity Analysis for Dose Exceedance Distances Using MACCS: Application to the OPR1000

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1. Introduction

The deployment of small modular reactors (SMRs) and other advanced nuclear reactor designs has renewed interest in revisiting the technical basis of emergency planning zones (EPZs). Although these designs incorporate enhanced passive safety features and simplified configurations that are expected to reduce accident frequency and consequences compared with conventional large light-water reactors, emergency preparedness remains a fundamental element of defense-in-depth. Traditional EPZ frameworks, developed using conservative distance-based criteria for large reactors, may not adequately reflect the risk profiles of SMRs. Recent regulatory developments, including 10 CFR 50.160 and Regulatory Guide 1.242, therefore permit performance-based and risk-informed EPZ sizing supported by realistic accident consequence analyses.

Mechanistic source term (MST)–based consequence assessments using the MELCOR Accident Consequence Code System (MACCS) provide a key analytical basis for such evaluations. However, predicted dose-exceedance distances are sensitive to assumptions related to source term characteristics, atmospheric dispersion, and emergency response parameters, particularly for low-dose criteria (e.g., 1–5 rem TEDE) [1]. This study investigates the sensitivity of dose-exceedance distances to major input parameters in the ATMOS and EARLY modules of MACCS using OPR1000 intact-containment scenarios. The results identify dominant modeling factors influencing EPZ evaluation and support the development of a robust performance-based emergency planning framework for SMRs and other advanced reactors.

2. Methods and Results

In this section, representative OPR1000 intact-containment scenarios are selected from Level 2 PSA results and a base-case MACCS model is established for the Hanul site. A discrete, one-parameter-at-a-time sensitivity framework is then defined and applied to quantify how key ATMOS and EARLY input assumptions influence 96-h effective-dose exceedance distances.

2.1 PSA-based Accident Scenario Selection

Level 2 PSA results for OPR-1000 full-power internal events were used to select representative accident scenarios for this study [2]. A total of 17 source term categories (STCs) were identified based on the combined Level 1 and Level 2 PSA results. Among them, STC1 and STC2, corresponding to no-containment-failure (NOCF) scenarios, account for approximately 59% of the total STC frequency and therefore represent the dominant contributors in terms of occurrence probability.

Although the containment remains intact in these categories, radionuclide releases are not strictly zero due to the assumed design leakage rate of 0.1 vol.%/day. To ensure conservative bounding of potential offsite consequences within these dominant categories, a largest-consequence approach was adopted for scenario selection. Accordingly, SBOR107-CET3 (STC1) and SBOR8–CET55 (STC2) were selected as representative accident scenarios for subsequent source term and sensitivity analyses, as summarized in Table I.

Table I: Representative Accident Scenarios Derived from the Level 2 PSA of the OPR1000.

Representative accident scenarios	Accident scenario explanation	Containment failure mode
SBOR107-CET3	Late Station Black out in which diesel generators fail to run	No Containment Failure(RV intact)
SBOR8-CET55	Late Station Black out in which diesel generators fail to run	No Containment Failure(RV rupture)

2.2 Base Case Definition for Sensitivity Analysis

2.2.1 ATMOS Module Configuration

In the base-case analysis, atmospheric transport and dispersion were modeled in the MACCS ATMOS module using the Gaussian plume formulation with a bounded vertical distribution. The plume release height (PLHITE) was obtained from the Level 2 source term analysis and set to 21.81 m. Initial lateral and vertical dispersion parameters (SIGYINIT and SIGZINIT), representing building wake effects, were estimated based on the containment building dimensions (width $W_b = 43.9\text{m}$ and height $H_b = 66.8\text{m}$) using Eq. (1):

$$\sigma_{y,init} = \frac{W_b}{4.3} \; and \; \sigma_{z,init} = \frac{H_b}{2.15} \qquad (1)$$

which yield $\sigma_{\mathrm{y,init}} = 10.2\text{m}$ and $\sigma_{\mathrm{z,init}} = 31.1\text{m}$.

Plume meander was modeled using the U.S. NRC Regulatory Guide 1.145 formulation (MNDMOD = NEW), consistent with the one-hour plume segment duration adopted in this study. Surface roughness effects were incorporated through the vertical dispersion scaling factor (ZSCALE), calculated using Eq. (2):

$$\text{ZSCALE} = (z_0/z_{0,\text{ref}})^{0.2} \tag{2}$$

where $z_{0,\text{ref}} = 3$cm corresponds to the reference surface roughness length used in the Prairie Grass experiments. A surface roughness length of $z_0 = 40$ cm, representative of woodland terrain near the Hanul site, was applied, yielding ZSCALE = 1.68. The lateral scaling factor (YSCALE) was set to unity.

The released activity was defined as the product of release fractions (RELFRC), derived from MUST Converter analyses [3], and core inventory (CORINV). The Surry SOARCA inventory was adopted and scaled to the OPR1000 thermal power (2,815 MWt), and the resulting inventory values were used as the base-case source term.

2.2.2 EARLY Module Configuration

The EARLY module was configured to evaluate early-phase radiological consequences without assuming protective actions. Normal-activity shielding and protection factors were applied (GSHFAC = 0.34, CSFACT = 0.75, PROTIN = 0.46).

The breathing rate (BRRATE) was set to 2.66 × 10^{-4} m^3/s, and the early-phase duration (ENDEMP) was defined as 96 hours, consistent with the regulatory dose evaluation period.

2.2.3 Reference Site and Base Case Results

The Hanul Nuclear Power Plant was selected as the reference site, and site-specific meteorological data representative of the southeastern coastal region of Korea were applied. Using the above base-case assumptions, dose-exceedance distances corresponding to 1, 5, and 10 rem were calculated for each accident scenario under mean, median, and 95th percentile meteorological conditions. The results are summarized in Table II.

Table II. Base Case Dose Exceedance Distances by Quantile for Representative Accident Scenarios.

Scenario	Quantile	Dose Exceedance Distance		
		1 rem	5 rem	10 rem
SBOR107-CET3	Mean	0.51 km	0.19 km	0.12 km
	Median	0.40 km	0.18 km	-
	95th Percentile	1.15 km	0.35 km	0.22 km
SBOR8-CET55	Mean	0.70 km	0.26 km	0.18km
	Median	0.59 km	0.24 km	0.17 km
	95th Percentile	1.88 km	0.43 km	0.27 km

2.3 Sensitivity Analysis Design

A discrete, one-parameter-at-a-time sensitivity design was developed using recommended values and, where available, uncertainty ranges/distributions for key MACCS user inputs documented in the MACCS technical bases and code manuals [4], [5], [6]. Based on this information, a limited set of representative levels was selected for each parameter. Table III summarizes the resulting test matrix across the ATMOS and EARLY modules, with the base-case level highlighted.

In the ATMOS module, the plume release height (PLHITE) was sampled from 0 m to the physical release elevation, consistent with guidance that identifies PLHITE = 0 m as a conservative option when building-wake effects are not explicitly modeled and the initial release elevation is less than approximately 2.5 times the building height. Initial plume spread was evaluated using paired SIGYINIT/SIGZINIT levels to represent coupled changes in the initial lateral and vertical dispersion. Surface effects were examined by varying ZSCALE, consistent with the MACCS roughness-based scaling of vertical dispersion relative to a Prairie Grass reference roughness length. Plume meander was treated as a categorical model choice through MNDMOD (e.g., NEW/OLD/OFF), reflecting the alternative meander formulations available in MACCS; guidance recommends MNDMOD = NEW when Pasquill–Gifford dispersion curves are applied with approximately one-hour plume segments, while other options may be appropriate depending on the dispersion parameterization.

In the EARLY module, key inputs were varied to represent uncertainty in early-phase dose modification and timing. These parameters affect both external and internal exposure pathways. CSFACT and GSHFAC were treated as dimensionless shielding/protection factors for cloudshine and groundshine, respectively, and PROTIN as the inhalation protection factor, using recommended generic values and ranges from the technical bases. The breathing rate (BRRATE) was varied because inhalation dose scales linearly with breathing rate, and ENDEMP was varied to examine sensitivity to the assumed duration of the early phase over which doses are integrated.

Table III. Test Matrix of Key MACCS Input Parameters and Their Assigned Levels (Base Case Highlighted).

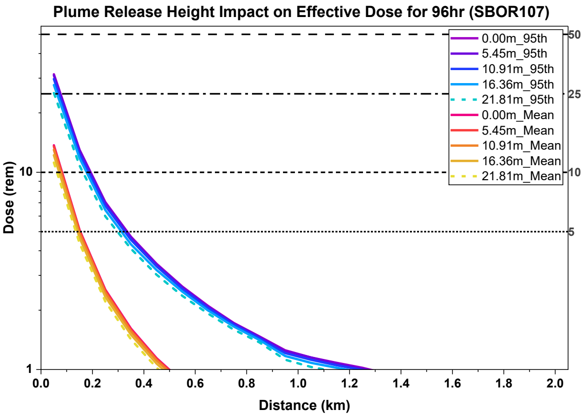
Module	**Card No.**	**Description**	**Unit**	**Assigned Levels**					
ATMOS	PLHITE	Plume Release Height	m	0	5.45	10.91	16.36	21.81	
	SIGYINIT & SIGZINIT	Initial Sigma-y & Sigma-z	m	2.55 18.64	6.22 24.88	10.20 31.10	13.46 37.32	17.05 43.50	
	MNDMOD	Plume Meander Model	-			NEW	RAF	OLD	OFF
	ZSCALE	Surface Roughness	-		1.46	1.68	1.82	1.93	2.02
EARLY	CSFACT	Cloudshine Shielding Factor	-		0.60	0.75	0.95		
	GSHFAC	Groundshine Shielding Factor	-	0.053	0.22	0.34	0.55		
	PROTIN	Inhalation Protection Factor	-		0.34	0.46	0.90		
	BRRATE	Breathing Rate	m^3/s	9.22 E-05	1.38 E-04	2.19 E-04	2.66 E-4	3.93 E-04	5.90 E-04

	ENDEMP	Duration of the Emergency Phase	s		86,400	345,600	604,800		

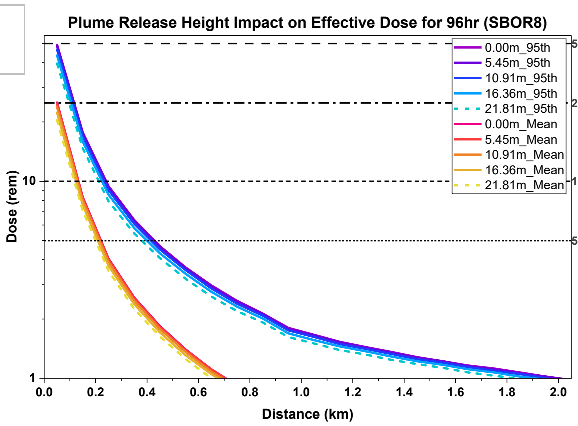
2.4 Sensitivity Analysis Results

As a demonstration, PLHITE in the ATMOS module and BRRATE in the EARLY module were selected to examine each parameter's impact on the 96-h effective dose. Fig. 1 presents the dose–distance curves for PLHITE for SBOR107-CET3 and SBOR8-CET55. In ATMOS, decreasing PLHITE from the base-case physical release elevation (21.81 m) toward ground level produced a consistent increase in the 96-h TED dose-exceedance distance for both source terms, indicating a more conservative prediction when the release is assumed closer to the surface. However, across the evaluated range from 0 m to the physical release elevation, the overall variation in exceedance distance remained limited.

Fig. 2 presents the dose–distance curves for BRRATE for SBOR107-CET3 and SBOR8-CET55. In EARLY, varying BRRATE produced a clearer and more monotonic response in dose-exceedance distance because inhalation dose scales directly with breathing rate. Across the recommended sampling range of 9.22E−05 to 5.90E−04 m³/s, higher breathing rates consistently increased dose-exceedance distances, while lower breathing rates decreased them. The effect was most apparent at lower dose thresholds, such as 1 rem and 5 rem, where exceedance distances showed the largest relative spread across the tested BRRATE levels, consistent with the tabulated results and the wider separation of curves in Fig. 2. In all cases, the 95th percentile exceedance distances were consistently larger than the corresponding mean values, reflecting the influence of parameter and meteorological uncertainty on the upper-tail dose predictions.

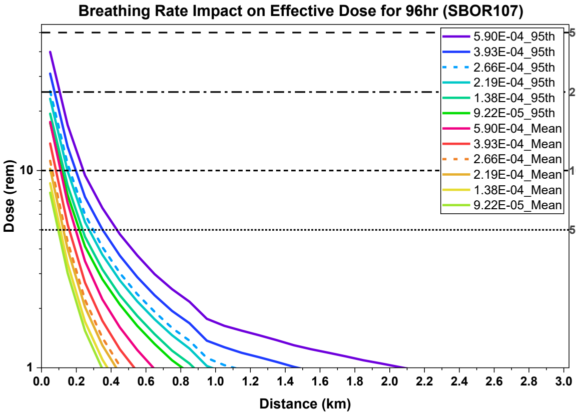


(a) SBOR107-CET3

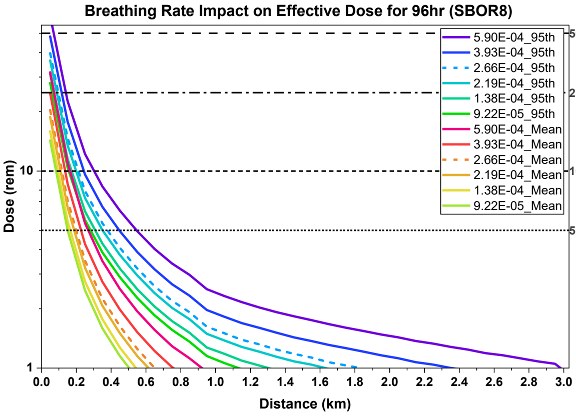


(b) SBOR8-CET55

Fig. 1. Dose–distance curves showing the impact of plume release height (PLHITE) on the 96-h effective dose: (a) SBOR107-CET3 and (b) SBOR8-CET55.



(a) SBOR107-CET3



(b) SBOR8-CET55

Fig. 2. Dose–distance curves showing the impact of breathing rate (BRRATE) on the 96-h effective dose: (a) SBOR107-CET3 and (b) SBOR8-CET55.

3. Conclusions

This study developed and demonstrated a discrete, one-parameter-at-a-time sensitivity analysis framework for evaluating dose-exceedance distances using MACCS, and applied it to two representative OPR1000 intact-containment scenarios selected from PSA-based source-term categories. A structured test matrix was established for key inputs in the ATMOS and EARLY modules using recommended values and available uncertainty ranges, and baseline 96-h TED dose-exceedance distances were quantified for 1, 5, and 10 rem under mean, median, and 95th-percentile meteorological conditions. Demonstration results showed that decreasing the plume release height PLHITE tended to increase exceedance distances, yielding more conservative outcomes, but the overall variation within the physically plausible range from ground level to the release elevation remained limited. In contrast, the breathing rate BRRATE produced a clear and monotonic effect on exceedance distance, with higher breathing rates consistently increasing the exceedance distance; the largest relative changes were observed for lower dose thresholds such as 1 and 5 rem.

Future work will extend the sensitivity analysis beyond the two illustrative parameters examined here by systematically evaluating all inputs defined in the test matrix. This expanded assessment will enable a ranked identification of dominant modeling drivers for dose-exceedance distances and provide a more comprehensive technical basis for performance-based and risk-informed emergency planning evaluations.

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