Comparison of Emergency Planning Zone Evaluation Methodologies: A Case Study on the OPR1000 Reactor

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***Keywords :** Emergency Planning Zone, Dose Aggregation, Severe Accident, MACCS, OPR1000

1. Introduction

The emergence of advanced reactors, with their enhanced safety features, has prompted a regulatory shift towards site-specific Emergency Planning Zones (EPZs). This shift has spurred the development of new methodologies: a design-specific, consequence-oriented approach documented by NuScale [1] and a risk-informed cumulative-curve (dose-aggregation) methodology described in NEI 24-05 [2].

This paper compares the NuScale and NEI 24-05 methodologies, examining their foundational principles and key analytical differences. To contextualize this comparison, a case study is presented applying key aspects of these frameworks to the OPR1000, thereby illustrating their practical application and divergent outcomes.

2. Methods and Results

The methodologies for establishing the plume exposure pathway EPZ presented in NuScale's topical report, and the Nuclear Energy Institute's technical report, NEI 24-05, share the common objective of justifying a reduced, site-specific EPZ for advanced reactors. Both approaches leverage insights from a plant-specific Probabilistic Safety Assessment (PSA). However, they diverge significantly in their philosophical underpinnings, core analytical techniques, and evaluation criteria, reflecting an evolution in risk-informed regulatory frameworks over time.

In this section, the two methodologies are summarized and compared, and a case study is conducted for the OPR1000.

2.1 NuScale's EPZ Size Methodology

NuScale's approach, as documented in the NRC-approved TR-0915-17772-NP-A (Rev. 3, 2022), is a design-specific, consequence-oriented methodology that uses risk-informed insights primarily for screening. The process is fundamentally a "bottom-up" approach that begins by compiling a comprehensive list of accident sequences from the PRA and then subjects them to a rigorous, multi-step screening process to identify the specific, bounding accidents that will form the technical basis for the EPZ size.

The main part of the NuScale methodology on EPZ calculation are three distinct dose-based criteria, which are summarized in Table I, applied to different categories of accidents.

Table I: Summary of NuScale EPZ Dose-Based Criteria

Criteria	Description
Criterion a (Design Basis Accidents, DBAs)	The larger distance at which dose does not exceed either a 1 rem TEDE(Total Effective Dose Equivalent) criterion at mean weather conditions or a 5 rem TEDE criterion at 95th percentile weather conditions for design-basis source term (DBST) with an exposure duration of 96 hours
Criterion b (Less Severe Accidents)	The larger distance at which dose does not exceed either a 1 rem TEDE criterion at mean weather conditions or a 5 rem TEDE criterion at 95th percentile weather conditions for screened-in less severe accident sequences with an exposure duration of 96 hours
Criterion c (More Severe Accidents)	The sufficient distance at which the conditional probability of exceeding 200 rem whole body acute dose drops off substantially for screened-in more severe accident sequences with an exposure duration of 24 hours

The final EPZ size is determined by the largest distance calculated from the independent evaluation of each accident sequence that is screened in to the analysis, as well as consideration of the site boundary (i.e., the minimum EPZ). This ensures that the EPZ is bounded by the most consequential, credible event identified through the screening process while not being smaller than the site boundary.

2.2 NEI 24-05's EPZ Size Methodology

NEI 24-05 (Rev. 0, 2025) presents a holistic, Risk-Informed Performance-Based (RIPB) methodology aligned with the modern Licensing Modernization Project (LMP) framework and the NRC's SMR/ONT emergency preparedness rule (10 CFR §50.160), but it is currently under NRC review and has not been approved or endorsed by the NRC. This "top-down" approach focuses on the aggregated risk profile of the entire plant rather than individual, bounding accident sequences.

The important analytical technique in this method is probabilistic dose aggregation. This process begins with the full spectrum of Licensing Basis Events (LBEs) identified through the LMP process, which includes all event sequence families with a frequency greater than 5E-7 per plant year. For each LBE with a radionuclide release, a dose-versus-distance curve is generated. These individual curves are then summed to produce a cumulative dose-versus-distance curve, which represents the total frequency of exceeding a given dose at each distance from the reactor.

The NEI 24-05 methodology compares this cumulative curve against two specific frequency-at-dose criteria derived from the historical planning basis of NUREG-0396, as summarized in Table II.

Table II: Summary of NEI 24-05 EPZ Frequency-at-Dose Criteria

Criteria	Description
Criterion A	The distance at which the cumulative exceedance of 1 rem (mean 96-hour TEDE) is evaluated at a frequency of 1E-5 per plant-year.
Criterion B	The distance at which the cumulative exceedance of 200 rem (mean 24-hour whole body dose or an acceptable surrogate, e.g., acute red marrow dose) is evaluated at a frequency of 1E-6 per plant-year.

The distance derived from these criteria—after accounting for uncertainties and potential cliff-edge effects—then informs a subsequent protective measures evaluation to determine the final EPZ size.

2.3 Key Methodological Differences

The fundamental differences between the two approaches are summarized below:

- Main Technique: NuScale uses a screening-based, per-sequence consequence evaluation to identify the bounding accident that defines the EPZ distance; NEI 24-05 uses probabilistic dose aggregation of LBE-specific dose-versus-distance curves to form cumulative (plant-level) frequency-at-dose curves.
- Accident Basis: NuScale starts from PRA sequences and screens by frequency (e.g., nonseismic core damage sequences with point estimate frequency < 1E-7 per module-year are screened out before consequence analysis); NEI 24-05 starts from the set of LMP-defined LBEs and then considers only LBEs with a radionuclide release.
- Evaluation Criteria: NuScale applies distinct dose-based criteria to categorized accidents (design basis, less severe, more severe) and determines the EPZ from per-sequence distances; NEI 24-05 compares cumulative frequency-at-dose curves against two metrics—1 rem (mean 96-hour TEDE) at 1E-5 per plant-year and 200 rem (mean 24-hour whole body dose or an acceptable surrogate) at 1E-6 per plant-year—with follow-on uncertainty/cliff-edge reviews.
- Regulatory Alignment: NuScale's approach predates the SMR/ONT emergency preparedness final rule and draws on the NUREG-0396 planning basis; NEI 24-05 is explicitly structured to implement 10 CFR § 50.33(g)(2) and §50.160 and to integrate emergency planning within the LMP/RIPB safety case, providing step-by-step guidance for PEP EPZ determination and emergency plan development.
- EPZ Selection Rule: Under NuScale, the final EPZ is the largest distance obtained from the screened-in sequence evaluations and is not allowed to be smaller than the site boundary; under NEI 24-05, the distance indicated by the frequency-at-dose comparison (after uncertainty and cliff-edge assessments) feeds a protective measures evaluation to decide the final EPZ.

2.4 A Case Study for the OPR1000

A case study was conducted to apply the NuScale EPZ sizing methodology to the OPR1000. The analysis excluded DBAs and instead focused on comparing the distances derived from three other criteria: less severe accidents, more severe accidents, and the site boundary (the minimum EPZ).

The classification of accident severity is based on the integrity of the containment structure. Less severe accidents are defined as sequences where the containment remains intact, leading to much smaller atmospheric releases. Conversely, more severe accidents involve containment failure or bypass, resulting in a significant, direct release of radionuclides to the environment. This distinction aligns with the NUREG-0396 classification, which separates accidents based on whether they involve containment failure and large atmospheric releases.

For this study, a set of accident sequences was selected from a total of 690 severe accident sequences that collectively account for 99% of the total accident frequency for the OPR1000 [3]. A screening process was applied based on the Core Damage Frequency (CDF) for nonseismic single module accident sequences. All sequences with a CDF greater than or equal to 1E-7 per module year were screened into the analysis. Sequences with a CDF below this threshold but greater than or equal to 1E-8 per module year were excluded from further consideration. Based on this criterion, three less severe accident sequences (SBOR, MLOCA, SBOS) and three more severe accident sequences (SLOCA, MLOCA, SGTR) were selected.

The analytical workflow involved performing source term analysis for each sequence using the MAAP code, followed by atmospheric dispersion and dose assessment using the MACCS code. For the MACCS analysis, several key parameters were set in accordance with NuScale TR recommendations. Common parameters for all sequences included a Stratified Random Sampling model for meteorology (METCOD=5) and a wind-shift dispersion model without rotation (IPLUME=3). Site-specific meteorological data from the Hanul nuclear power plant site in Korea was used.

Specific input parameters varied by accident severity class. For less severe accidents, a 96-hour exposure duration (ENDEMP=345600) was used. For more severe accidents, the exposure duration was 24 hours (ENDEMP=86400). For both classes, protective measures such as evacuation were not considered (EVATYP=None), and shielding factors were set to 1.0 for cloudshine (CSFACT), 0.7 for groundshine (GSHFAC), and 1.0 for inhalation (PROTIN). Following the NuScale TR, red marrow dose was used as an acceptable surrogate for acute whole body dose for the more severe accident analysis.

For the less severe accidents, the MLOCA sequence resulted in the largest release fraction and the highest dose. The MACCS analysis determined that the distance at which the dose did not exceed the criterion of either 1 rem Total Effective Dose Equivalent (TEDE) under mean weather conditions or 5 rem TEDE under 95th percentile weather conditions was 0.9-1.0 km.

For the more severe accidents, the results from the three sequences were aggregated into a single conditional dose versus distance curve. This was achieved by calculating a weighted average using the following formula:

$$p_j(D > D_0) = \sum_{i=1}^{n} f_i p_{ij} / f_{total} \quad (1)$$

Using Eq. (1) p_j, the total conditional probability of exceeding a given dose D_0 at distance j is calculated by summing the contributions of all individual accident sequences. For each sequence i, its conditional probability of dose exceedance (p_{ij}), determined over numerous weather trials, is weighted by its individual frequency (f_i). The sum of these weighted probabilities is then normalized by the total frequency of all sequences considered (f_{total}).

The final step involved interpolating the MACCS results for each of the three sequences to find the probability of exceeding a 200 rem dose at each distance. These probabilities were then weighted by their respective sequence frequencies and summed using the Eq. (1). The results of this procedure are summarized in Table III and yielded the comprehensive "Probability of Dose Exceedance Versus Distance Curve" shown in Fig. 1. The analysis concludes that the distance at which the conditional probability of exceeding a 200 rem red marrow dose drops off substantially is approximately 15-16 km.

Table III: Calculation Results for the Probability of Dose Exceedance

		Sequences			
		S1(SLOCA)	S2(MLOCA)	S3(SGTR)	Total CDF
	CDF	1.75E-07	1.26E-07	1.15E-07	4.16E-07
	Distance (km)	Cond. Prob. of exceeding 200 rem for sequence i at distance j			Total Cond. Prob. of exceeding 200 rem at distance j
1	0.05	9.99E-01	1.00E+00	9.89E-01	9.96E-01
2	0.15	8.55E-01	9.34E-01	7.08E-01	8.38E-01
3	0.25	6.45E-01	8.09E-01	4.45E-01	6.40E-01
4	0.35	5.61E-01	7.44E-01	2.28E-01	5.25E-01
5	0.45	4.61E-01	6.86E-01	1.42E-01	4.41E-01
6	0.55	2.83E-01	6.18E-01	9.87E-02	3.34E-01
7	0.65	1.94E-01	4.66E-01	7.70E-02	2.44E-01
8	0.75	1.76E-01	3.37E-01	5.96E-02	1.93E-01
9	0.85	1.61E-01	2.93E-01	3.78E-02	1.67E-01
10	0.95	1.39E-01	2.63E-01	1.62E-02	1.43E-01
11	1.05	1.28E-01	2.41E-01	1.06E-02	1.30E-01
12	1.15	1.19E-01	2.24E-01	6.73E-03	1.20E-01
13	1.25	1.10E-01	2.13E-01	5.30E-03	1.12E-01
14	1.35	1.04E-01	2.01E-01	5.46E-03	1.06E-01
15	1.45	9.57E-02	1.92E-01	3.72E-03	9.97E-02
16	1.55	8.70E-02	1.83E-01	1.10E-03	9.25E-02
17	1.65	8.15E-02	1.78E-01	0.00E+00	8.84E-02
18	1.75	7.59E-02	1.73E-01	0.00E+00	8.46E-02
19	1.85	7.14E-02	1.71E-01	0.00E+00	8.19E-02
20	1.95	6.79E-02	1.68E-01	0.00E+00	7.95E-02
21	2.05	6.55E-02	1.67E-01	0.00E+00	7.82E-02
22	2.55	5.52E-02	1.74E-01	0.00E+00	7.61E-02
23	3.05	5.54E-02	1.78E-01	0.00E+00	7.73E-02
24	4.05	5.29E-02	1.69E-01	0.00E+00	7.36E-02
25	5.05	4.81E-02	1.51E-01	0.00E+00	6.61E-02

26	6.05	3.29E-02	1.27E-01	0.00E+00	5.24E-02
27	8.05	1.30E-02	8.26E-02	0.00E+00	3.05E-02
28	10.05	5.16E-03	5.15E-02	0.00E+00	1.78E-02
29	12.05	2.06E-03	2.38E-02	0.00E+00	8.10E-03
30	14.05	7.74E-04	1.42E-02	0.00E+00	4.63E-03
31	16.05	0.00E+00	6.07E-04	0.00E+00	1.84E-04

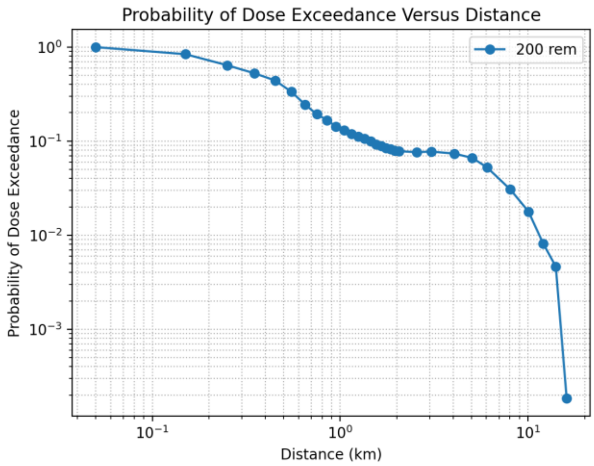

Fig. 1. Probability of Dose Exceedance Versus Distance Curve for More Severe Accidents of OPR1000

To determine the final EPZ size, the distances from the three criteria were compared:

- Less Severe Accidents: The distance is 0.9-1.0km.
- More Severe Accidents: The distance is 15-16km.
- Site Boundary (Minimum EPZ): 0.7km for Large Light Water Reactor.

Since the final EPZ is determined by the largest of these distances, the EPZ for the OPR1000 is established at 15-16 km, driven by the criterion for more severe accidents.

3. Conclusions

This paper presented a comparative analysis of two distinct EPZ sizing methodologies: NuScale's consequence-oriented, per-sequence screening and dose-comparison approach and NEI 24-05's risk-informed cumulative curve (dose aggregation) approach aligned with the LMP and §50.160. To demonstrate a practical application, a case study was performed by applying the NuScale methodology to the OPR1000, excluding the DBA criterion.

The case study yielded specific distances for each criterion. The analysis for less severe accidents determined a controlling distance of 0.9–1.0 km, based on the 1 rem/5 rem TEDE criteria. For more severe accidents, the analysis concluded that the distance at which the conditional probability of exceeding a 200 rem acute red marrow dose dose drops off substantially is 15-16 km. These results were compared against the Site Boundary, which represents a minimum EPZ of 0.7 km. In accordance with the NuScale framework, the final EPZ is determined by the largest of these distances. Therefore, this study establishes the EPZ for the OPR1000 at 15-16 km, driven entirely by the criterion for more severe accidents.

Future work will focus on applying the NEI 24-05's methodology to the same OPR1000. This will enable a direct comparison that offers valuable insights into how these modern methodologies assess the safety profile of a large reactor and inform the future of emergency preparedness regulation.

Acknowledgement

This study was supported by the Nuclear Safety Research Program through the Regulatory Research Management Agency for SMRs(RMAS) and the Nuclear Safety and Security Commission(NSSC) of the Republic of Korea.(No. RS-2025-02310628)

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