Evaluation of the Emergency Planning Zone for Nuclear Power Plant during the Pre-Defueled Stage of Decommissioning under Conservative Meteorological Conditions

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Abstract: Due to limited capacity in the Spent Fuel Pool (SFP), there is still fuel in the core of the Chinshan Nuclear Power Plant (NPP). This study evaluates the Emergency Planning Zone (EPZ) for the Chinshan NPP during the pre-defueled stage of decommissioning and uses the MELCOR Accident Consequence Code System (MACCS) to assess Level 3 risk results in terms of individual effective dose and annual exceedance probability of dose thresholds during the emergency phase. The extremely conservative meteorological conditions (i.e., a fixed wind blowing toward the south at 0.1 m/s, stability class G and no rainfall) are considered in this work to establish an upper-bound estimation for EPZ evaluation. The results show that under the Design Basis Accident (DBA) case, the individual effective dose at 0.5 km from the midpoint between the two reactor units is below 50 mSv (regulatory criterion in Taiwan). Under the Severe Accident (SA) case, the annual exceedance probabilities of 50 mSv and 2 Sv at 0.5 km from the midpoint are both below the regulatory criteria of 3.0×10^{-5} and 3.0×10^{-6} (regulatory criteria in Taiwan), respectively. In brief, the DBA and SA results indicate that all the EPZ criteria can be satisfied within 0.5 km from the midpoint between the two reactor units under the conservative assumptions adopted in this study and the current 8-km EPZ provides sufficient conservatism in Taiwan. The findings of this study can serve as a technical reference for EPZ review under similar decommissioning conditions.

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1. INTRODUCTION

The Emergency Planning Zone (EPZ) [1] is defined as the area where emergency response plans are implemented and protective actions for the public are promptly carried out in the event of a nuclear accident. To reduce the health risks to the public in the vicinity of a Nuclear Power Plant (NPP) during a nuclear accident, the EPZ is established in advance and regular drills in EPZ are conducted to ensure that effective protective actions can be implemented promptly when an accident occurs. According to the 2022 Enforcement Rules of the Nuclear Emergency Response Act in Taiwan [2], the nuclear facility operators are required to revise the EPZ every three years and the EPZ must be reviewed and approved by the Nuclear Safety Commission (NSC) prior to its official announcement.

The Chinshan NPP, located in Shimen District, New Taipei City, is the first commercial NPP in Taiwan. The NPP employs Boiling Water Reactor (BWR) units of the General Electric BWR-4 design, with a rated capacity of 636 MW per unit and utilizes a Mark I containment system. The NPP consists of two units: Unit 1 began operation in 1978 and Unit 2 was shut down in 2019. Both units are currently undergoing decommissioning. However, due to limited Spent Fuel Pool (SFP) capacity, the part of the spent fuel at NPP remained temporarily stored in the reactor in the early phase of decommissioning (i.e., pre-defueled stage of decommissioning), which is relatively uncommon in international NPP decommissioning practice. Although the NPP is no longer in operation, the reactor still contains nuclear fuel; therefore, its safety management is maintained in accordance with the regulatory requirements associated with operating NPP.

In this work, the “annual exceedance probability” refers to the annual exceedance probability of dose thresholds, rather than the exceedance frequency of external hazard events. This study employs the MACCS (MELCOR Accident Consequence Code System) to assess Level 3 risk results in terms of individual effective dose and annual exceedance probability during the emergency phase (i.e., 7 days) after the accident. The extremely conservative meteorological conditions (i.e., a fixed wind blowing toward the south at 0.1 m/s, stability class G and no rainfall) are considered in this work to establish an upper-bound estimation for EPZ evaluation. This study investigates whether the current officially designated 8.0 km EPZ remains sufficient to cover such severe accident scenarios. The results can serve as a technical reference for EPZ review under similar decommissioning conditions.

2. EPZ EVALUATION CRITERIA

According to Article 3 of the "Enforcement Rules of the Nuclear Emergency Response Act [2], the EPZ evaluation criteria in Taiwan are as follows:

- The projected radiological dose outside the EPZ resulting from the Design Basis Accidents (DBA) shall not exceed the evacuation intervention level specified in the "Protective Actions Guidelines (PAG) for Nuclear Emergency."
- For the Severe Accidents (SA), the annual probability of the projected radiological dose outside the EPZ exceeding the evacuation intervention level specified in the PAG shall be less than 3×10^{-5}.
- For the SA, the annual probability of the projected radiological dose outside the EPZ exceeding 2 Sv shall be less than 3×10^{-6}.

The evacuation intervention level specified in the PAG is 50–100 mSv. In this study, a conservative value of 50 mSv is adopted as the assessment criterion to determine the EPZ.

3. RESEARCH METHOD

3.1. System Description and Modeling Assumptions

The Chinshan NPP is configured with an open reactor vessel head and a hydraulic connection between the Reactor Pressure Vessel (RPV) and the SFP, as shown in Figure 1. According to the current operational requirements, one train of the Residual Heat Removal (RHR) system is required to remain in operation to remove decay heat from the reactor core and spent fuel in SFP [3]. In addition, this study adopts a conservative assumption that the secondary containment system is not credited [3]; in the event of a severe accident, the radionuclides are assumed to be directly released into the environment. Since fuel melting in SFP occurs later than that in the reactor core and beyond the Level 3 emergency phase (i.e., 7 days) in this study, the contribution of the SFP to the individual effective dose is not included in the EPZ evaluation.

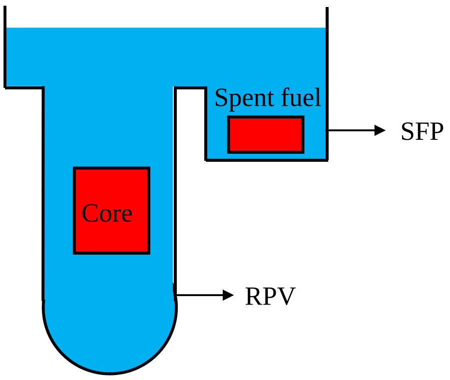

Figure 1: Schematic Diagram of the Hydraulic Connection between the RPV and SFP

This evaluation is based on the EPZ review and revision report [4] approved by the NSC. The methodology for determining the EPZ boundary includes core radioactivity inventory calculations (ORIGEN 2), source term analyses for DBA and SA (RADTRAD 3.03 and MAAP 5.04) and individual effective dose and annual exceedance probability assessment (MACCS 3.7). The overall evaluation framework is illustrated in Figure 2.

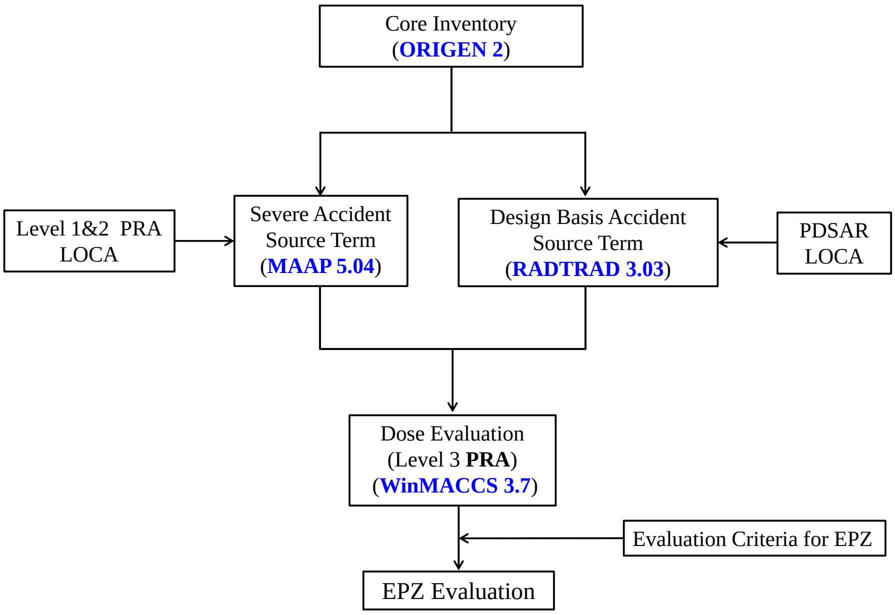

Figure 2: Overall Evaluation Framework for EPZ

3.2. Core Radioactivity Inventory Calculation

The core radioactivity inventory is calculated based on the parameters of Unit 2, as it has a shorter cooling time due to its later shutdown (approximately 2800 days, from June 2, 2017 to January 31, 2025). According to the report [4], the one-unit assumption for the DBA case is based on the core inventory of Unit 2, whereas the conservative two-unit assumption for the SA case is implemented by doubling the core inventory of Unit 2. The core radioactivity inventories for the DBA and SA scenarios are presented in Tables 1 and 2, respectively. The inventories are further grouped into nine radionuclide groups and used as input to MACCS 3.7.

Table 1: Core Radioactivity Inventory (Ci) for DBA [4]

Nuclide	*DBA*
I-131	0.00E+00
I-132	0.00E+00
I-133	0.00E+00
I-134	0.00E+00
I-135	0.00E+00
Kr-83m	0.00E+00
Kr-85m	0.00E+00
Kr-85	4.95E+05
Kr-87	0.00E+00
Kr-88	0.00E+00
Kr-89	0.00E+00
Xe-131m	0.00E+00
Xe-133m	0.00E+00
Xe-133	0.00E+00
Xe-135m	0.00E+00
Xe-135	0.00E+00
Xe-137	0.00E+00
Xe-138	0.00E+00

Table 2: Core Radioactivity Inventory (Ci) for SA [4]

Nuclide	*SA*	*Nuclide*	*SA*
Kr-85	9.88E+05	Te-131m	0.00E+00
Kr-85m	0.00E+00	Te-132	0.00E+00
Kr-87	0.00E+00	Te-134	0.00E+00
Kr-88	0.00E+00	Sb-127	0.00E+00
Xe-131m	0.00E+00	Sb-129	0.00E+00
Xe-133	0.00E+00	Sr-89	2.02E-09
Xe-133m	0.00E+00	Sr-90	1.10E+07
Xe-135	0.00E+00	Sr-91	0.00E+00
Xe-135m	0.00E+00	Sr-92	0.00E+00
Xe-138	0.00E+00	Ba-139	0.00E+00
I-131	0.00E+00	Ba-140	0.00E+00
I-132	0.00E+00	Ru-103	5.18E-14
I-133	0.00E+00	Ru-105	0.00E+00
I-134	0.00E+00	Ru-106	2.90E+05
I-135	0.00E+00	Rh-105	0.00E+00
Cs-134	1.94E+06	Tc-99m	0.00E+00
Cs-136	0.00E+00	Ce-141	0.00E+00
Cs-137	1.43E+07	Ce-143	0.00E+00
Rb-86	0.00E+00	Ce-144	1.54E+05
Rb-88	0.00E+00	Pu-238	5.00E+05
Rb-89	0.00E+00	Pu-239	5.16E+04
Y-90	1.10E+07	Pu-240	6.90E+04
Y-91	5.02E-07	Pu-241	1.29E+07
Y-92	0.00E+00	Np-239	2.16E+03
Y-93	0.00E+00	La-140	0.00E+00
Zr-95	1.23E-05	La-141	0.00E+00
Zr-97	0.00E+00	La-142	0.00E+00
Nb-95	2.74E-05	Nd-147	0.00E+00
Mo-99	0.00E+00	Pr-143	0.00E+00
Te-127	2.56E-02	Am-241	2.18E+05
Te-127m	2.62E-02	Cm-242	2.98E+03
Te-129	0.00E+00	Cm-244	2.00E+05
Te-129m	0.00E+00		

3.3. Source Term Calculation

According to the Pre-Defueled Safety Analysis Report (PDSAR) for the Chinshan Nuclear Power Plant [5], the Loss-Of-Coolant Accident (LOCA) results in the largest radioactive release and is therefore selected as the representative DBA. The LOCA source term is calculated using RADTRAD 3.03 and the results are summarized in Table 3.

The Fuel Uncovery Frequency (FUF) is defined as the frequency of spent fuel uncovery and conservatively assumed to be equivalent to the fuel damage frequency [4]. Based on the Probabilistic Risk Assessment (PRA), the most severe accident sequence in the Chinshan NPP is a large-break loss-of-coolant accident (i.e., LOCA) with all mitigation systems unavailable. For LOCA case, the radioactive release frequency of the reactor core is conservatively taken as the sum of all accident sequence frequencies ($1.91E\times10^{-6}$/year). The LOCA source term is calculated using MAAP 5.04 and the results are summarized in Table 4.

Table 3: Source Term for DBA [4]

Accident	*Plume*	*Group*								
		1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
		NG	*I*	*Rb-Cs*	*Sb-Te*	*Sr*	*Ru*	*La*	*Ce*	*Ba*
LOCA	1	9.6E-01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
	2	4.0E-02	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
	3	1.6E-03	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
	4	6.1E-05	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00

Table 4: Source Term for SA [4]

Accident	*Plume*	*Group*								
		1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
		NG	*I*	*Rb-Cs*	*Sb-Te*	*Sr*	*Ru*	*La*	*Ce*	*Ba*
LOCA	1	5.85E-01	0.0E+00	4.89E-01	4.62E-01	7.92E-02	3.16E-01	4.69E-04	9.62E-03	1.14E-01
	2	3.53E-02	0.0E+00	5.44E-03	2.50E-02	9.68E-03	1.39E-01	2.52E-05	2.36E-03	5.27E-02
	3	7.77E-07	0.0E+00	6.16E-07	4.79E-06	4.02E-05	9.93E-06	2.20E-12	1.37E-07	2.25E-04
	4	3.16E-01	0.0E+00	2.42E-01	2.81E-01	1.48E-01	2.71E-01	8.58E-04	1.61E-02	1.87E-01

3.4. Individual Effective Dose and Conditional Exceedance Probability Assessment

To evaluate the impact of radioactive releases on the environment, this study utilizes only the ATMOS (atmospheric transport and deposition) and EARLY (emergency-phase calculations) modules of the MACCS code [6]. The atmospheric dispersion module is based on the Gaussian plume model [7] to simulate the transport, dispersion, deposition and radioactive decay of released radionuclides in the atmosphere. Based on the Pasquill–Gifford curves [8] (i.e., σ_y and σ_z as functions of downwind distance), ground-level radionuclide concentrations are calculated in the MACCS using lookup tables for σ_y and σ_z. The extremely conservative meteorological conditions (i.e., a fixed wind blowing toward the south at 0.1 m/s, stability class G and no rainfall) are considered in this work. The atmospheric stability classes are categorized from A to G, where class A represents the most unstable atmosphere, under which released radionuclides are more readily dispersed and diluted in the environment; conversely, class G represents the most stable atmosphere, under which radionuclides are less likely to disperse. In addition, the absence of rainfall prevents wet deposition, allowing the radionuclides to persist in the atmosphere and further enhancing potential exposure.

The individual effective dose and conditional exceedance probability are obtained from the MACCS code; the calculation time is defined from the arrival of the first released plume after the accident at any downwind radial grid point (Time = 0) to 7 days. In this study, the spatial grid is defined using radial segmentation starting from the midpoint of the line connecting the two reactors. The domain is divided at 0.5 km intervals from 0 to 10 km and at 1.0 km intervals from 10 to 25 km (i.e., total 35 radial segments). In addition, there are four plumes release in this work and the duration of each plume release is set to 24 hours [4]. The relevant release parameters for DBA and SA are summarized in Tables 5 and 6, respectively.

Table 5: Plume Release Parameters for DBA [4]

Accident	*Plume*	*Release Duration (h)*	*Release Start Time (h)*	*Release Heat (Watts)*	*Release Height (m)*
LOCA	1	24	0	0	238
	2	24	24	0	238
	3	24	48	0	238
	4	24	72	0	238

Stack Height: 238 m

Table 6: Plume Release Parameters for SA [4]

Accident	*Frequency (1/year)*	*Plume*	*Release Duration (h)*	*Release Start Time (h)*	*Release Heat (Watts)*	*Release Height (m)*
LOCA	1.91×10^{-6}	1	24	57.57	8.12E+05	43.58
		2	24	81.57	2.46E+05	43.58
		3	24	105.57	2.24E+05	43.58
		4	24	129.57	9.34E+05	43.58

Roof Height: 43.58 m

The individual effective dose calculations in this study are performed using the dose conversion factors provided in Federal Guidance Report No. 13 (FGR 13) [9]. The factors are specified according to radionuclide type, target organ and exposure pathway (i.e., cloudshine, groundshine, inhalation, resuspension inhalation and skin exposure). The ground-level radionuclide concentrations are converted into organ doses using these coefficients. The organ doses are then weighted and summed according to the tissue weighting factors defined in ICRP Publication 60 [10] to obtain the individual effective dose. Based on the report [4], the conservative no-evacuation assumption is adopted in this study. In other words, the public is assumed to remain in place and maintain normal living activities for 7 days following the accident. Accordingly, a shielding factor of 0.6 [11] and a breathing rate of 2.66×10^{-4} m³/s (adult male) [12] are used.

3.5. Annual Exceedance Probability Assessment

The annual exceedance probability employed in this work is defined as the frequency-weighted annual exceedance probability. Note that the frequency-weighted annual exceedance probability is equal to the conditional exceedance probability obtained from the MACCS code multiplied by the radioactive release frequency (i.e., 1.91×10^{-6}/year) derived from the Level-2 PRA. For SA case, the EPZ is determined based on the spatial distribution of the annual exceedance probability. The EPZ boundary is defined as the maximum distance at which the annual exceedance probabilities corresponding to 50 mSv and 2 Sv are less than 3.0×10^{-5} and 3.0×10^{-6}, respectively.

4. RESULTS AND DISCUSSION

4.1. Results for DBA Scenario

For DBA scenario, the variation of individual effective dose with downwind distance (toward the south) from the midpoint between the two reactor units is shown in Figure 3. The results indicate that the individual effective dose at all downwind distances is below 50 mSv. Due to the plume release height of 238 m, the radionuclides undergo atmospheric dispersion and dilution before reaching the ground, which results in relatively lower ground-level concentrations and individual effective doses in the near-field downwind region. As a result, both the concentration and dose initially increase with downwind distance and then gradually level off. The results indicate that the individual effective dose at a distance of 0.5 km to the south of the midpoint between the two reactor units is 5.67×10^{-3} mSv, which is well below 50 mSv. These results indicate that, under the conservative meteorological conditions adopted in this study, the impact of DBA case (LOCA) on individual effective dose during the pre-defueled stage of decommissioning for the Chinshan NPP remains below the evacuation intervention level (50 mSv) specified in the PAG.

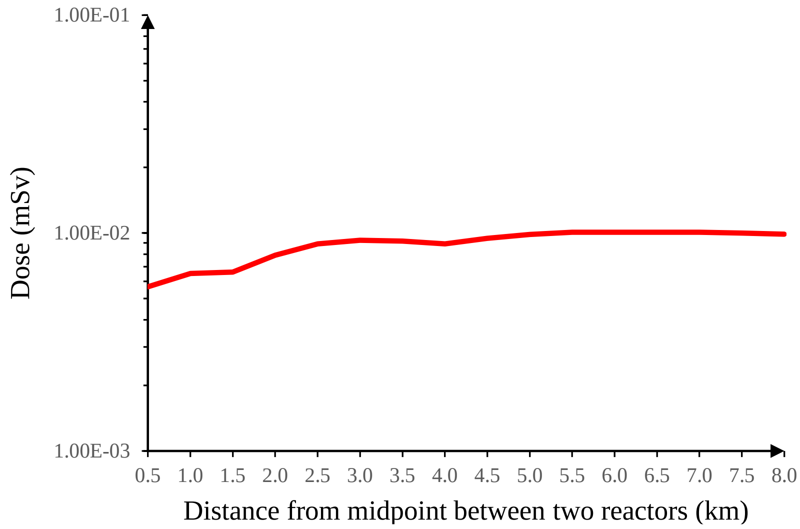

Figure 3: Individual Effective Dose *versus* Downwind Distance for DBA

4.2. Results for SA Scenario

For SA scenario, the variation of annual exceedance probability with downwind distance (toward the south) from the midpoint between the two reactor units is shown in Figure 4. Due to the low wind speed and highly stable atmospheric conditions, the plume dispersion near the ground is limited, which results in MACCS-predicted individual effective doses at various downwind distances readily reaching both the 50 mSv and 2 Sv dose thresholds. In other words, the conditional exceedance of 50 mSv and 2 Sv dose thresholds becomes almost certain, resulting in the conditional exceedance probabilities predicted by the MACCS approaching unity (i.e., 1). Note that the annual exceedance probabilities of 50 mSv and 2 Sv are obtained by multiplying the conditional exceedance probabilities from the MACCS code by the SA release frequency of 1.91×10^{-6} /year listed in Table 6. Therefore, Figure 4 shows that the annual exceedance probabilities for both 50 mSv and 2 Sv are 1.91×10^{-6}, which are lower than the corresponding criteria in Taiwan of 3.0×10^{-5} and 3.0×10^{-6}, respectively. Although the conditional probability of exceeding dose thresholds is close to unity under the assumed meteorological conditions, the annual exceedance probability (i.e., frequency-weighted annual exceedance probability) remains low due to the extremely low frequency of the severe accident sequence (i.e., 1.91×10^{-6} /year). In brief, the results reveal that the EPZ already meets the all regulatory criteria in Taiwan [2] at a distance of 0.5 km from the midpoint between the two reactor units.

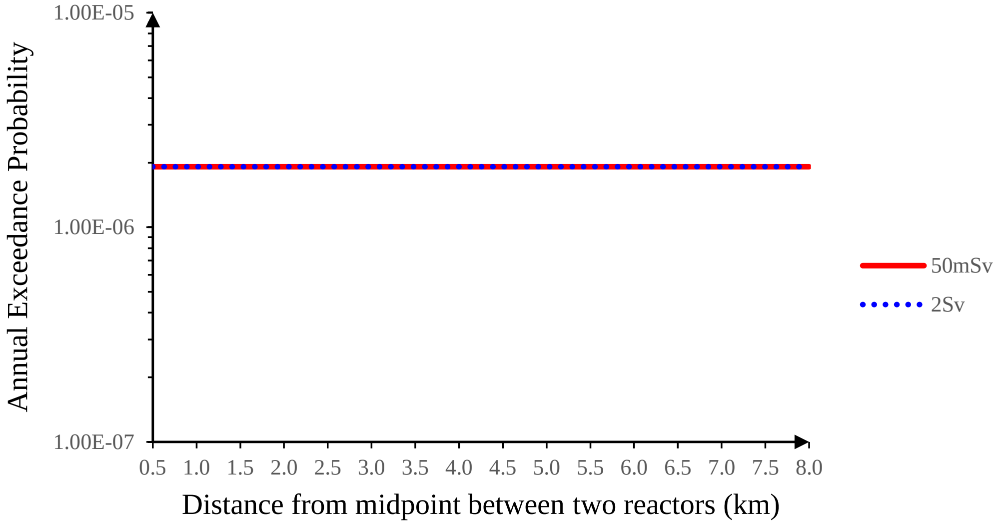

Figure 4: Annual Exceedance Probability *versus* Downwind Distance for SA

5. CONCLUSION

The purpose of this study is to evaluate the EPZ of the Chinshan NPP during the pre-defueling stage of decommissioning under conservative assumptions. The extremely conservative meteorological conditions (i.e., a fixed wind blowing toward the south at 0.1 m/s, stability class G and no rainfall) are considered in this work to establish an upper-bound estimation for EPZ evaluation. The MACCS 3.7 is employed to assess Level 3 risk results in terms of individual effective dose for DBA case and annual exceedance probability for SA case during the emergency phase (i.e., 7 days). The results reveal that the individual effective dose at a distance of 0.5 km to the south of the midpoint between the two reactor units is 5.67×10^{-3} mSv, which is well below 50 mSv (regulatory criterion in Taiwan). Due to the low wind speed and highly stable atmospheric conditions, the plume dispersion near the ground is limited, resulting in MACCS-predicted individual effective doses at various downwind distances readily reaching both the 50 mSv and 2 Sv dose thresholds simultaneously; this explains why the conditional exceedance probabilities for 50 mSv and 2 Sv predicted by the MACCS approach unity (i.e., 1) along the downwind distance. Because the annual exceedance probability (i.e., frequency-weighted annual exceedance probability) is equal to the conditional exceedance probability obtained from the MACCS code multiplied by the radioactive release frequency (i.e., 1.91×10^{-6}/year) derived from the Level-2 PRA, the results show that the annual exceedance probabilities for both 50 mSv and 2 Sv at a distance of 0.5 km to the south of the midpoint between the two reactor units are 1.91×10^{-6}, which are lower than the corresponding criteria in Taiwan of 3.0×10^{-5} and 3.0×10^{-6}, respectively. In brief, the EPZ for the Chinshan NPP during the pre-defueled stage of decommissioning is within 0.5 km from the midpoint between the two reactor units. Therefore, the current 8-km EPZ in Taiwan provides sufficient conservatism under the conservative conditions considered in this study. The findings of this study can serve as a technical reference for EPZ review under similar decommissioning conditions.

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