Probabilistic Evaluation of Emergency Planning Zone for SMART Reactor in Saudi Arabia

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1. Introduction

An evaluation of the size of the emergency planning zone (EPZ) for small modular reactors (SMRs) is a development goal for SMR to enhance their safety and economy. Multiple methods have been proposed to evaluate the appropriate size of EPZ, including deterministic and probabilistic approaches. In this paper, the probabilistic approach is going to be discussed.

Since small modular reactors (SMRs), such as SMART reactor, have considerable safety features compared with large power reactors. SMR forum, which IAEA has operated, indicated the need for new approaches to determine the size of EPZ for SMRs because of their enhanced safety features [1]. Therefore, this paper focuses on determining the size of SMART's emergency planning zone by following probabilistic approach methodology that are presented in US.NRC 1.242 [2].

2. Overview of SMART System

SMART is an integral pressurized water reactor with a maximum thermal power of 365 MW. Unlike a conventional loop-type reactor, SMART contains major primary components of RCS such as the core, pressurizer (PZR), reactor coolant pumps (RCPs), and steam generators (SGs) in a single reactor pressure vessel (RPV) [3]. Figure 1 shows the schematic of the SMART system. The SMART system includes four trains of passive residual heat removal system (PRHRS), four trains of passive safety injection system (PSIS), two trains of automatic depressurization system (ADS), one train of chemical and volume control system (CVCS).

3. Background

In USA, NUREG-0396 [4], which was issued in 1978 before TMI accident, is still backbone in the current EPZ regulation as a technical basis for the determination of EPZ size. NUREG-0396 [4] report recommended 10 miles EPZ of plume exposure pathway for the commercial reactors above 250 MWth. Since the introduction of the EPZ rule (10 CFR 50.47) in 1980 based on NUREG-0396 [4] recommendation, the 10 miles requirement of plume exposure pathway EPZ on the commercial reactors has not been changed for more than 30 years in U.S.A.

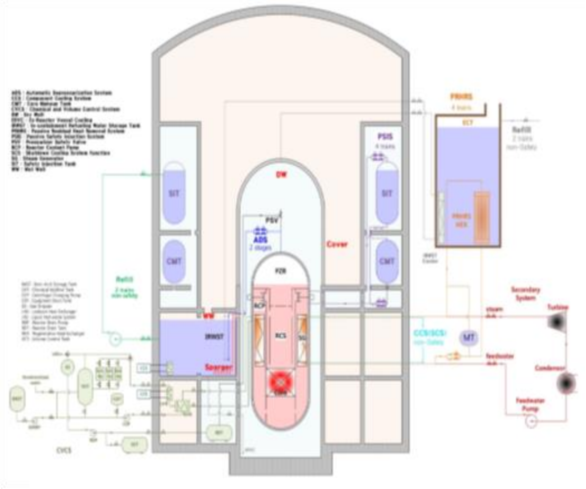


Figure 1. Schematic diagram of SMART reactor

In the 2000's, SMR developers in the United State requested the exemption of the 10 miles requirement of EPZ under the technical basis of SMR, i.e., lower power level and enhanced safety.

In recently, as a result of a lot of discussions about an adequate EPZ policy for SMR more than 20 years between US NRC and SMR's developers, as shown in the NRC position papers [5][6] and developer reports including NEI report [7], there have entered the final stage of applying the site boundary EPZ. In especial, NuScale Company submitted a new plume exposure pathway EPZ of NuScale SMR, which is near site boundary size, to US NRC as a topical report [8]. The EPZ setup methodology adopted in the NuScale is the methodology suggested in the NEI guidance [7].

4. Basic criteria

Based on those criteria in NUREG-0396 [4], NEI [7] suggested the following three criteria including slight modification for clearance of the classification of accident sequences such as 'more severe' and 'less severe' accidents in NUREG-0396 [4] in order to use acceptable assumptions for the SMR. As reflecting this request, the classification of accident sequences in Reg. Guide 1.242 [2] are interpreted as the following conditions:

Condition a: Projected doses from the design-basis accidents would not exceed 10 mSv (1 rem) TEDE over 96 hours outside the EPZ.

Condition b: Projected doses from most sequences that result in a radiological release would not exceed 10 mSv (1 rem) TEDE over 96 hours outside the EPZ.

Condition c: For the worst sequences that result in exceeding 10 mSv (1 rem) over 96 hours off site from a radiological release, immediate life-threatening doses would generally not occur outside the EPZ.

5. The HotSpot code for calculating off-site consequences

HotSpot Health Physics code is a free license code created by Lawrence Livermore National Laboratory (LLNL) to provide Health Physics personnel, emergency response personnel, and emergency planners with a fast, field-portable calculation tool for evaluating accidents involving radioactive materials [9]. It is based on the Gaussian model that provides a first-order approximation of the radiation effects associated with the short-term atmospheric discharge of radioactive materials. Therefore, it is designed for short-range and short-term prediction [9]. The Gaussian model generally produces results that agree well with experimental data in simple meteorological and terrain conditions [9].

6. Methods

Figure 2 represents a summarized flow chart of the evaluation methodology followed by this paper. A short overview of each step, starting from selecting initiating events to the comparison criteria, is presented in this section. Because the steps in the generalized methodology in Reg. Guide 1.242 Appendix A [2] are equivalent to the deterministic approach as described in the previous published paper [10], this paper described the following difference features focused on key issues of probabilistic evaluation.

1. Classification of accident sequences.

2. Evaluation of conditional probability of exceeding dose level for a specific accident sequence.

3. Aggregation of conditional probabilities by using relative frequencies of accident sequence according to the NEI proposal [7].

6.1 Classification of Accident Sequences

According to the rationale in NUREG-0396 Appendix A [4], an approach based on “a spectrum of consequences, tempered by probability considerations” was adopted in NUREG-0396 [4] evaluation for this purpose. Accident sequences were classified as “less” severe accidents and “more” severe accidents according to their consequences and each accidents classes. It is noted, focused on the evaluation of EPZ size, that less severe accidents are applied to the determination of EPZ size, while more severe accidents are applied to assuring the avoiding of their consequences.

In NUREG-0396 [4], accident sequences were classified by physical state of containment integrity, i.e., cases of intact containment were classified as less severe accident, while cases of failed containment were classified as more severe accidents. NEI’s 2013 [7] adopted classical classification approach in NUREG-0396 [4], i.e., the determination between less and more severe accidents is depend on whether the containment is intact or not.

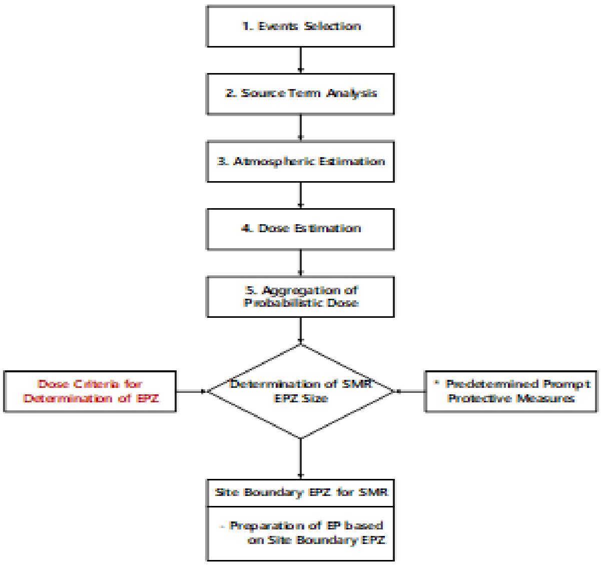


Figure 2. Generalized probabilistic evaluation process

6.2 Evaluation of Conditional Probability of Exceeding Dose Level

An evaluation of conditional probability of exceeding dose level is related to the atmospheric dispersion analysis which follow a given accident sequence and its source term. Thus, the related weather condition could not be specified without specifying the accident occurring condition. A consequence analysis according to atmospheric dispersion of accidental release of radioactive material is not able to use a specific accident condition because weather could not to be fixed.

Annual cumulative distribution of consequence from a joint frequency distribution of weather is used in the evaluation. As an example, Joint Frequency Distribution (JFD) for an annually observed weather data of a specific site could be made by an annual distribution of weather by wind direction, wind speed, and stability class.

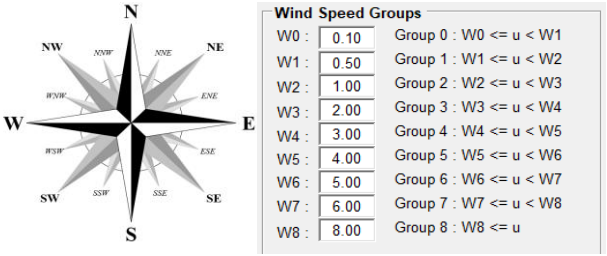
$$f_{seg} = \frac{N_{seg}}{N_t} = \frac{N_{seg}}{\sum_d \sum_s \sum_c N_{dsc}} \quad (1)$$

f_{seg} : a specific weather segment′s frequency [1/yr]

N_{seg}: weather counts of a specific weather segment [numbers]

N_t: total number of weather (e.g. 8760 counts of hourly based weather conditions per year)

d, s, c: wind direction, wind speed group, stability class, respectively



W0 : 0.10 Group 0 : W0 <= u < W1
W1 : 0.50 Group 1 : W1 <= u < W2
W2 : 1.00 Group 2 : W2 <= u < W3
W3 : 2.00 Group 3 : W3 <= u < W4
W4 : 3.00 Group 4 : W4 <= u < W5
W5 : 4.00 Group 5 : W5 <= u < W6
W6 : 5.00 Group 6 : W6 <= u < W7
W7 : 6.00 Group 7 : W7 <= u < W8
W8 : 8.00 Group 8 : W8 <= u

Figure 3. 16-wind compass and wind speed grouping using HotSpot

6.3 Aggregation of Conditional Probabilities

NEI's in their report [7] proposed an aggregation of conditional probabilities by using relative frequencies of accident sequence as following steps:

1. Calculate the probability of exceeding 200-rem whole body acute dose as a function of distance for each of the selected scenarios.
2. For a given distance, sum the scenario frequency-weighted probabilities over all scenarios.
3. Normalize (divide) by total CDF.
4. Plot the normalized sums vs. distance and determine the distance at which the result drops below 1E-3"

That approach, i.e., frequency-weighted conditional probabilities over all scenario was also adopted by NuScale's proposal [8] as following equation:

$$P_d^t(D > D_o) = \sum_{i \in all} \frac{f_i}{f_t} P_d^i(D > D_o) \quad (2)$$

D_o : Objective dose (dose limit)

P_d : Exceedance probability of $D > D_o$ at distance d

f : Accident sequence frequency (1/reactor_year): likelihood

i : i's accident sequence

t : Total accident sequences

A bounding distance of which results drops below 1E-3 will be used in the determination of EPZ boundary in this approach.

7. Source Term Calculations

As a result of the PSA level 1 and 2, to set up the source term categories (STC), the grouping parameters are selected based upon appropriate attributes that impact fission product release and accident sequences. This selected set of parameters defines the unique source term characteristics of each release category, e.g., source term magnitude, composition, release timing and so on.

According to the preliminary level 2 PSA of SMART, the five source terms categories (STC) shown in Figure 4 was classified. STC 1 was assigned accident sequences belongs to 'no containment failure'. STC 2, STC 3, STC 4, and STC 5 was assigned belongs to 'upper containment area (UCA) failure', 'lower containment are (LCA) failure', 'containment isolation failure: No ISO' and 'containment bypass: BYPASS', respectively.

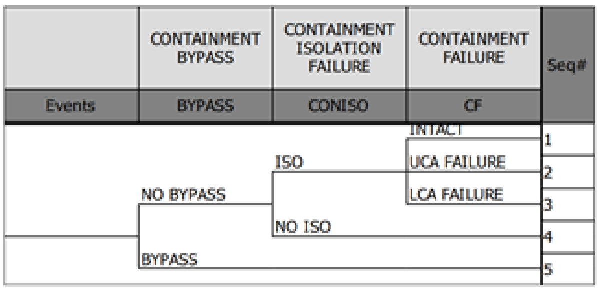


Figure 4. Source Term Category Logic Diagram

Table 1. Source term results of which PSA selected accident sequences

Source term group	STC 1 No CF	STC 2 CF: UCA Failure	STC 3 CF: LCA Failure	STC 4 CF: Isolation Failure	STC 5 CF: Bypass Failure
ST1 (Xe)	1.72E-03	4.08E-01	5.12E-01	4.37E-02	4.85E-01
ST2 (I)	8.43E-06	3.06E-05	1.76E-03	1.29E-02	1.53E-01
ST3 (Cs)	8.79E-06	3.09E-05	1.54E-03	1.22E-02	1.32E-01
ST4 (Te)	8.00E-06	8.98E-05	7.38E-04	1.11E-02	9.03E-02
ST5 (Sr)	3.75E-07	3.02E-08	4.13E-06	3.65E-04	2.93E-03
ST6 (Ru)	4.60E-12	4.60E-12	4.60E-12	4.60E-12	4.60E-12
ST7 (La)	2.89E-10	2.04E-11	2.36E-09	2.34E-07	1.06E-07
ST8 (Ce)	7.49E-13	1.75E-13	4.94E-12	5.42E-10	9.15E-11
ST9 (Ba)	4.05E-08	1.01E-07	8.97E-06	8.35E-05	4.12E-05

7.1. Probabilistic Analysis results

From the source term results, STC 1 as shown in Figure 5 would be set up to most sequences according to Reg. Guide 1.242 classification because their dose level sufficiently lower than 10 mSv during 4 days for a desired distance. While, STC 2, 3, 4 and 5 as shown in Figures 6, 7, 8 and 9 respectively would be set up to the worst sequences because their dose level much higher than 10 mSv during 4 days for a desired distance.

Table 2. Source term categories and related frequency fractions

STC	Containment Failure Mode	Freq. Fraction, f_i/f_{total}	Remark
1	NO CF	89.5 %	Most sequences
2	CF: UCA Failure	2.9 %	The worst sequences
3	CF: LCA Failure	3.1 %	
4	CF: Isolation Failure	0 %	
5	CF: Bypass Failure	7.1%	

STC 1: No CF

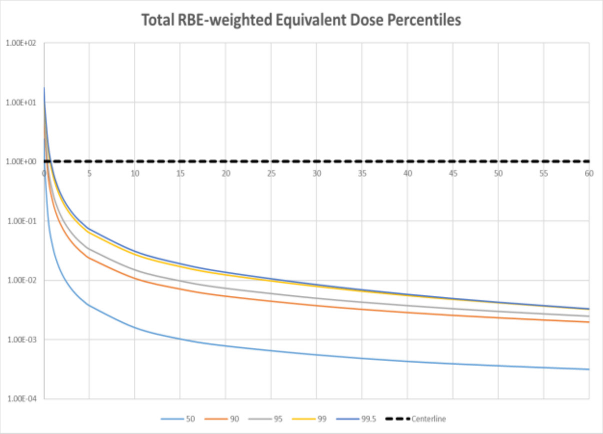


Figure 5. STC 1 No containment failure

STC 2: UCA Failure

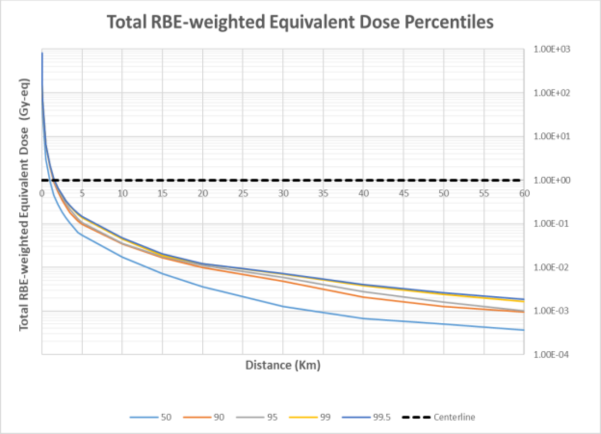


Figure 6. STC 2 UCA Failure

STC 3: LCA Failure

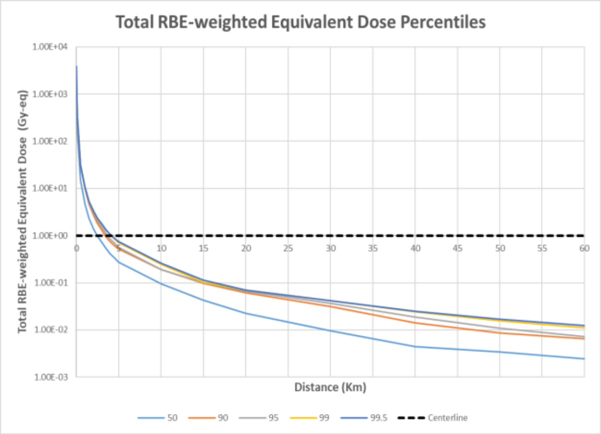


Figure 7. STC 3 LCA Failure

STC 4: Isolation Failure

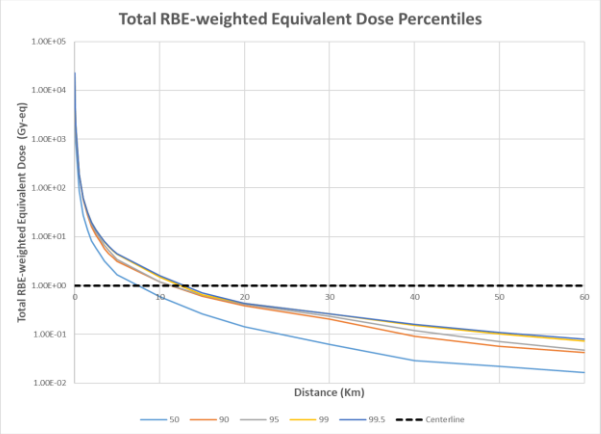


Figure 8. STC 4 Isolation Failure

STC 5: Bypass Failure

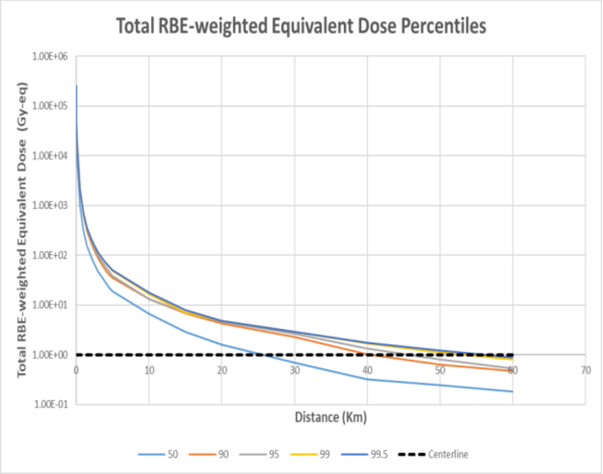


Figure 9. STC 4 Isolation Failure

8. Conclusion

As shown in the probabilistic analysis results, bounding distances of 4 km below 1E-3 conditional probability based on NuScale and Reg. Guide 1.242 [2] approaches are too large to apply a site boundary of EPZ. This is primarily due to a release amount of radioactive materials of STC5 accident sequence as an extreme case, In order to reduce a release amount of radioactive materials for given extreme accident sequences, firstly it is necessary to improve the design features of SMART. Secondary, an approach to classification of the accident sequences including screening criteria of accident sequences could be considered in the application area such as NuScale proposal in TVA (Tennessee valley Agency)'s ESP (Early Site Permit) process [11]. They proposed a limit value of frequencies as the classification and screening criteria of accident sequences, and they insisted that there is no case of the worst sequences. In SMART case as a feasibility, there are extremely low frequencies of STCs. Since STCs are almost below 1E-8 per reactor-year, the STC5 as an extreme accident sequences could be eliminated if a kind of reasonable screening values could be used in the screening of accident sequences.

For the current applied approaches that have been proposed in this paper and the previous published paper [10] are discussing the applicability of EPZ scale-down size for the Saudi site. The concept of the SMR-EPZ is still under development worldwide and many countries are evaluating their regulations to accommodate the new applied methodologies.

ACKNOWLEDGEMENTS

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