Transactions of the Korean Nuclear Society Autumn Meeting
Changwon, Korea, October 20-21, 2022

Source Term Aspects on Dose Criteria of SMR's EPZ Size Determination according to U.S. NRC's New Regulatory Guide

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1. Introduction

Small Modular Reactors (SMRs) are being developed worldwide, which purport enhanced safety performance with inherent, passive and novel safety design features based on small thermal power [1]. SMR developers are insisting on the need for an alternative emergency planning zone (EPZ) regulation[1] as a basic requirement for their development instead of the EPZ regulation for commercial nuclear power plants [2]. The United States Nuclear Regulatory Commission (U.S. NRC) has recently entered the final stage of rulemaking of a new alternative emergency preparedness (EP) regulation based on the "site boundary" EPZ to be applied to SMRs [3]. The new alternative EP regulation consists of 10 CFR 10.160 and Regulatory Guide 1.242 (Draft Guide 1350) [4, 5]. In order for a SMR to have its site boundary EPZ approved from U.S. NRC, it should be demonstrated that the SMR has a capability of establishing the site boundary EPZ according to the methods presented in Reg. Guide 1.242 Appendix A and B.

The key method to demonstrate a site boundary EPZ is based on projected doses assessments as followings: (1) for design basis accidents (DBAs) and most sequences, the doses outside the EPZ would not exceed 10 mSv TEDE over 96 hours[2]; (2) for the worst sequences, it is suggested that "immediate life-threatening dose" would generally not occur outside the EPZ. These dose-oriented criteria may be difficult to understand most SMR's developing engineers for design, safety analysis, severe accidents and probabilistic safety assessments.

This paper focus on a reverse estimation of source term aspects as surrogate measures from these dose criteria in order to demonstrate the capability of SMR's safety performance to apply the site boundary EPZ. This is because source term is easier and directive to understand the design goals to establish the site boundary EPZ to SMR's engineers.

It is noted that other technical issues related to the application of the new proposal for "site boundary" EPZ such as a classification of accident sequences and related issues were out of scope in this paper.

2. Methods and Results

2.1 Dose criteria for the alternative EPZ

The dose criteria of Reg. Guide 1.242 Appendix A described as follows:

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.

These dose criteria can be classified into two types as follows: (1) condition a and b mean the reference dose that determines the site boundary EPZ; and (2) condition c suggests a dose limit of the consequence for the extreme accident sequences. These conditions for the determination of EPZ size are equivalent to the following expression in NUREG-0396 as the technical basis of EPZ of US NRC [7]:

> *"The Task Force has concluded that both the design basis accidents and less severe core-melt accidents should be considered when selecting a basis for planning predetermined protective actions and that certain features of the more severe core-melt accidents should be considered in planning to assure that some capability exists to reduce the consequences of even the most severe accidents."*

Under this context, the meaning of condition c, specified as a condition for evaluating the coping capability of the emergency plan against the extreme accidents, means that it does not include the occurrence of victims even in those accidents.

The first conditions are clearly indicated that the dose limit to determine the EPZ size is a value of 10 mSv TEDE over 96 hours, whereas the second condition may not clearly define the dose limit value.

[1] EPZ is a designed zone for emergency preparedness, which is a basis for public protection from hypothetical radiation release accidents.

[2] This criterion is from the Protective Action Guides (PAG) of U.S. Environmental Protection Agency (U.S. EPA) [6]

In order to apply the second condition, it should be required the some interpretation of the phrase of "immediate life-threatening dose." The "immediate" in this phrase means an acute or deterministic health effect in the radiological health effect models. Under this assumption, a threshold dose of that model could be applied to an "immediate life-threatening dose" as a representative dose limit. This is because a threshold dose means that a fatality below that value does not occur in that model. It is noted that the threshold dose of the red marrow that is considered as the representative target organ could be used in order to represent an immediate life-threatening dose for condition c.

Historically, the 2 Sv has been described in NUREG-0396 as a representative application to show that a capability exists to reduce the consequences of even the most severe accidents. In NuScale's proposal [8], the same value of acute red marrow dose was used for condition c.

Whereas, there were the different recommended dose limits in US EPA manual [6] and IAEA safety standards series [9, 10]. In the latest EPA PAG manual, 1 Gy to 2 Gy in Table 3-2 is presented as the case of mortality minimal dose limit. Meanwhile, according to Part 3 and 7 of the IAEA safety standard series, 1 Gy-Eq[3] for the acute external exposure or 2 Gy-Eq for the acute internal exposure is suggested as the generic criteria for doses to prevent deterministic health effects, respectively.

In this paper, 10 mSv of effective dose (ED) was considered as a dose criterion for condition a and b and 1 to 2 Gy-Eq of the acute red marrow were considered as a dose criterion for condition c. It is noted that the acute red marrow dose adjusted for the RBE values for each radiation type as applied in IAEA was applied to the dose evaluation.

2.2 Relationship between Dose and Source Term

Typically, the dose assessment is performed by applying a specific atmospheric dispersion model considering the site characteristics and meteorological conditions to the source term of specific accident sequences. Basically, the release amount of fission products, i.e., the source term, of a specific accident sequences is approximately related to the dose according to distance. For example, as a simplified conservative model described in Reg. Guide 1.145 [11], the dose is directly proportional to source term because the dilution factor χ/Q in the equations is directly related to dispersion factor by distance. In a detailed dispersion model such as a Gaussian plume model, the relationship between source term and dose maintains a similar fashion. From this relationship, an approximated source term from the dose could be estimated by using a reverse relationship between source term and dose.

[3] Gy-Eq means that non-standard relative biological effects (RBE) values for each radiation type were used in the evaluation of dose.

2.3 Reverse Approximation

The following method was applied to approximate the level of source term:

1. Selection of accident sequences according to the level of a representative nuclides (Cs-137) of source term
2. Estimation of dose according to distance for each accident sequence
3. Determination of approximate source term with respect to dose criteria

About 50 - 70 radioactive materials including fission products as a source term are considered in the consequence analysis. Because the exposure characteristics of radioactive materials are different to each other, it cannot be treated collectively. Furthermore, since the release amount of radioactive materials varies depending on phenomenological behaviors of radioactive materials considering accident progresses, it is difficult to represent the source term with a single radionuclide. Despite these shortcomings, one radionuclide representing the source term could provide convenience of simplification and reverse approximation.

In this paper, Cs-137 as a representative nuclide was considered for the selection of accident sequences. Seven accident sequences were selected with the range of 10 to 15 order of magnitude of the release amount (Bq) of Cs-137. This paper adopted the absolute amount of radioactive materials for accident sequences was used applied in order to reversely estimate dose.

Additionally, the containment status, i.e., intact or damaged, were considered to select accident sequences because these status could be affected on the release characteristics of radioactive materials even considering the enhanced containment features. Three accident sequences for containment intact and four accident sequences for containment damaged were considered.

It is note here that for a comparison of selected accident sequences, the surrogate source term of the Early Site Permit (ESP) document of Tennessee Valley Authority (TVA) Clinch River Nuclear Site [12] were considered as a representative example for applying the site boundary EPZ of the US NRC. According to TVA's ESP approval document, it specifies the upper bounded source term for the applied nuclear power plants to be installed at TVA site.

Table 1 shows the seven considering accident sequences and TVA surrogate source term.

Figure 1 shows the release amount (Bq) of Cs-137, I-131 and Kr-85 for the seven accident sequences and TVA surrogate source term. Kr-85 was included as a representative nuclide for noble gases isotopes for a comparison of containment status.

It is note that the selected accident sequences do not reflect the characteristics of a specific SMR because the key purpose of this paper derives the release amount of Cs-137 from selected accident sequences to be adequate to EPZ's dose criteria. Basically, the selected accident sequences were derived from the reference data of accident sequences in a SMR, WASH-1400 [13] and NUREG/CR-2239 [14].

Dose according to distance for each accident sequence was estimated by RCAP code [15], which has been developed by KAERI. The estimation models of dispersion of RCAP code was set to equivalent to MACCS2 code model features in this study.

2.4 Results

Fig. 2 shows the dose estimation results according to distance as a mean value of dose for all selected accident sequences.

As shown in Fig. 2, it is helpful to understand the characteristics of dose according to distance of accident sequences comparing with dose criteria such as 10 mSv for most sequences (intact containment) and 1 or 2 Sv for the worst sequences (damaged containment).

For most sequences, a dark red line in Fig. 2 means 10 mSv as the dose criterion that determines the site boundary EPZ. The intersected distances between a dark red line and dose lines of most sequences indicate the site boundary distances. The range of these distances bounds from about 0.4 km to 1 km.

If a desirable distance of SMR's site boundary would be below 1 km, the most 2 case which are bounded on about 1 km could not be applicable to a reasonable site boundary. This is because Reg. Guide Appendix A recommends that a considering dose value should use more serious values such as a 99.9 %tile (i.e., 0.1 % conditional probability).

Although the limiting released amount of Cs-137 depends on considering site boundary, it could be considered below 1 km as a reasonable range of site boundary. The most 0 and most 1 cases are approximately suitable to site boundary as the limiting accident sequences, the estimation results reveals that about 2.17E12 Bq of Cs-137 is a limiting release amount as shown in Table 1.

Whereas for the worst sequences which is containment damaged cases, a dashed red line in Fig. 2 is 2 Sv line as an immediately life-threatening dose. In these cases, the two types of acute effective dose and red marrow dose were estimated in order to obtain an insight of difference between the two types of doses. As considering this paper purpose to approximately estimate the order of magnitude of the representative source term, i.e., Cs-137, it could be estimate that there is no significant difference between the two types of dose.

As similar reason of most sequences, the intersected distances between a dashed red line and dose lines of the worst sequences indicate the site boundary distances. The range of these distances bounds below 1.3 km. The worst 1 and 2 cases are approximately suitable to site boundary, but worst 3 case does not to site boundary. It is observed that 1.85E14 Bq of Cs-137 is a limiting release amount for the worst sequences.

Although the release amount of Cs-137 could not be precisely determined, the order of magnitude of the release amount could be identified from the estimated results. For an application of site boundary EPZ, it is observed that an approximately Tera (1E12) Bq is a bounded release amount of Cs-137 for most sequences and also an approximately 100 Tera (1E14) Bq is a bounded release amount for the worst sequences.

It is noted that the worst 0 case considered for an applicability of 10 mSv as the dose criterion was not fit to determine a site boundary EPZ as shown in Fig. 2. This feature could be affected on several factors, but it seem to be a primary factor related to the release of noble gas radioisotopes. As shown in Table 1 and Fig. 1, although the release amount of Cs-137 of the worst 0 case is much smaller than that of the most 2 case, the release amount of Kr-85 as a representative noble gases of the worst 0 case is much larger than that of the most 2 case.

Since a primary factor affected on the large release of noble gases is the integrity of containment, it is identified that the sequences where the noble gases is not effectively controlled could not be included in most cases for determining site boundary EPZ. This is related to the accident classification, of which discussion topics is out of scope in this paper.

It is noted here one that the TVA's surrogate source term provides some insights for understanding the source term features related to noble gases effects.

2.5 TVA Surrogate Source Term

The TVA's surrogate source term is a representative source term for the SMRs to be built on the TVA site, which is a condition of the approval of the TVA ESP. Firstly, in order to understand the characteristics of the TVA's surrogate source term, it is necessary to show the pale blue line with marked box in Fig. 2 as the dose estimated results. This dose line intersects 10 mSv line at about 0.6 km distance. This means that the TVA's surrogate source term could be applied in an estimation of the site boundary EPZ.

Although the amount of Cs-137 of this source term is slightly higher than that of the most 2 case, the dose estimated results is lower than that of the most 2 case. Moreover, the result is less than the most 1 case of which the amount of Cs-137 is less than that of the most 2 case. In order to explain the reason for this result, the amount of each isotopes of TVA's surrogate source term were compared with those of the most 1 and the worst 0 cases as shown in Fig 3.

Fig. 3 reveals that there are additional features of the TVA's surrogate source term, i.e., it seems that there is almost no release of radioisotope belongs to noble gases. This feature means that this feature is due to the containment status. This insight would be helpful in understanding the new alternative regulation for SMRs EPZ by US NRC.

3. Conclusions

This paper introduced an application of the site boundary EPZ as a key request for the development of SMRs. The US NRC is playing a leading role in an application of the site boundary EPZ for SMRs, and is realizing it through the rulemaking of 10 CFR 50.150 and relevant Reg. Guide 1.242. This alternative EP rule to apply the site boundary EPZ has a consequence-oriented approach based on the dose criteria. For a convenient use of this new rule, this paper focus on an approximate estimation of the source term from the dose criteria of the EPZ determination of US NRC's new rule by a reverse estimation.

An approximate source term represented by the order of magnitude of the release amount of Cs-137 was estimated according to the dose criteria. According to the results, it seems that for most sequences as the reference accident sequences an approximate upper bound of source term were estimated as about Tera (1E12) Bq of Cs-137 under the containment intact condition. Whereas, for the worst sequences an approximate upper bound were estimated as about 100 Tera (1E14) Bq of that without containment intact condition.

It is expected that the insights obtained in this paper could be utilized for design, safety analysis, PSA and severe accident assessment for a development of SMR in order to apply the site boundary EPZ.

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Table 1. Seven considering accident sequences and TVA surrogate source term

Name	Dose Criteria	Applicability	Containment Status	Release Amount (Bq)		
				Cs-137	I-131	Kr-85
Most 0	PAG	OK	Intact	1.08E+12	5.18E+12	1.87E+13
Most 1	PAG	OK	Intact	2.17E+12	1.04E+13	3.74E+13
Most 2	PAG	Not OK	Intact	3.25E+12	1.55E+13	5.61E+13
TVA	PAG	OK		3.29E+12	2.51E+13	1.22E+14
Worst 0	PAG; Acute	Not OK (PAG)	Damaged	3.82E+11	1.91E+12	4.51E+14
Worst 1	Acute	OK	Damaged	3.82E+12	1.91E+13	4.51E+15
Worst 2	Acute	OK	Damaged	1.85E+14	1.11E+15	5.61E+15
Worst 3	Acute	Not OK	Damaged	1.48E+15	8.01E+15	4.84E+14

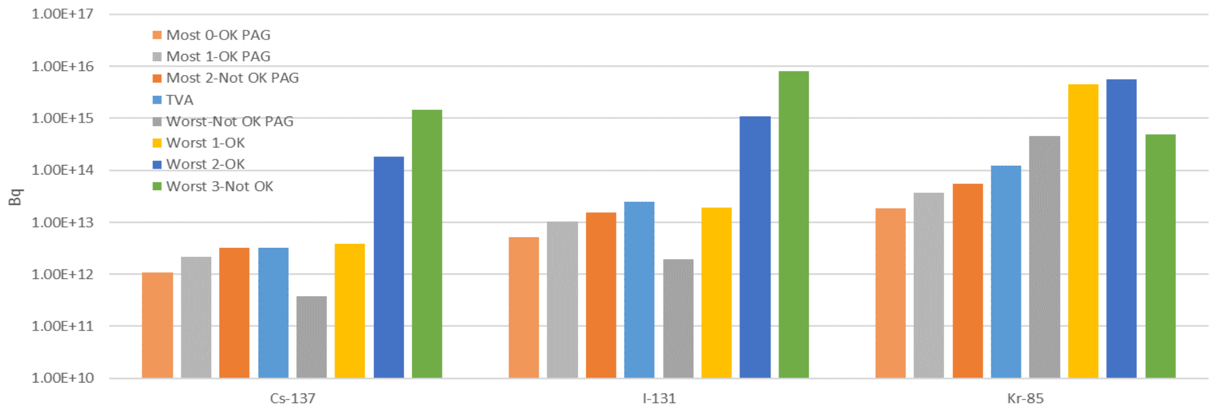

Fig. 1. The Release amount of Cs-137, I-131 and Kr-85 of seven considering accident sequences and TVA surrogate source term

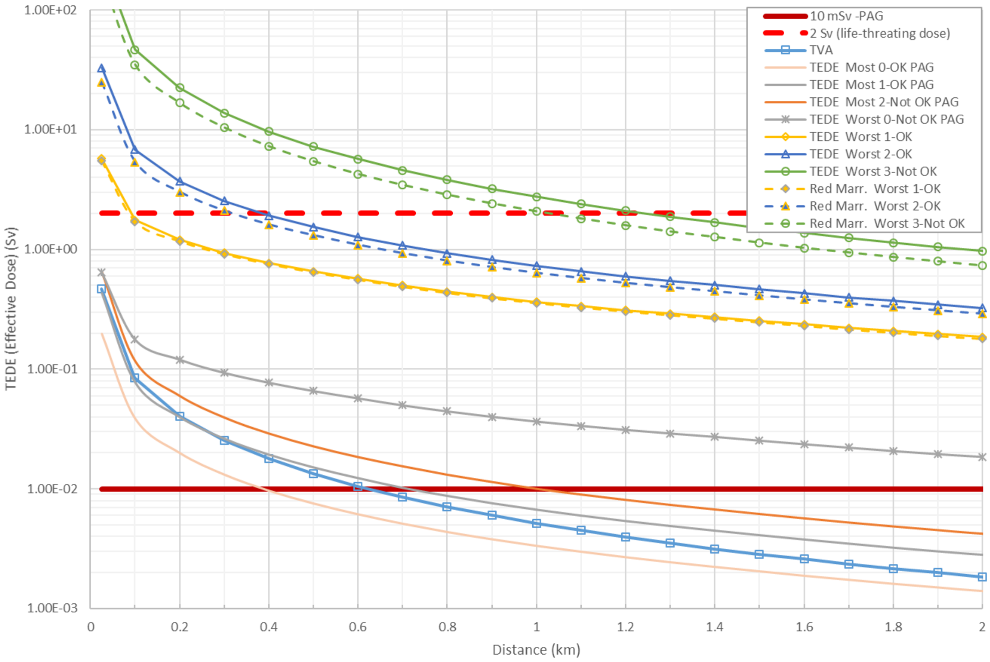

Fig. 2. The dose estimation results according to distance for all selected accident sequences.

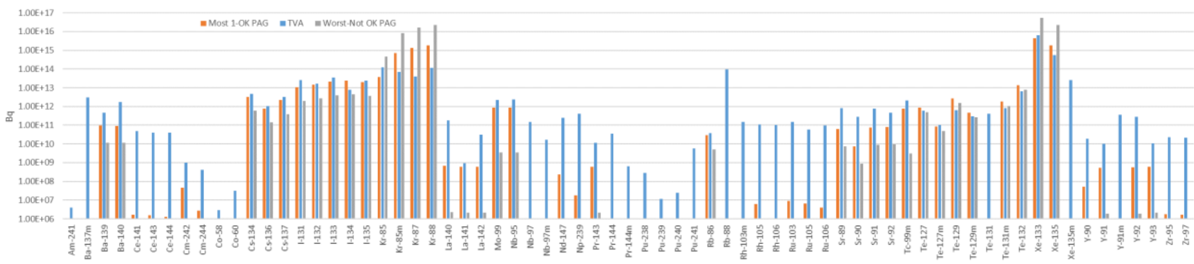

Fig. 3. Comparison of the amount of each radioisotopes between TVA's surrogate source term, the most 1 and the worst 0 cases source term.