Transactions of the Korean Nuclear Society Autumn Meeting
Changwon, Korea, Oct 24-25, 2024

An EPZ Determination with Under-Development Codes for a Molten Salt Reactor

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Keywords : EPZ, F-C Target, Molten Salt Reactor, PSA, Consequence

1. Introduction

For the licensing of non-LWR advanced reactors, the technology inclusive, risk informed, performance-based regulation (TI-RIPB) was proposed by NEI 18-04 [1] and endorsed by the NRC as RG. 1.233 [2]. In ref. [3], MSRE [4] was analyzed by the TI-RIPB method and one of the consequences (~ 5 rem) was calculated by hand. After the hand calculation of consequences, the mechanistic source term (MST) code, MELCOR, has been under-developed for MSR [5]. Thus, with the recent results of under-developed MELCOR for MSR, first, the Emergency Planning Zone (EPZ) of MSRE is roughly determined, and then the consequences calculated at the Exclusion Area Boundary (EAB) for 30 days are marked on the F-C curve. For non-LWR advanced reactors, the distance of EPZ and EAB is usually the same for economic and administrative reasons.

Recently, KAERI has started a long-term research project to build molten salt reactors (MSRs), the details of which cannot be disclosed. In addition, Seaborg is attempting to obtain a license from the Korean nuclear regulatory body for his compact MSR (CMSR) for an energy barge through a venture company, BEES Inc. However, the current Korean nuclear regulation is not yet prepared for the non-light water SMR, so the US TI-RIPB described in RG 1.233 could be a good reference regulation. Probabilistic Safety Assessment (PSA), which plays an important role in the design and licensing in the TI-RIPBR, is performed at the conceptual, preliminary, detailed, and final design stages for an MSR. Also, EPZ determination and consequence analysis are performed according to the different PSA results.

This paper shows the EPZ determination and consequence given PSA and MST results.

2. Methods

2.1 *New Regulation in MSR Design*

In order to accept various non-light water MSR designs, the US NRC prepared a new regulation called 'TI-RIPB', RG. 1.233[2], which incorporates NEI 18-04[1]. According to RG. 1.233, each accident sequence of new MSR should meet the Frequency-Consequence (F-C) target, and the Licensing Basis Events (LBEs) such as Design-Basis Event (DBE) and Beyond Design-Basis Event (BDBE) are determined by the frequency of the event. Although this TI-RIPB has not yet been accepted by the Korean nuclear regulatory body, this paper describes the methodology on the basis of TI-RIPB.

2.2 MSRE PSA

Since the design of KAERI MSR is proprietary, MSRE PSA is used to describe the EPZ determination and consequence.

The calculated frequency and consequences for MSRE are shown in Fig. 1 [3].

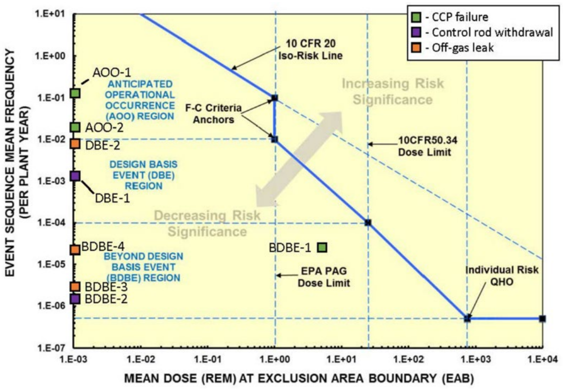

Fig. 1. MSRE accident sequences and Frequency Consequence Target of RG. 1.233

In Fig. 1, the consequence BDBE-1 value (~ 5 rem) is calculated by hand [3, 4]. However, it can be calculated by MST by the MACCS code instead of hand calculation, and it is discussed in the following sections.

The frequency and consequences of the event sequences shown in Fig. 1 is explained in Table 1. In Table 1, the event sequence BDBE-5 is the BDBE which is derived from initiating event 'fuel pump failure' as shown in Fig. 2 [6].

Table 1. Frequency and Consequences of Event Sequences of MSRE

Event Category	Frequency (/yr)	Consequence (rem)
AOO-1	0.115	negligible – no release
AOO-2	1.78E-2	negligible – no release
DBE-1	1.18E-3	negligible – no release
DBE-2	9.97E-3	Minimal
BDBE-1	2.39E-5	~5 rem
BDBE-2	1.56E-6	negligible – no release
BDBE-3	3.47E-6	Minimal
BDBE-4	2.20E-5	negligible – no release
BDBE-5	2.99E-6	?

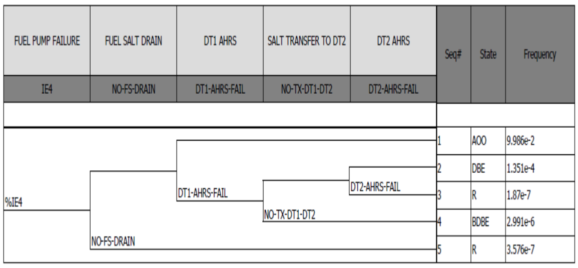

Fig. 2 Event tree for fuel pump failure developed in BEES Inc.

2.3 Mechanistic Source Terms and Release Fraction

The molten salt can retain many radionuclides when the molten salt changes to the solid state. Thus, the amount of radionuclides released to the environment is generally less than that of LWRs during an accident.

MSR MST models are currently being developed and implemented in MELCOR in the USA. Although the computer code is still under development, the first results were published in 2022 [5], from which the MSTs of MSRE could be roughly captured.

Let's assume that the BDBE-1 of Table 1 is similar to 'spill accident without water' and BDBE-5 of Table 1 is similar to 'spill accident with water'. The release fractions of the source term for important radionuclides during two beyond design-basis accidents are given in Ref. [5]. For example, we can read the value inside the red dot circle marked in Fig. 3, i.e. the Xe release fraction is 2.0E-3. Similarly, in Fig. 4, the I release fraction is 4.0E-4. Thus, the release fraction of Xe/Kr, I, Cs, Ce radionuclide groups can be found in Ref. [5].

In the MACCS2 code [7], which calculates the exposure dose in the vicinity of the reactor after an accident, the release fractions of nine (9) radionuclide groups are used.

The release fractions of the radionuclide groups Sr, La and Ba are derived from Ref. [8]. Although the MSR of Ref. [8] is the SAMOSAFER MSR, which is different from the MSRE, it is assumed that the release fraction would be similar. In Fig. 5, the mass of the inventory is shown [8]. In Fig. 6, the mass of aerosols in the confinement is shown [8]. Thus, if we assume that all aerosols in the confinement are released to the environment, we can obtain the release fraction by the aerosols.

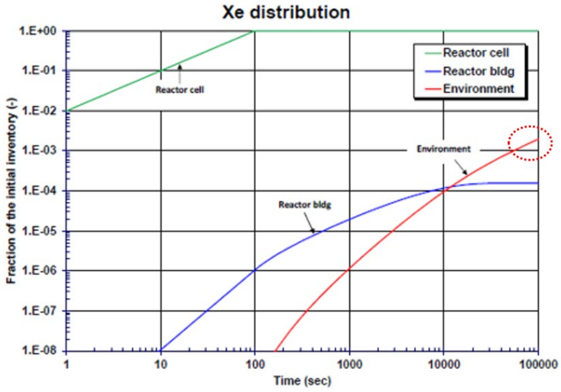

Fig. 3 Xe release fraction during salt spill accident without water in MSRE [5]

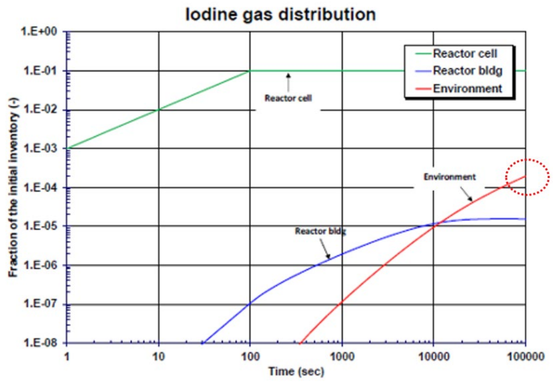

Fig. 4 I release fraction during salt spill accident without water in MSRE [5]

Element	Mass [kg]	Initial activity [PBq]
Cs	11.2	5 500
Zr	182	22 600
Np	170	2 200
Pu	355	200
Sr	26.5	19 200
Ba	13.4	28 500
La	37.6	30 400
Ce	129	22 900
Nd	170	3 200

Fig 5. Mass and activity of initial inventory before accident [8]

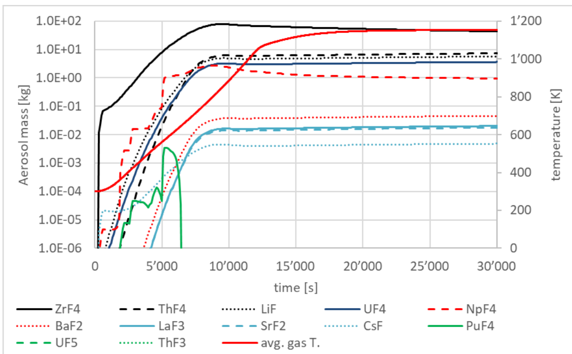

Fig 6. Aerosols in the confinement after accident [8]

Since there is also vapor mass in the confinement after the accident [8], we can obtain the release fraction from the aerosols and vapors. The release fractions of the Sr, La and Ba radionuclide groups are derived in this way.

The release fractions of the source term for 9 radionuclide groups in the MACCS2 code are shown in Table 2 and Table 3. The release fractions of Te and Ru are only assumed.

Table 2. Release fraction of BDBE-1: Spill Accident without water

XE/KR	I	CS	TE	SR	RU	LA	CE	BA
2.0E-3	4.0E-4	2.2E-4	2.2E-4	2.64E-3	2.0E-10	5.3E-4	2.0E-10	4.5E-3

Table 3. Release fraction of BDBE-5: Spill Accident with water

XE/KR	I	CS	TE	SR	RU	LA	CE	BA
8.0E-4	5.0E-5	4.0E-8	4.0E-8	2.64E-3	4.0E-8	5.3E-4	4.0E-8	4.5E-3

2.4 EPZ Determination

In RG. 1.242 [9], the EPZ determination criteria of NUREG-0396 [10] are interpreted as follows;

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

Criterion 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.

Criterion 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.

Criterion a would apply to DBEs and is not a critical criterion for advanced reactors. As shown in Fig. 1 or Table 1, the EPZ distance is not determined by Criterion a because the effects of DBEs are negligible.

In Criterion c, if the conditional probability of a dose exceeding 200 rem whole body acute suddenly drops to 1.0E-3 at a distance, the distance is the EPZ distance. However, the conditional probability of the dose exceeding 200 rem whole body acute does not occur. Perhaps MACCS2 is not accurate less than 500 m around the reactor. Since it is known that MACCS4 [11] can handle this problem, criterion c should be checked later by MACCS4.

For the BDBE-1 case, the exposure dose is shown in Fig. 7. Thus, the EPZ distance can be determined to be 580 m.

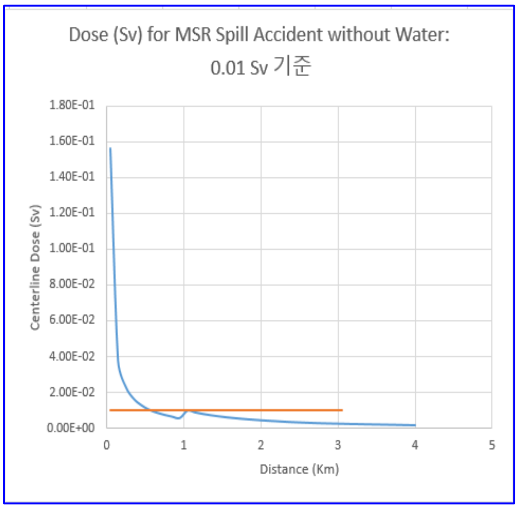

Fig. 7 Dose for BDBE-1: Salt spill accident without water

For the BDBE-5 case, the exposure dose is shown in Fig. 8. Thus, the EPZ distance can be determined to be 470 m.

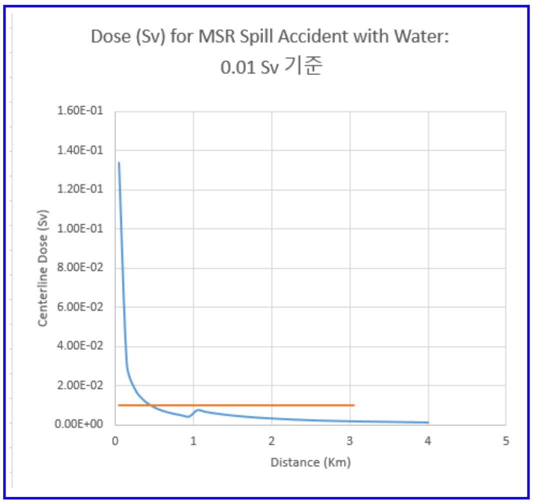

Fig. 8 Dose for BDBE-5: Salt spill accident with water

If we assume that the EPZ distance for the minimum consequence is 20 m, the EPZ distances for the different BDBEs can be summarized as shown in Table 4. Thus, by aggregating the frequency fraction of BDBEs, the EPZ distance would be 284 m.

2.5 Consequences of BDBEs

Since the EPZ distance is determined, the dose consequences at the EAB are calculated for 30 days and the results can be marked on the F-C curve. For non-LWR advanced reactors, the distance of EPZ and

EAB is usually the same for economic and administrative reasons. Because if the EPZ includes public residents, the utility should practice the emergency situation with the public residents every year, and should accept many administrative manpower loss.

Table 4. EPZ distances for the different BDBEs

Event Category	Frequency (/yr)	Consequence (rem)	Freq (%)	EPZ Distance (m)
BDBE-1	2.39E-05	~5 rem	44	580
BDBE-2	1.56E-06	negligible-no release	3	0
BDBE-3	3.47E-06	Minimal	6	20
BDBE-4	2.20E-05	negligible-no release	41	0
BDBE-5	2.99E-06	~	6	470
EPZ distance by aggregating the frequency fraction				284

The consequence of BDBE-1 calculated at EAB (= EPZ) is about 2 rem, and that of BDBE-5 is 1.6 rem. These new consequences are marked in the F-C curve as shown in Fig. 9.

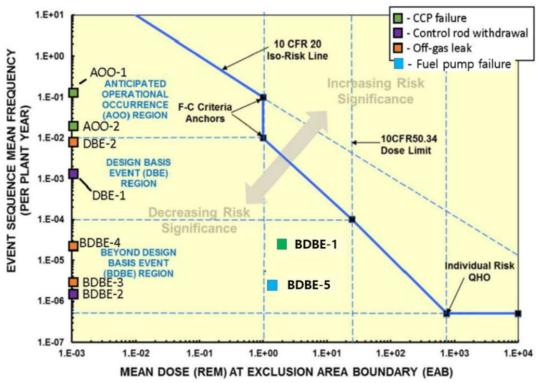

Fig. 9 MSRE accident sequences and New F-C Curve

3. Conclusions

Although the computer code, such as MELCOR, to model and calculate the MSR MST is not complete and is still under development, its MST results can be used to calculate the EPZ distance and eventually the consequences at the EAB. Thus, the MSRE EPZ distance is derived as 284 m, and the BDBE-1 consequence is calculated as 2 rem (it was 5 rem by hand calculation). The BDBE-5 consequence derived from the fuel pump failure initiating event is 1.6 rem. However, for more accurate results, the following should be considered.

- For more accurate EPZ, the MACCS4 code should be used since it is more accurate near the reactor.
- Also, the initial inventory is used slightly less than that of MSRE, and which may result in a short EPZ distance.
- The nine radionuclide groups in MACCS2 are used for this paper. However, it is recommended to use slightly different and more radionuclide groups for MSR.

Acknowledgement

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (Ministry of Science and ICT) (RS-2023-00261295).

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