Determination of Emergency Planning Zone Distance for SMART Reactor in Saudi Arabia

Omar Natto [a*], Sultan AlFafi [a], Seokjung Han [b], Kilyoo Kim [b], Sangbaik Kim [b]
[a]*KACARE (King Abdullah City for Atomic and Renewable Energy)*
[b]*KAERI (Korea Atomic Energy Research Institute)*
[*]*Corresponding author: o.natto@energy.gov.sa*

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. As a deterministic approach, there are two main representative methods using a critical case of accident by IAEA [1] and a comprehensive evaluation approach that considers all types of accidents by US NRC [2]. Both of them have a wide range of uncertainties depending on their assumptions.

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 [3]. Therefore, this paper focuses on determining the size of SMART's emergency planning zone by following deterministic evaluation methodologies that are presented in appendix I of the IAEA's EPR-NPP report [3].

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) [4]. Fig.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. Methods

Fig. 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.

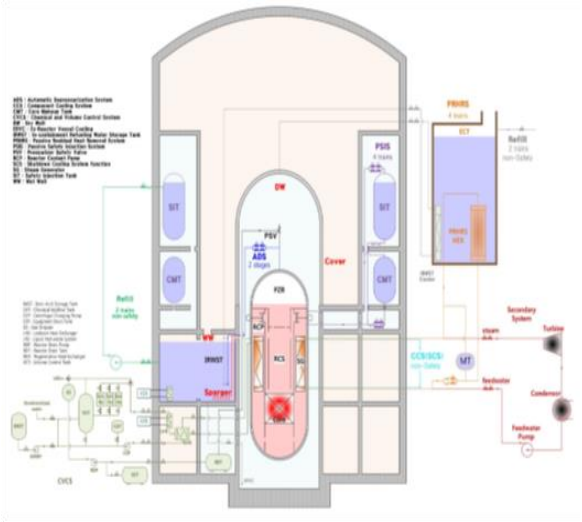

Figure 1 Schematic diagram of SMART reactor

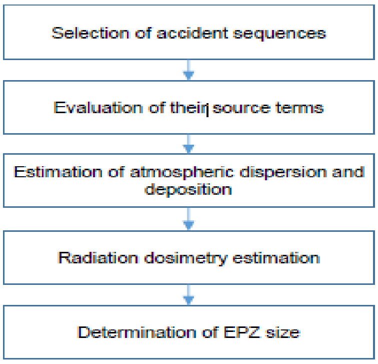

Figure 2 Flow-chart of EPZ evaluation methodology

3.1 Selecting Events

Since the SMART-PPE project has prepared PSAR (Preliminary safety Analysis Report), including PAMP (Preliminary Accident Management Program), containing accident analysis of DBA (Design Basis Accident), SA (Severe Accident), and PSA (Probabilistic Safety Assessment), all of those reports were used for the deterministic approach in the SMART EPZ evaluation. As a starting point of source term determination for EPZ, extreme accident scenarios are selected based on the results of previous consequence studies such as NUREG-1150 [5] and previous PSA studies for domestic nuclear power plants [6]. Based on those studies and the Core Damage Frequency (CDF) results in the level 2 PSA of SMART reactor, SGTR (Steam Generator Tube Rupture) and SBO (Station Blackout) selected were selected.

A- Steam Generator Tube Rapture scenario

The SGTR is one of the extreme accident scenarios affecting residents and the environment as a containment by-pass sequence. In the SGTR scenario, a heat transfer tube in the steam generator ruptures simultaneously with the main steam line break, accompanied by failures of safety systems (Passive Safety Injection System (PSIS) and Passive Residual Heat Removal System (PRHR)) of severe accidents. Table 1 shows the results of the progression of the accident using MELCOR [7]. Since the main steam line and a steam generator tube rupture simultaneously, the reactor and the main feedwater pump trip immediately. Subsequently, core damage occurs because of the loss of coolant. After the initiation of core damage, when the core exit temperature is over 923 ^{o}K, following table 1, the Severe Accident Management Guideline (SAMG), the Automatic Depressurization System (ADS), and the Cavity Flooding System (CFS) are actuated with 30 minutes delay time. Because of the External Reactor Vessel Cooling (ERVC) through CFS, the reactor vessel is not failed, and containment failure and the Molten Core Concrete Interaction (MCCI) in the cavity do not occur. However, during the core melt progression, many fission products were directly released to the environment through the secondary system due to the steam line break.

Table 1 MELCOR analysis of core damage progression for SGTR scenario

Events	1 Tube Break (sec.)
MSL break & SGTR	0
Reactor trip & MFW trip	0
RCP trip	6549.08
Start of core uncover	21118.3
core dry-out	28362.3
Oxidation start	28650
Candling start	32250.2
At SAMG + 30minutes, ADS vent to RRT direct ECT loop close & CFS starts	(28093.4+1800.0) = 29893.4
Massive relocation of corium to Lower head	~45000
Reactor Vessel Failure by creep rupture	Not occur
MCCI start	NA
LP dry-out	71471.5

B- Station Blackout accident scenario

Another case is the Station Blackout (SBO), which is also an extreme accident with a high core damage frequency (CDF) in the Level 2 PSA of SMART. It is initiated with a complete loss of the off-site grid and the onsite AC distribution system. This initiating event leads to manual reactor trips by operators or automatically reactor trips by the Reactor Protection System (RPS), mainly upon low feedwater flow. Table 2 shows the accident progression and core damage results using the MELCOR code. The class 1E 125V DC power system includes batteries at a maximum capacity of 72 hours. It is designed to provide the necessary power to safety-related plant loads, including a passive safety system. However, PSIS and PRHR are assumed not to work in this scenario. The base case in the table represents that the CFS fails to fill the reactor cavity, and the external reactor vessel cooling is not successful. When the ERVC is successful in the case of ERVC, the reactor vessel is cooled, and the MCCI does not occur. In both cases, there is no containment failure up to 2 days in the calculation. Hence, the total release fraction of fission product to the environment through the containment leakage is small.

Table 2 MELCOR analysis of core damage progression for SBO scenario

Events	Time [sec]: Base
SBO (initiating)	0
Rx, RCP, and MFW trip	0
SRV start to open	2217.3
if P_LCA > 1.6 bar, vent from SIT-BD to IRWST before SAMG + 20 min., after close	2374
Start active core uncover	32582.1
Active core dry-out	40581.1
Oxidation start (total H_2 mass, %)	44650.1 (87.53, 44)
ERVC start and ADS open, Vent from SIT-BE to RRT at SAMG + 30 min.	(44080.1 + 1800.0 =) 45880.1
Candling start (Zr)	51450.9
Massive relocation of corium to lower head	60000/80000
LP dry-out	71927.4
Reactor vessel failure by creep rupture	94693.9
MCCI start	94694.9

3.2 Source Term

Source term grouping approach is adopted in the typical probabilistic safety analysis (PSA). The release source term of accident scenarios is grouped based on their physic-chemical characteristics. Estimation of the atmospheric release source term for this work was obtained for the EPZ determination study based on deterministic computational assessment using severe accident assessment code (MELCOR) to generate detailed information on how radioactive nuclides from molten fuel are transported with the primary circuit, then inside the reactor containment and finally into the atmosphere. Thus, it can usually predict the processes before the atmospheric release. The off-site dose assessment considered here could be the time-average inventory or a worst-case one from EoC (high burn-ups). The reactor core radioactive inventory was calculated using ORIGEN code [8]. Table 3 shows the major source terms release calculated by MELCOR code for the SGTR and SBO sequences.

Table 3 FP release activity during SGTR and SBO (Bq)

Chemical Characters of Groups	Nuclide	Activity of FP release in case of SGTR	Activity of FP release in case of SBO
Nobel Gas	Kr-85	3.67E+14	2.71E+12
	Kr-85m	6.85E+15	5.07E+13
	Kr-87	1.33E+16	9.81E+13
	Kr-88	1.82E+16	1.34E+14
	Xe-133	4.26E+16	3.15E+14
	Xe-135	1.82E+16	1.35E+14
Halogens	I-131	1.23E+16	2.67E+12
	I-132	1.78E+16	3.85E+12
	I-133	2.55E+16	5.53E+12
	I-134	2.91E+16	6.30E+12
	I-135	2.41E+16	5.22E+12
Alkali metals	Rb-86	3.78E+13	7.67E+09
	Cs-134	4.41E+15	8.95E+11
	Cs-136	1.05E+15	2.12E+11
	Cs-137	2.87E+15	5.83E+11
Alkaline Earths	Sr-89	4.00E+14	6.50E+10
	Sr-90	4.74E+13	7.70E+09
	Sr-91	4.91E+14	7.98E+10
	Sr-92	5.12E+14	8.32E+10
	Ba-139	6.22E+14	1.01E+11
	Ba-140	6.04E+14	9.82E+10
Platinoids	Rh-105	9.10E+10	3.19E+06
	Ru-103	1.35E+11	4.71E+06
	Ru-105	9.62E+10	3.37E+06
	Ru-106	5.86E+10	2.05E+06
Trivalents	Y-90	7.94E+11	3.06E+06
	Y-91	8.18E+12	3.15E+07
	Y-92	8.42E+12	3.24E+07
	Y-93	9.14E+12	3.52E+07
	La-140	9.91E+12	3.81E+07
	La-141	9.23E+12	3.55E+07
	La-142	9.05E+12	3.48E+07
	Pr-143	9.05E+12	3.48E+07
	Nd-147	3.60E+12	1.39E+07
	Am-241	2.18E+09	8.40E+03
	Cm-242	6.98E+11	2.69E+06
	Cm-244	4.19E+10	1.61E+05
Tetravalents	Ce-141	2.36E+13	5.36E+10
	Ce-143	2.28E+13	5.19E+10
	Ce-144	1.85E+13	4.22E+10
	Zr-95	2.56E+13	5.83E+10
	Zr-97	2.47E+13	5.60E+10
	Np-239	2.69E+14	6.11E+11
	Pu-238	1.03E+11	2.33E+08
	Pu-239	7.03E+09	1.60E+07
	Pu-240	6.83E+09	1.55E+07
	Pu-241	3.86E+12	8.78E+09
Early transition elements	Nb-95	1.02E+13	3.91E+07
	Mo-99	1.55E+11	5.41E+06
	Tc-99m	1.36E+11	4.77E+06
Chalcogens	Te-127	1.20E+15	1.39E+11
	Te-127m	1.20E+14	1.38E+10
	Te-129	3.73E+15	4.29E+11
	Te-129m	6.40E+14	7.37E+10
	Te-131m	2.61E+15	3.01E+11
	Te-132	1.90E+16	2.19E+12

3.3 Site Meteorology

This work uses meteorological observations for a proposed site of the first nuclear power plant in Saudi Arabia. In particular, they were using the data from a weather station, which was installed in 2019, to collect the meteorological data of the site, including wind speed, wind direction, and temperature at different elevations. The data were obtained for each second on this period (01/10/2019 - 01/10/2021). The data were averaged to be hourly to prepare the meteorological input file for the HotSpot code [9]. Fig 3 shows the hourly wind rose for the year 2021. It presents different wind speed distributions, but the dominant direction of winds in most examined cases is to the southwest.

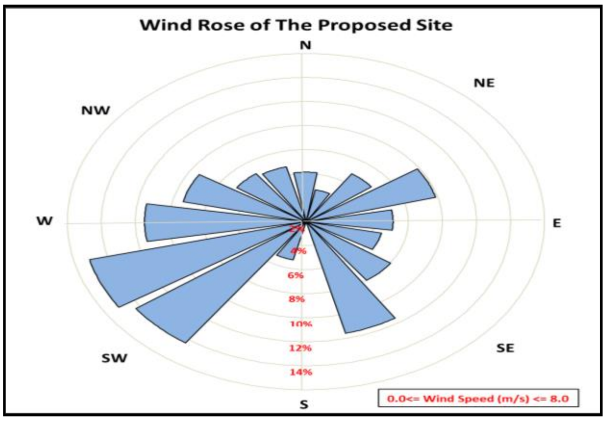

Figure 3 Wind rose for the proposed site

- Stability Classification

Although there are many stability classification schemes, the temperature difference (delta temperature) scheme, i.e., ΔT/ΔZ, has been adopted in this study, as shown in Table 4. The vertical temperature difference is the preferred method for determining Pasquill stability classes at nuclear power plants for licensing purposes. It is an effective indicator for the worst-case stability conditions (e.g., Pasquill stability classes E, F, and G) [10]. The frequency histogram of the stability classes for the proposed site is shown in Fig. 4. From the histogram, most of the data fall within three stability classes (Class D, E and F). After obtaining all the source term releases and the meteorological data of the site, HotSpot code can be used to calculate effective doses at various distances from the proposed site of the SMART power plant.

Table 4. Stability classification by the vertical temperature gradient

Stablitiy Classification	Pasquill Stability Category	ΔT/Δz (℃/100 m)
Extremely Unstable	A	< -1.9
Moderately Unstable	B	-1.9 ~ -1.7
Slightly Unstable	C	-1.7 ~ -1.5
Neutral	D	-1.5 ~ -0.5
Slightly Stable	E	-0.5 ~ 1.5
Moderately Stable	F	1.5 ~ 4.0

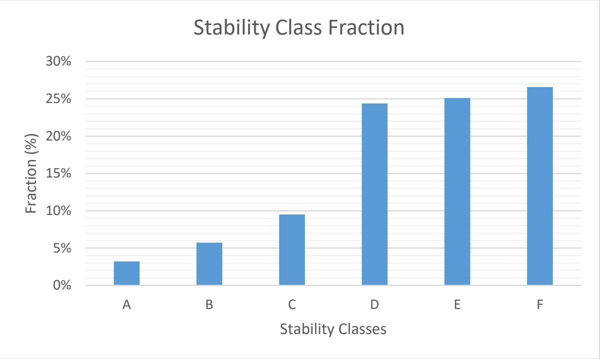

Figure 4 Frequency Histogram of the stability classes for the proposed site

3.4 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. 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].

3.5 IAEA Dose Criteria for Protective Action

This evaluation uses the generic criteria for doses to prevent or mitigate deterministic/stochastic health effects, which were recommended in the Radiation Protection and Safety of Radiation Sources: International Basic Safety Standard (General Safety Requirements named as the IAEA GSR part 3 [11]. The nine (9) protective action criteria posed on the different human organs to set up PAZ and UPZ are mentioned in Ref. [12, 13]. In Table 5, the dose criteria of different of targets and organs among various pathways are shown.

Table 5. IAEA derived radiation dosimetry criteria for determining the size of EPZ

Zone	Target-organ	Pathway	Duration		Criterion	
			Application	IAEA		
PAZ	Red marrow	Total acute dose			1.0	Gy-Eq[1]
		Cloud shine	Simulation[2]	10 hour		Gy-Eq
		Ground shine	Simulation	10 hour		Gy-Eq
		Acute Inhalation[3]	30 days	30 days		Gy-Eq
UPZ	Effective dose	Inhalation (committed)	50 year	50 year	0.1	Sv

4. Results and Discussion

The following results represent the generated analysis of the selected scenarios (SBO and SGTR) using HotSpot code. This study is focusing on the analysis of the effective dose (ED) and the red marrow, which are equal to 0.1 Sv and 1.0 Gy-Eq, respectively.

4.1 SBO

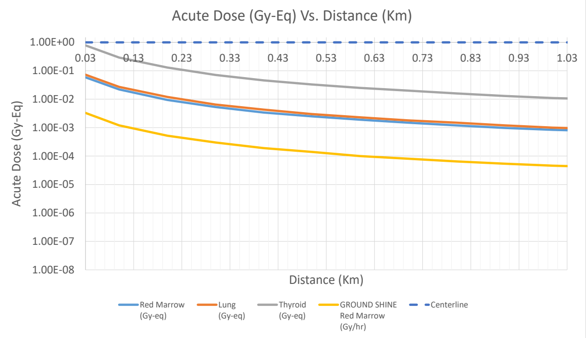

Figure 5 Red Marrow acute dose along with the distance

As shown in figure 5, the dose value is under the criteria limits refereeing to (Table 5), which is less than 1.0 Gy-Eq of red marrow organ target, and the estimated distance is less than 0.05 Km.

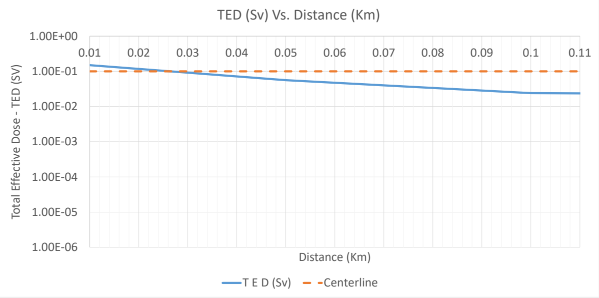

Figure 6 Total effective dose along with the distance

As shown in figure 6, the dose value intersects with the criteria limit line, which is 0.1 Sv based on the total effective dose (TED), and the estimated distance is almost 0.03Km.

4.2 SGTR

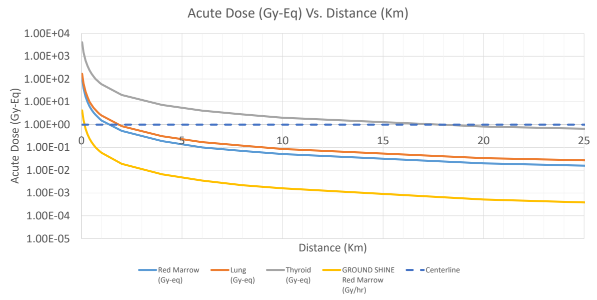

Figure 7 Red Marrow acute dose along with the distance

As shown in figure 7, the source term released amount is large compared with SBO due to the estimated events within the accident scenario. Different pathways have been analyzed, an intersection with the criteria limit line of 1.0 Gy-Eq based on the red marrow limits, and the estimated distance is almost 2 km.

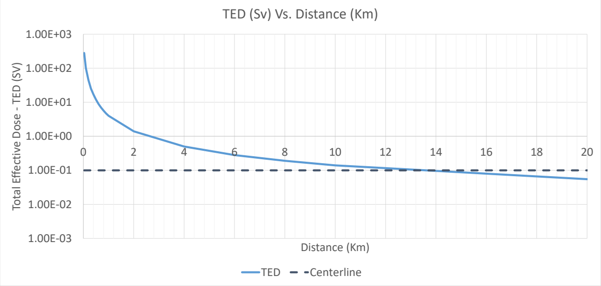

Figure 8 Total effective dose along with the distance

As shown in figure 8, the dose value intersects with the criteria limit line, which is 0.1 Sv based on the Total effective dose (TED); due to a large amount of the released source term, the estimated distance is almost 14.0 km.

5. Conclusion

A deterministic approach was used to determine the emergency planning zone of SMART reactor based on IAEA criteria. The calculation methodology started by selecting two accident scenarios based on their severity and contribution to the core damage frequency of the reactor. Then, an evaluation of their source terms release was performed using MELCOR. Furthermore, post-processing of the meteorological data of the proposed site in Saudi Arabia was carried out to obtain hourly average data to prepare the input files of the HotSpot code. After preparing the input files of source term release data and the meteorological data for SMART reactor, dosimetry estimation can be obtained using HotSpot code. Finally, a determination of the emergency planning zone was obtained.

In the case of SBO, it was satisfied along with all possible distances. On the other hand, for the SGTR accident, which is considered as the most severe accident in terms of source term release, the results of the EPZ show relatively large values.

ACKNOWLEDGEMENTS

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