Evaluation of Cs-137 Release Frequency Exceeding 100 TBq using MPAS Level 2 PSA Model and MELCOR

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1. Introduction

Article 9 (Risk Assessment) of the Nuclear Safety Commission Notice No. 2026-1 [1] stipulates, as one of the Probabilistic Safety Assessment (PSA) performance objectives, that the frequency of exceeding 100 TBq of Cs-137 release shall be maintained below 1.0E-06 per year. This frequency serves as a key regulatory risk metric derived from Level 2 PSA source term analysis.

Accordingly, the regulatory body is required to conduct an independent review to verify the validity and adequacy of the results submitted by the licensee.

In this study, the APR1400 Multi-Purpose Probabilistic Analysis of Safety (MPAS) Level 2 PSA model was used to select representative accident sequences that characterize the release behavior of each containment damage state. For each representative sequence, source term analyses and Cs-137 release calculations were conducted using the severe accident analysis code MELCOR [2]. Based on the calculated Cs-137 release quantities, the exceedance of the 100 TBq threshold was decided for each containment damage state. This evaluation resulted in a systematic procedure for selecting representative accident sequences and quantifying Cs-137 releases to estimate the Cs-137 release frequency exceeding 100 TBq.

Furthermore, the results of this study were benchmarked against the licensee's analysis [3] to ensure the robustness of the regulatory verification model developed herein.

2. Methods and Results

The APR1400 MPAS Level 2 PSA model, developed for regulatory verification purposes, incorporates the latest domestic and international methodologies for Level 2 PSA, including newly implemented accident management strategies described in the Accident Management Plan (AMP) of the Korean licensee. The APR1400 MPAS Level 2 PSA model consists of Plant Damage State Logic Diagram (PDSLD), Containment Event Tree (CET), Decontamination Event Tree (DET), and Source Term Category Logic Diagram (STCLD) [4].

This study assesses the frequency of Cs-137 releases exceeding 100 TBq by performing MELCOR-based source term analyses for representative accident sequences derived from the APR1400 MPAS Level 2 PSA model. The overall methodology consists of the following steps:

1. Selection of accident sequences for analysis
2. Source term analysis using MELCOR
3. Quantification of the Cs-137 Release Frequency Exceeding 100 TBq
4. Comparison with the licensee’s analysis results

The detailed methodology and results for each step are described in the following sections.

2.1 Selection of Accident Sequences for analysis

In Level 2 PSA, containment damage assessment and source term analysis are conducted sequentially through Plant Damage State (PDS) analysis, CET analysis, and Source Term Category (STC) analysis. Among these steps, the behavior of radioactive materials is explicitly evaluated during the source term analysis stage.

Conducting individual source term analyses for all accident sequences identified in the containment event tree is impractical and inefficient. Therefore, accident sequences exhibiting similar fission product release characteristics are grouped, and representative sequences are selected for detailed source term analysis.

In this study, the release characteristics of each source term category were reorganized according to containment damage states, and representative accident sequences were selected for each damage state. The procedure for selecting representative accident sequences for each containment damage state is summarized as follows:

1. Select accident sequences that result in relatively large radiological source term releases and have relatively high frequencies within each containment damage state.
2. Examine the severe accident progression paths of the selected sequences to ensure that key severe accident phenomena essential for source term evaluation are adequately represented.
3. Define the containment failure pressure, containment failure time, and failure conditions for each damage state based on the characteristics of the representative sequences.

Following this procedure, the representative accident sequences for each containment damage state in the APR1400 MPAS Level 2 PSA model are summarized in Table 1.

Table 1. Representative Accident Sequence Selection Results

Containment Damage State	Representative Accident Sequence		
	PDSET Sequence	STC	Contribution (%)
NOCF[1)]	TLOCCW[8)]-28	2	40.6
ECF[2)]	TLOCCW-34	4	13.9
LCF[3)]	TLOCCW-30	9	30.3
BMT[4)]	TLOCCW-31	11	26.4
CFBRB[5)]	MLOCA[9)]-2	12	85.8
NOTISO[6)]	SBOS[10)]-300	14	6.3
BYPASS[7)]	ISLOCA[11)]-2	16	0.1

1) NOCF: No Containment Failure
2) ECF: Early Containment Failure
3) LCF: Late Containment Failure
4) BMT: Base-mat Melt Through
5) CFBRB: Containment Failure before the Reactor vessel Breach
6) NOTISO: NOT Isolation (Containment isolation system failure)
7) BYPASS: fission product release Bypassing containment
8) TLOCCW: Total Loss of Component Cooling Water
9) MLOCA: Medium-break Loss of Coolant Accident
10) SBOS: Station Blackout with emergency diesel generator fails to start
11) ISLOCA: Interfacing System Loss of Coolant Accident

2.2 Source term analysis using MELCOR

For each representative accident sequence corresponding to a containment damage state, the initiating event, safety-significant system availability, containment failure conditions (including failure pressure, failure time, and leakage/rupture model), and release pathways to the environment were defined as input conditions for the MELCOR analysis. The principal characteristics of each representative accident sequence are summarized as follows:

- NOCF: Total Losss of Component Cooling Water (TLOCCW); Failure of secondary heat removal; RCP Seal LOCA; RCS depressurization achieved; Cavity flooding available; Containment heat removal available.
- ECF: TLOCCW; Failure of secondary heat removal; RCP Seal LOCA; Failure of RCS depressurization; Cavity flooding available; Containment heat removal available; Containment failure at the time of reactor vessel failure
- LCF: TLOCCW; Failure of secondary heat removal; RCP Seal LOCA; RCS depressurization achieved; Cavity flooding available; Failure of containment heat removal; Containment failure due to overpressure
- BMT: TLOCCW; Failure of secondary heat removal; RCP Seal LOCA; RCS depressurization achieved; Failure of cavity flooding; Containment heat removal available; Containment Basemat Melt-Through
- CFBRB: Medium-break LOCA (MLOCA); Safety injection achieved; Failure of containment heat removal; Containment failure due to overpressure
- NOTISO: Station Blackout (SBO); Secondary heat removal achieved; Failure of Containment isolation
- BYPASS: Interfacing System LOCA (ISLOCA)

In this research project, a methodology for evaluating Cs-137 release quantities using MELCOR was developed in 2023[5].

The principal boundary conditions and accident progression characteristics of the selected representative accident sequences were incorporated into the MELCOR input model, and source term analyses were conducted by applying the developed Cs-137 evaluation method. The results are summarized in Table 2.

Table 2. Results of Evaluating MPAS Level 2 PSA Cs-137 release quantities

Containment Damage State	Cs-137 Release Quantities (TBq)
NOCF	~10.0
ECF	~100,000.0
LCF	~10,000.0
BMT	~10.0
CFBRB	~10,000.0
NOTISO	~100,000.0
BYPASS	~100,000.0

The evaluation results indicate that all containment damage states except NOCF and BMT result in Cs-137 release quantities exceeding 100 TBq.

2.3 Quantification of Cs-137 Release Frequency Exceeding 100 TBq

The CET quantification results for the APR1400 MPAS Level 2 PSA model are summarized in Table 3.

Table 3. Result of MPAS Level 2 PSA CET Quantification

Containment Damage State	Frequency (/yr)	Contribution (%)
NOCF	~2.0E-06	44.7
ECF	~1.0E-08	0.2
LCF	~2.0E-06	47.0
BMT	~1.5E-07	3.5
CFBRB	~1.5E-07	3.1
NOTISO	~1.5E-08	0.3
BYPASS	~5.5E-08	1.2

The frequency and fractional contribution of Cs-137 releases exceeding 100 TBq for the APR1400 MPAS Level 2 PSA model, quantified based on the source term analysis results for each containment damage state, are summarized in Table 4.

Table 4. Cs-137 Release Frequency Exceeding 100 TBq for the MPAS Level 2 PSA Model

Release Category	Frequency (/yr)	Contribution (%)
Cs-137 (>100 TBq)	~2.5E-06	51.8

2.4 Comparison with the licensee's analysis results

To verify the validity of the Cs-137 release frequency exceeding 100 TBq quantified for the APR1400 MPAS Level 2 PSA model, a comparative analysis was performed against the Cs-137 evaluation results for the APR1400 plant submitted by the licensee.

For each containment damage state, a representative STC from the licensee's analysis exhibiting characteristics similar to the corresponding representative accident sequence in the MPAS Level 2 PSA model was selected. The Cs-137 release quantities of the two representative sequences were then compared. The comparison results are presented in Table 5.

Table 5. Comparison of Cs-137 Release Quantities of APR1400 Level 2 PSA

Containment Damage State	AMP STC	Licensee	MPAS
		Cs-137 release quantities (TBq)	
NOCF	10	~1.0	~10.0
ECF	15	~10,000.0	~100,000.0
LCF	20	~100.0	~10,000.0
BMT	11	~0.01	~10.0
CFBRB	7	~10,000.0	~10,000.0
NOTISO	6	~10,000.0	~100,000.0
BYPASS	3	~100,000.0	~100,000.0

Both analyses indicate that the containment damage states corresponding to NOCF and BMT result in Cs-137 release quantities below 100 TBq. However, for the same containment damage states, the Cs-137 release quantities calculated using the MPAS model were generally higher than those reported by the licensee.

It is noteworthy that the two analyses rely on different computational frameworks: the licensee's evaluation was based on the MAAP code, while the present study employed MELCOR to ensure a technically independent assessment of Cs-137 release quantities.

3. Conclusions

In this study, source term analyses were performed based on the APR1400 MPAS Level 2 PSA model to verify the adequacy of the frequency of exceeding 100 TBq of Cs-137 release calculated in the PSA submitted by the licensee. The Cs-137 release quantities for each containment damage state were quantified, and the corresponding exceedance frequency was evaluated.

The analysis of representative accident sequences demonstrated that the NOCF and BMT resulted in Cs-137 release quantities below the 100 TBq threshold. This finding is consistent with the results obtained by the licensee using the MAAP code. Such consistency between two independent analyses enhances the credibility of the source term evaluation for these specific containment damage states.

However, for the same containment damage states, the Cs-137 release quantities evaluated using MELCOR were generally higher than those obtained using MAAP. In particular, differences of approximately two orders of magnitude for LCF and three orders of magnitude for BMT were observed. These differences are primarily attributed to the distinct modeling approaches for release through the design leakage rate and aerosol behavior in each code. This suggests that further investigation into the aerosol deposition and transport models within MELCOR and MAAP is warranted to resolve these technical discrepancies

The frequency of Cs-137 releases exceeding 100 TBq evaluated based on the APR1400 MPAS Level 2 PSA model was approximately 2.5E-06 per year, exceeding the regulatory limit. This result is considered to be primarily influenced by the conservatively evaluated frequency of the TLOCCW initiating event in the Level 1 PSA, which led to an increased frequency of the LCF containment damage state.

This study established a systematic source term analysis procedure based on representative accident sequences for various containment damage states. The methodologies developed herein provide a robust framework for the independent regulatory verification of Level 2 PSA results. For future applications, particularly in Level 3 PSA, the selection of representative sequences at the STC level and more detailed source term analyses will be required to enhance the precision of off-site consequence assessments.

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