Development of Source Term Uncertainty Analysis Framework for BWR Plants Using MAAP Code

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Abstract: The guideline for safety improvement assessment in Japan requires the implementation of PRA. As part of Level 2 PRA, a source term uncertainty analysis must be performed to demonstrate that Cs-137 release to the environment is less than 100 TBq even considering uncertainty of analytical model or phenomenological uncertainty. In this study, the source term uncertainty analysis framework was established using the MAAP code for a representative BWR plant. In this paper, we present the framework: selection release categories, selection of accident sequences, selection of uncertainty parameters, and performing uncertainty analysis.

Keywords: Level 2 PRA, MAAP Code, Source Term, Uncertainty Analysis, BWR

1. INTRODUCTION

The accident at the Fukushima Daiichi Nuclear Power Plants has led to a series of shutdowns of nuclear power plants (NPPs) in Japan, but in recent years, the nuclear power plants have been restarted. According to the guideline for safety improvement assessment in Japan [1], utilities are required to submit a safety analysis report (SAR) to the Nuclear Regulation Authority (NRA) within six months after the first regular inspection following the restart of NPPs. The guideline requires the implementation of probabilistic risk assessment (PRA) in the SAR and the following four items must be evaluated: (1) core damage frequency (CDF), (2) containment failure frequency (CFF), (3) frequency of Cs-137 release exceeding 100 TBq, and (4) effective dose at the site boundary.

Of the above four evaluation items, (3) uses the indicator of whether the amount of Cs-137 release to the environment exceeds 100 TBq. In the case of a large release sequence such as primary containment vessel (PCV) failure or PCV bypass, it is considered that the Cs-137 release will exceed 100 TBq. On the other hand, for sequences where the Cs-137 release would be extremely small, it is necessary to confirm that the Cs-137 release does not exceed 100 TBq even if the uncertainty of the analytical model or phenomenological uncertainty are considered, because the Cs-137 release might exceed 100 TBq when the uncertainties are considered.

Based on the above, the objective of this study is to establish a framework of source term uncertainty analysis for BWR plants using the MAAP code for SAR submission after the restart of reactors.

2. ANALYSIS CONDITIONS

2.1. PLANT CONDITIONS

In this study, source term uncertainty analysis will be performed for a representative BWR5 plant with a Mark-I improved PCV. The PCV has a drywell (D/W) and a suppression chamber (S/C), and the S/C has suppression pool (S/P) water. The fission products (FP) release pathway is assumed to be from the D/W through the reactor building (R/B) to the environment.

2.2. ANALYSIS CODE

The MAAP4.0.7 (Modular Accident Analysis Program Version 4.0.7) [2] code which has been used in the severe accident analysis for restart application review by NRA, is used for the source term analysis in this study.

The MAAP is a severe accident analysis code managed and developed by EPRI (Electric Power Research Institute) and can analyze thermal hydraulics and FP behavior in a plant up to core damage, reactor pressure vessel (RPV) failure, PCV failure, and FP release to the environment.

3. SOURCE TERM UNCERTAINTY ANALYSIS FRAMEWORK

This chapter summarizes the framework of source term uncertainty analysis using an example analysis of a representative BWR-5 plant.

3.1. SELECTION OF RELEASE CATEGORIES

Some accident sequences set up in containment event tree (CET) have similar FP release behavior (release amount, release timing, migration pathway, and mitigation measures) to the environment. By grouping similar accident sequences and representing multiple sequences within a group by a single accident sequence, the number of cases for source term analysis can be reduced. For this purpose, accident sequences identified in CET are classified into release categories.

The classification of release categories for the source term uncertainty analysis is shown in Table 1. Since the purpose of the source term uncertainty analysis is to confirm whether the Cs-137 release exceeds 100 TBq when the uncertainties in the analysis are considered, the release categories are simplified and classified based on the amount of Cs-137 release only. In release category A (PCV failure, PCV isolation failure and PCV bypass), it is estimated that a large release with a Cs-137 release exceeding 100 TBq would occur in sequences where mitigation facilities lose their functions. On the other hand, in release category B (PCV leakage) and category C (PCV venting), the Cs-137 release is estimated to be much smaller than that in release category A. Note that PCV failure in release category A includes D/W failure and S/C failure. The Cs-137 release in S/C failure might not exceed 100 TBq because FP scrubbing can be expected at S/P in BWR. However, in this study PCV failure was not subdivided into D/W failure and S/C failure and conservatively assumed that Cs-137 release would exceed 100 TBq even in the case of S/C failure.

Based on the results of the classification of release categories, release categories B and C, where the Cs-137 release is assumed to be less than 100 TBq, were selected as the target categories for source term uncertainty analysis to confirm whether the Cs-137 release exceeds 100 TBq when considering the uncertainties. Since the Cs-137 releases of release category B (PCV leakage) and release category C (PCV venting) are considered to be almost equivalent, this study representatively focuses on release category B (PCV leakage).

Table 1. Classification of Release Categories

Release Category	Symbol	The Amount of Cs-137 Release
PCV failure	A	Estimated to be greater than 100 TBq
PCV isolation failure and PCV bypass		
PCV leakage (PCV integrity)	B	Estimated to be several orders of magnitude smaller than release category A
PCV venting	C	

3.2. SELECTION OF ACCIDENT SEQUENCES

Next, accident sequences are selected for release category B (PCV leakage) and release category C (PCV venting), where the Cs-137 release does not exceed 100 TBq, among the release categories classified in Table 1. As mentioned in section 3.1, this study representatively focuses on release category B (PCV leakage).

A representative accident sequence, in which core damages, RPV fails and PCV heat removal starts at 24 hours to prevent PCV venting, is selected for typical release category B (PCV leakage). Also, the following four representative plant damage states (PDS) are selected as candidates of accident sequences, and the PDS with the largest Cs-137 release among four PDSs was selected as the target of source term uncertainty analysis.

- TQUX: Representing short-term core damage PDSs due to transient initiating event
- TW1-HP: Representing long-term core damage PDSs due to transient initiating event
- AE: Representing short-term core damage PDSs due to LOCA initiating event
- AW1: Representing of long-term core damage PDSs due to LOCA initiating event

Figure 1 shows the calculation results of the Cs-137 release in the base case, where uncertainties are not considered, for each of the four representative PDSs in the case of PCV leakage. The Cs-137 releases for all four PDSs were less than 100 TBq in the PCV leakage. Based on the calculation results of Cs-137 release, AE was selected as the target PDS for uncertainty analysis because its Cs-137 release was the largest among the four PDSs in this study.

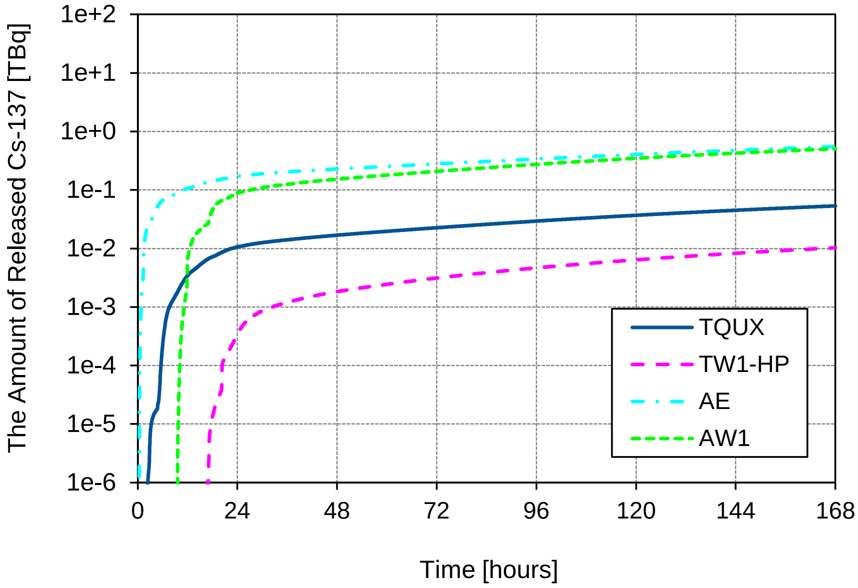

Figure 1. Comparison of Cs-137 Release among Four PDSs in PCV Leakage
(without considering uncertainties)

3.3. SELECTION OF UNCERTAINTY PARAMETERS

The MAAP code used for source term analysis contains input data on physical model, heat up, fission products, primary system, engineering safeguards functions, topology, debris, material type, etc. Parameters related to physical phenomena that significantly affect the source term are selected as the parameters for which uncertainty is taken into account.

The following processes are assumed for the release of FP to the environment after core damage: release from the fuel, deposition and revaporization on RPV, deposition and revaporization on PCV, FP scrubbing in S/P, aerosol removal by PCV spray, and deposition in R/B. To select uncertainty parameters, MAAP parameters that have a significant impact on the Cs-137 release to the environment were extracted from these processes, and sensitivity analysis of the Cs-137 release was performed by changing the parameter values. The upper and lower limits listed in the EPRI report on MAAP uncertainty analysis [3] were adopted for those of each parameter, and sensitivity analyses for Cs-137 release were performed using twenty data sets created at equal intervals within the range of upper and lower limits.

As the results of the sensitivity analysis to select uncertainty parameters, the following three parameters (FCSHVP, FVPREVP, AJUNC0(i)) had significant impact on the Cs-137 release, and the results of sensitivity analysis are shown in Figure 2 to Figure 4.

- FCSHVP: Multiplier to the vapor pressures of CsOH for vapor and aerosol equilibrium (Figure 2)
- FVPREV: Multiplier to the vapor pressures of CsI and CsOH for revaporization calculations (Figure 3)
- AJUNC0(i): D/W to R/B leakage area (Figure 4)

In the figures the Cs-137 releases of base case (without considering uncertainties) are plotted with red circle. In Figure 4, the horizontal axis is normalized by the leakage area of base case, representing the design leakage rate. It was clarified that FCSHVP increases the Cs-137 release by two times, FVPREV by two times, and AJUNC0(i) by four times.

In this study, these three parameters were selected as the target parameters for the source term uncertainty analysis.

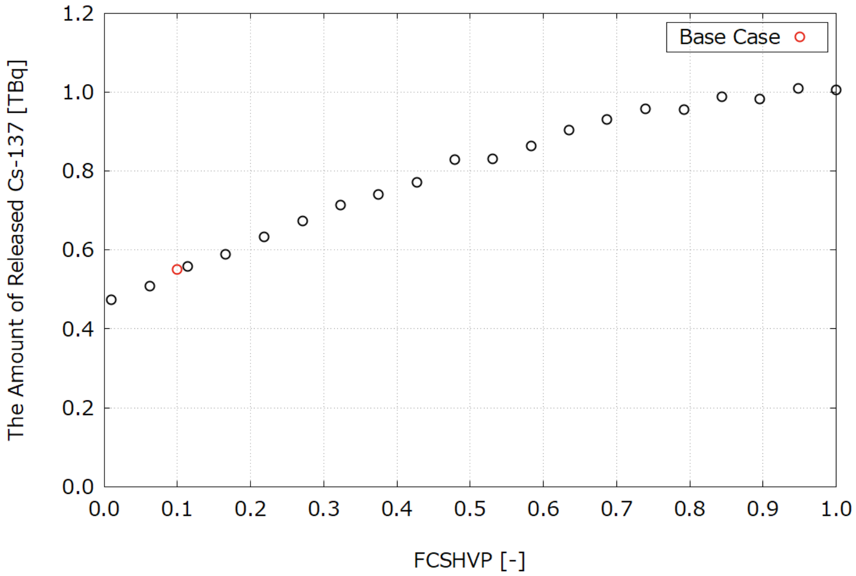

Figure 2. Results of Sensitivity Analysis of FCSHVP to Cs-137 Release

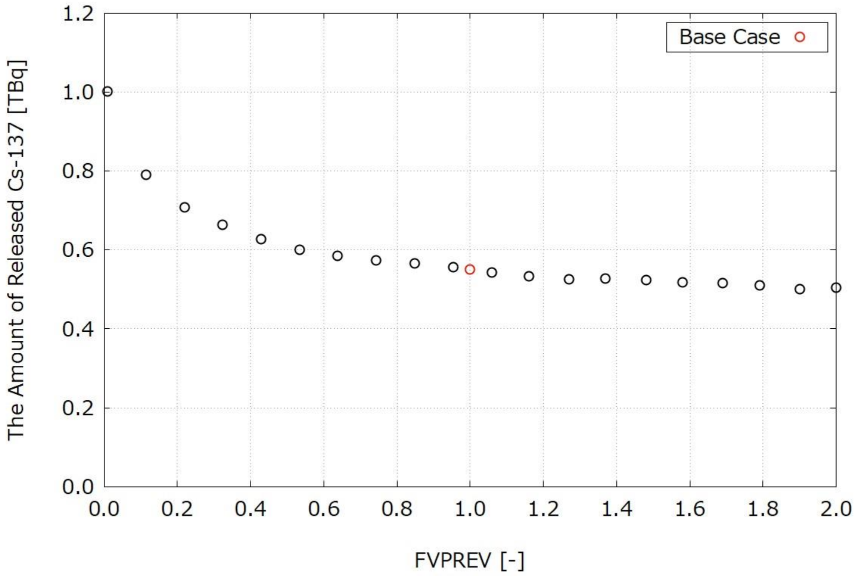

Figure 3. Results of Sensitivity Analysis of FVPREV to Cs-137 Release

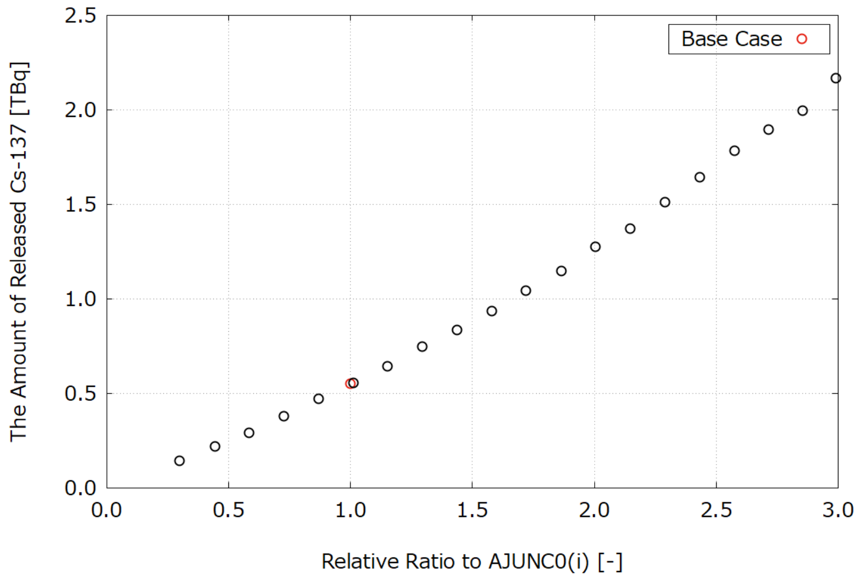

Figure 4. Results of Sensitivity Analysis of AJUNC0(i) to Cs-137 Release

3.4. PERFORMING UNCERTAINTY ANALYSIS

Finally, probability distributions are set for the selected uncertainty parameters, and a random data set for the parameters is generated using the Monte Carlo method. Then a source term uncertainty analysis is performed using these input data.

First, probability distributions for each uncertainty parameter were set referring probability distributions listed in the EPRI report on MAAP uncertainty analysis [2]. Next, a random data set for each parameter was generated by the Monte Carlo method using the probability distributions. Here, Latin Hypercube Sampling (LHS), which is more efficient than simple random sampling, was employed for the Monte Carlo method. The number of samples for the uncertainty analysis was set 60 cases. Here, if the number of samples N is determined so that at least one of the evaluation result samples is in the top 5% of the evaluation result population distribution with 95% prediction accuracy, then solving the inequality $1 - 0.95^N \geq 0.95$ leads to $N \geq 59$. In this study, 59 was rounded up to 60, and 60 cases were adopted as the number of sampling.

The random data set for uncertainty parameters was generated under the above conditions, and the source term uncertainty analysis was performed using MAAP with the data set. The statistics of Cs-137 release are shown in Table 2, scatter plot of Cs-137 release is shown in Figure 5, histogram of Cs-137 release is shown in Figure 6, and horsehair plot of Cs-137 release behavior is shown in Figure 7, respectively. In Table 2, since the maximum of Cs-137 release is 1.89 TBq, it was confirmed that the Cs-137 release does not exceed 100 TBq even considering the uncertainty of the MAAP parameters as the result of the source term uncertainty analysis.

In this study, the maximum Cs-137 release of 1.89 TBq does not exceed 100 TBq in the uncertainty analysis with 60 cases using LHS. Each uncertainty parameter has the range and probability distribution to be consistent with the release category, therefore, as long as the uncertainty analysis is performed within the condition, it is possible to estimate that Cs-137 release does not exceed 100 TBq even if millions of uncertainty analyses are performed.

Table 2. Statistics of Cs-137 Release

Item	Value [TBq]
Average	0.68
Standard deviation	0.27
Minimum	0.17
Maximum	1.89

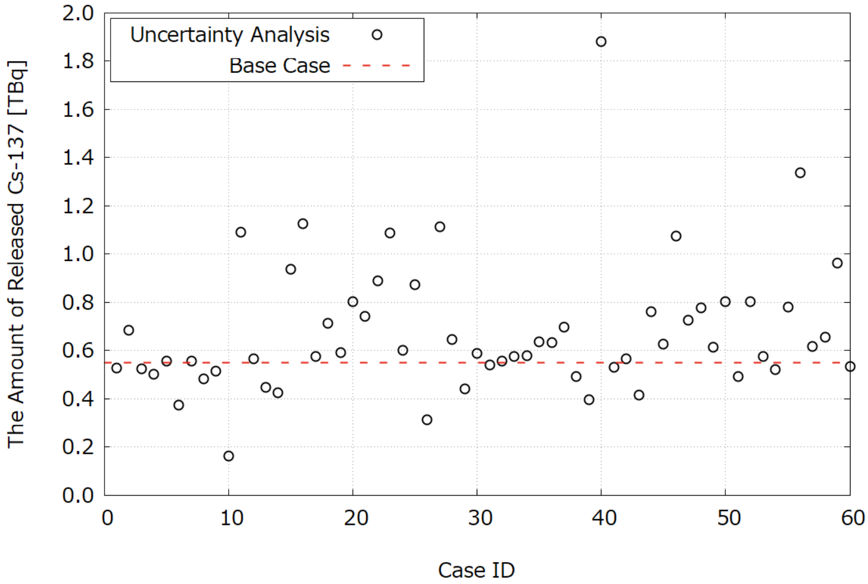

Figure 5. Scatter Plot of Cs-137 Release

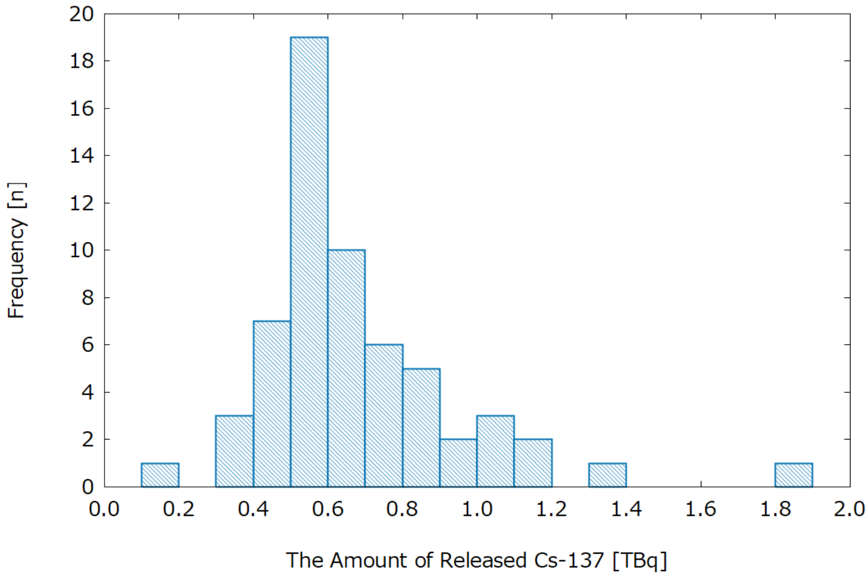

Figure 6. Histogram of Cs-137 Release

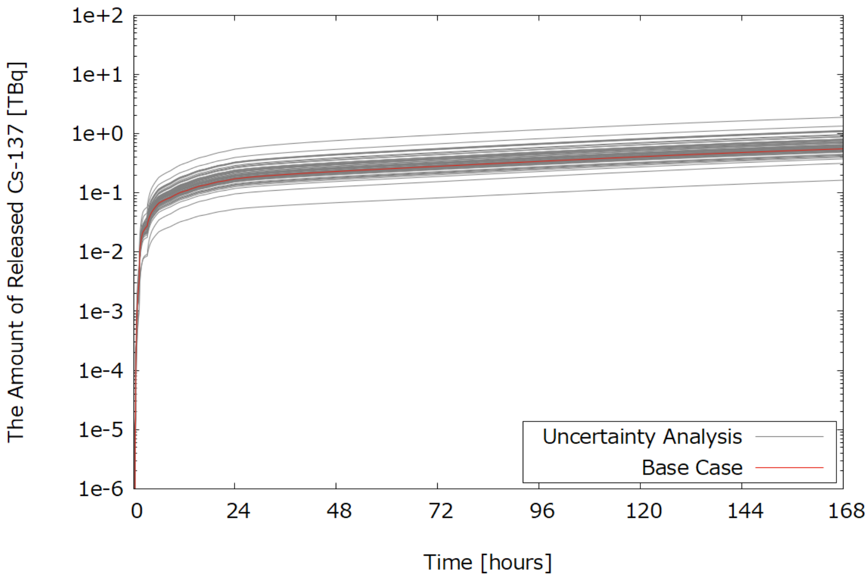

Figure 7. Horsehair Plot of Cs-137 Release Behavior

4. CONCLUSION

In this study, a source term uncertainty analysis framework was established for a typical BWR plant. This framework aims to assess the uncertainty of Cs-137 release. By conducting this uncertainty analysis, it can be confirmed that the release categories in which the amount of Cs-137 released exceeds 100 TBq are only PCV failure, PCV isolation failure and PCV bypass, and the frequency of Cs-137 release more than 100 TBq can be set to the frequency of these sequences.

The source term uncertainty analysis framework was presented based on an analysis example in the release category of PCV leakage for each of the following steps: selection of release categories, selection of accident sequences, selection of uncertainty parameters, and performing uncertainty analysis. As a result of the source term uncertainty analysis, it was confirmed that the Cs-137 release did not exceed 100 TBq even considering the uncertainties of the parameters in the release category of PCV leakage.

In this study, the source term uncertainty analysis framework focused on the release category of PCV leakage was presented. Not only PCV leakage but also PCV venting is assumed as a release category with Cs-137 release less than 100 TBq, and the source term uncertainty analysis for PCV venting can also be performed using the same framework as that of PCV leakage presented in this study.

References

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[3] M. Nudi, "Severe Accident Uncertainty Quantification and Analysis Using the Modular Accident Analysis Program (MAAP)", EPRI (2021).