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Uncertainty analysis for important source terms using MELCOR and MERTAG

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1. Introduction

Since the Fukushima nuclear power plant accident in 2011, countries operating nuclear power plants have been much interested in checking and enhancing their safety. In particular, the probabilistic safety assessment (PSA) has been mainly carried out in three stages to evaluate the safety of nuclear power plants. Since the leakage of radioactive material into the environment occurred, due to the Fukushima nuclear accident, the PSA methodology that evaluates the impact on the environment, people and society has attracted attention.

Probabilistic safety assessment should reflect various factors because it needs to consider all possible accidents. Due to the characteristics of these probabilistic safety evaluations, uncertainty is taken care of in the evaluation results. In other words, since there is uncertainty about the results of the probabilistic safety evaluation, Korea Institute of Nuclear Safety (KINS) suggests that uncertainty analysis be performed at all stages of the probabilistic safety evaluation as a regulatory standard for LWRs.[1]

Introduced in this study, MERTAG is a program that performs the uncertainty analysis of the radiation source term more conveniently. Uncertainty analysis is based on sufficient samples. Due to the huge amount of sample data necessary to obtain meaningful results considerable manpower and time are required. To carry out this process more simply and quickly, the MERTAG program has been developed to analyze the results of uncertainty about the radiation source terms.

2. Methodologies of the program

In this study, the MELCOR code is selected as the severe accident analysis code and program has been developed to analyze the radiation source term uncertainties by reading the PTF files, which are the result files of MELCOR.

The MELCOR code generates an output file by simulating a severe accident in time. The output data is time series data, and the file extension is PTF (MELCOR Plot File). A PTF file is a binary file that is encoded in binary format of 0 and 1, but not a text file that can be recognized by humans. Since it is difficult to understand the data contained in a binary file with a text file editor Notepad, a dedicated program is required to process binary data is required.

A PTF file is composed of a set of blocks, and the general structure is shown in Table 1[2]. Each block consists of a set of Header, Specials, and Time Records Sections. The Header Section contains information about the file name and the number and unit of variables. The Specials contains information about non-time series data such as the Cavity package. In addition, there is information necessary as input to MACCS, which is a three-step probabilistic stability evaluation code. Time Records Section has time series data that can be plotted. This is the part that MERTAG program should focus on to perform uncertainty analysis.[3]

Table 1. Common PTF File Structure

<table>
<tr><th>Block</th><th>Section</th><th>Subsection</th></tr>
<tr><td rowspan="6">Block 1</td><td rowspan="2">Header</td><td>Title</td></tr>
<tr><td>Key</td></tr>
<tr><td rowspan="2">Specials</td><td>Special Data</td></tr>
<tr><td>Special Data</td></tr>
<tr><td rowspan="2">Time Records</td><td>Time Record</td></tr>
<tr><td>Time Record</td></tr>
<tr><td rowspan="4">Block 2</td><td rowspan="2">Header</td><td>Title</td></tr>
<tr><td>Key</td></tr>
<tr><td rowspan="2">Time Records</td><td>Time Record</td></tr>
<tr><td>Time Record</td></tr>
<tr><td>…</td><td>…</td><td>…</td></tr>
<tr><td rowspan="4">Block N</td><td rowspan="2">Header</td><td>Title</td></tr>
<tr><td>Key</td></tr>
<tr><td rowspan="2">Time Records</td><td>Time Record</td></tr>
<tr><td>Time Record</td></tr>
</table>

As can be seen in Table 2, there is a slight time difference in MELCOR calculation even when the same time step is set. This difference makes it difficult to perform statistical analysis over the same time period. To perform statistical analysis, interpolation is performed on time series data by applying the concept as shown in Figure 1. For statistical analysis, a new base time is created by inputting a time step. Based on the newly created base time, linear interpolation is applied to all samples to perform the interpolation function for time series data. In this study, the time and time steps listed in Table 3 are applied to all the samples of the radiation source term emission groups generated in the previous study. Based on Table 3, base times are created in units of 10 seconds from -1000 to 15000 seconds, 50 seconds from 15000 seconds to 50000 seconds, and 100 seconds from 50000 seconds to 518400 seconds, respectively.

Table 2. MELCOR calculation time for each sample

Base	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
50000	50001.8593	50001.4492	50000.0195	50000.7851	50001.4609
50100	50101.8593	50101.4492	50100.0195	50100.7851	50101.4609
50200	50201.8593	50201.4492	50200.0195	50200.7851	50201.4609
50300	50301.8593	50301.4492	50300.0195	50300.7851	50301.4609
50400	50401.8593	50401.4492	50400.0195	50400.7851	50401.4609
50500	50501.8593	50501.4492	50500.0195	50500.7851	50501.4609
50600	50601.8593	50601.4492	50600.0195	50600.7851	50601.4609
50700	50701.8593	50701.4492	50700.0195	50700.7851	50701.4609
50800	50801.8593	50801.4492	50800.0195	50800.7851	50801.4609
50900	50901.8593	50901.4492	50900.0195	50900.7851	50901.4609
51000	51001.8593	51001.4492	51000.0195	51000.7851	51001.4609

Table 3 Time and time step to generate the base time used for interpolating time series data

Time [seconds]	Time Step
-1,000	10
0	10
500	10
1,000	10
15,000	50
50,000	100
100,000	100
300,000	100
518,400	100

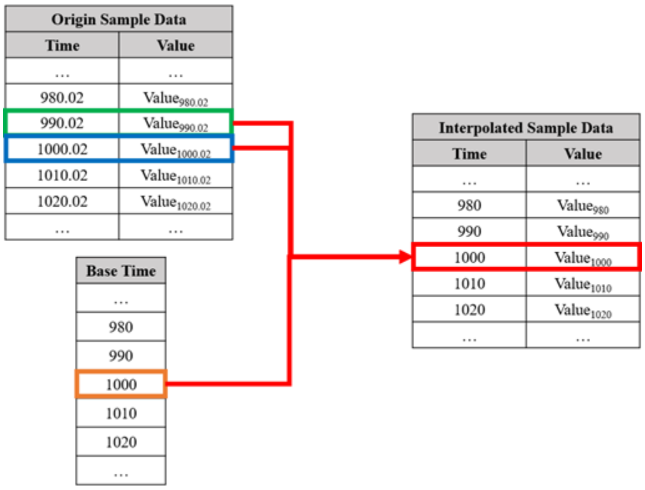

Fig. 1. Structural diagram for interpolating existing data to perform statistical analysis

Statistical processing is performed using interpolated time-series data in the step of generating the radiation source terms uncertainties. Statistical processing consists of N sample data at each time point. The statistical processing method adopted in this program is largely three steps. First, the arithmetic mean and standard deviation of N data at each time point are calculated. Next, the mean (μ) and standard deviation (σ) of the lognormal distribution are calculated from the arithmetic mean and standard deviation. Finally, the 5th, 50th, and 95th quartiles of the lognormal distribution are estimated using the calculated mean and standard deviation of the lognormal distribution. Figure 2 is a schematic diagram showing the statistical processing method in the MERTAG program.

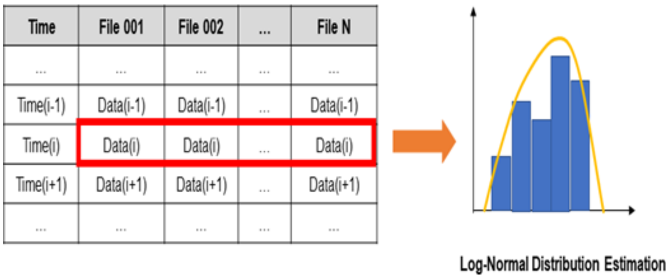

Fig. 2. Statistical processing logic diagram for uncertainty analysis of MERTAG program

3. Uncertainty analysis

3.1. Source terms uncertainty analysis

The radioactive source terms mean that radioactive materials leaked result from a severe accident. Since severe accidents have such characteristics as high temperature and high pressure, it is difficult to analyze phenomena through experiments. To analyze the severe accident phenomenon, computer codes capable of simulating the severe accident are used. Representative codes that can simulate severe accidents are MAAP (Modular Accident Analysis Program) and MELCOR (Methods for Estimation of Leakages and Consequences of Releases). By using these codes, it is possible to analyze the phenomenon and progress of a severe accident, and the characteristics of the source terms emitted to the outside of the containment building. In this study, MELCOR code is selected as the severe accident analysis code. There are several previous studies in which uncertainty analysis has been performed MELCOR code [4, 5, 6, 7, 8, 9, 10, 11]. Although the analysis methods used in previous studies are not all the same, uncertainty analysis has been performed using the MELCOR. In this study, referring to similar parts of previous studies, the following four-step analysis process is applied.

- Step 1: Select a representative severe accident and analyze the phenomenon,
- Step 2: Select MELCOR code uncertainty variables,
- Step 3: Select the number of samples for uncertainty analysis and use the MELCOR code, and
- Step 4: Analyze of source terms uncertainty.

3.2. Reference plant

In this study, source terms and risk uncertainty analysis are performed by selecting OPR1000 (Optimized Power Reactor 1000), as a reference plant. OPR1000 is a pressurized light water reactor with the capacity of 1,000 MWe, and the design specifications of the furnace are summarized in Table 4 [12].

Table 4. OPR1000 design specifications

Design variables	Value	Unit
Total core thermal hydraulic power at full power operation	2,815	Mwt
Number of fuel assemblies	177	packet
Number of fuel rods	41,772	-
RCS pressure	2,500	Psia
RCS temperature	343.3	˚C
RCS operating pressure	2,250	Psia
RPV pressure	2,500	Psia
RPV temperature	343.3	˚C
RPV operating pressure	2,250	psia

3.3. Selected severe accident

To perform source term uncertainty analysis for the reference plant, a source term release group (Source Term Category, STC) to be analyzed are selected. STC No. 4 is selected among STCs by referring to the model developed in previous studies [13, 14]. The characteristics of the representative initiating accident process of this STC are shown in Table 5. For variables subject to uncertainty analysis, 25 input variables are selected by referencing and citing the results of previous studies [4, 7, 8, 9, 10, 11]. In addition, for the distribution information of each uncertainty variable, the results of previous studies are cited [4, 7, 8, 9, 10, 11]. Tables 6 summarizes input variables and their distribution information.

Table 5. STC4 Characteristics

STC	4
Initiating event	SBO-R
Containment failure	ECF-RUPTURE
SAMG entry time	7.6h
Core failure	7.6h
RPV failure	9.7h
Containment failure	9.7h
Release time	9.7h

Table 6. Source terms uncertainty input variables and distribution information

	Group	Information	Value
1	In-Vessel Accident Progression	Zircaloy melt breakout temperature	2,400K
2		Molten clad drainage rate	1kg/m-s
3		Radial molten debris relocation time constant	60s
4		Radial solid debris relocation time constant	360s
5	Containment Behavior	Containment convection heat transfer coefficient	1
6	-	TSPCB (MELCOR 1.8.5)	1s
7	-	SC7160(1,1) (MELCOR 1.8.5)	0.139K
8	-	TPFAIL (MELCOR 1.8.5)	1,573.15
9	-	Containment Failure Pressure	9.2E+05Pa
10	Hydrogen Generation	Fuel rod collapse temperature	2,500K
11		Fractional local dissolution of UO2 in molten Zr	0.2
12		Melt relocation heat transfer coefficient	7,500W/m2-K
13		Particulate debris characteristic size following relocation to lower plenum	0.0125m
14		Falling debris quenching parameters	100 W/m2-K
15		Porosity of fuel debris beds	0.2
16		Thermal radiation exchange parameters	0.1
17	Aerosol Depletion Rate Analysis	Aerosol shape factors for diffusive, thermophoretic and gravitational settling deposition velocities	1
18		Particle slip factor in Cunningham slip correction	1.257
19		Particle-particle agglomeration sticking probability	1
20		Boundary layer thickness for diffusion deposition	1.00-E05m
21		Factor in Thermal Accommodation coefficient	2.25
22		Gas/particle thermal conductivity ratio in thermophoresis deposition velocity	0.05
23		Turbulent energy dissipation in agglomeration coefficients	0.001
24		Aerosol particle effective material density	1,000kg/m3
25		Heat/Mass Transfer multiplier for steam condensation in containment	5E+05

3.4. Confidence level due to sample size

A number of samples for uncertainty analysis are selected by citing the required sample size for each confidence level as shown in Table 7 as presented in previous studies [5]. In this study, it is determined that the minimum number of samples required to have 95% confidence level among 95% of the distribution for the uncertainty factor is 93, so the number of samples per each source term emission group is selected as 100. All 100 samples generated using Latin Hypercube Sampling (LHS) are calculated with the MELCOR code, and 100 PTF files are created as the result of calculations.

Table 7. Required sample size for each confidence level

Confidence level	Sample size to span p =			
(%)	0.9	0.95	0.99	0.999
90	37	76	388	3,888
95	46	93	473	4,742
99	64	130	661	6,635
99.9	88	180	919	9,228

3.5. Results

Multiple PTF files are read through the MERTAG program, and the analysis results are output in table and graph formats within the program. In addition, the function to save tables as CSV (comma-separated values) extension files and graphs as PNG (portable network graphics) extension files is also built into the program.

Figures 3 and 4 show uncertainty analysis results of the total amount of Cs nuclides and I2 nuclides emitted to the environment over time of STC 4 of the reference plant using MERTAG.

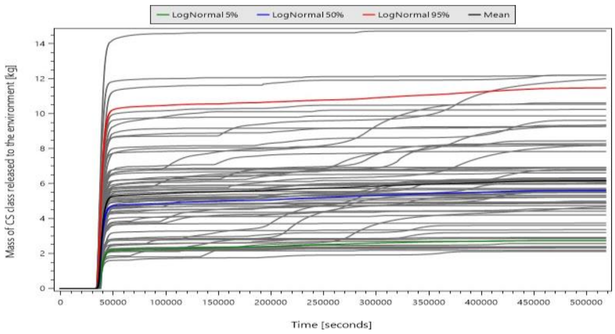

Fig. 3. Uncertainty analysis results of the total amount of Cs nuclides released into the environment according to the time of STC 4 [kg]

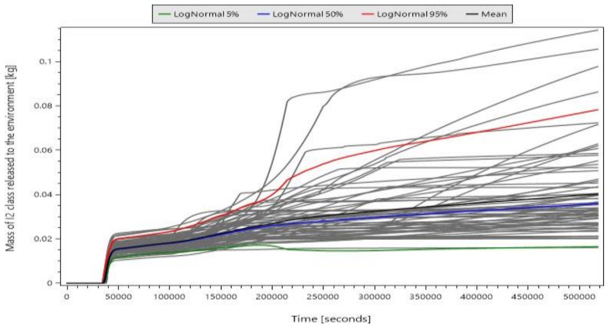

Fig. 4. Uncertainty analysis results of the total amount of I2 nuclides released into the environment according to the time of STC 4 [kg]

4. Conclusion

As more studies use probabilistic safety assessment, the importance of performing uncertainty analysis is increasing. In particular, if the analysis of the uncertainty result of the radiation source terms is performed manually, considerable manpower and time must be invested.

To solve this problem, the MERTAG program is developed to analyze the radiation source term uncertainty. Selected in this study, are STCs and uncertainty analysis target variable according to the accident circumstances, where 100 samples with a confidence level of 95% or higher are input into MELCOR codes using Latin Hypercube Sampling. The uncertainty analysis methodology is established by analyzing the PTF file through the MERTAG program. The MERTAG program accurately reads the values required for analysis from the large amount of PTF files, which are the calculation result files of the MELCOR code. In addition, it shows satisfactory performance in data interpolation task, which is a preprocessing task for statistical analysis, and the statistical processing task.

Acknowledgments

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