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Severe Accident Risk Assessment for SMART-100

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1. Introduction

SMART-100 is a small modular reactor (SMR) that improves safety by applying the passive safety system and economic efficiency by increasing output compared to the existing SMART. It applied for standard design approval (SDA) in December 2019, and is currently in the review stage. According to the recent revision of the Nuclear Safety Act, nuclear power plants (NPPs) must achieve their safety goals by performing probabilistic safety assessment (PSA). Deterministic safety assessment (DSA) was the basis in the early stages of NPPs, but the need for PSA gradually emerged, and now both DSA and PSA must be legally performed to license and extend the life of NPPs.

PSA can be largely divided into Level 1, 2, and 3, of which the objective of the Level 2 PSA is to ascertain the likelihood, magnitude, and timing of radioactive materials releases to the environment following a severe accident. The AIMS-L2 code was developed by KAERI to perform Level 2 PSA, which is characterized by significantly improving the ease of interface, importance analysis, and sensitivity/uncertainty analysis compared to the previous Level 2 PSA code. This code is used to analyze the model of plant damage state (PDS), containment event tree (CET), source term category (STC), and sensitivity/uncertainty analysis of SMART-100 to quantify the severe accident risk of the SMART-100.

According to the 2016 revision of the Nuclear Safety Act, the frequency of all event scenarios in which Cs-137 releasing exceeding 100TBq must be satisfied to be less than 1.0E-6/yr. By performing severe accident risk assessment of SMART-100, it is confirmed that the large early release frequency (LERF) and Cs-137 frequency meet the regulatory standard value.

2. Methods and Results

This section describes Level 2 PSA methodology with specific variables which is a systematic method to stochastically evaluate severe accident phenomena of NPPs using AIMS-PSA and AIMS-L2 code.

2.1 Plant Damage State Event Tree (PDS-ET) Development

Among the severe accident mitigation systems considered by SMART-100, PDS-ET was developed by adding CFS (Cavity Flooding System), Backup Spray, and CIS (Containment Isolation System) to the existing Level 1 PSA event tree model with severe accident system headings, and a total of 19 internal event models were developed.

As a result of Level 1 PSA of SMART-100 internal events, the total core damage frequency (CDF) was 6.203E-8/yr. The total CDF of the PDS-ET model that conducted additional branching for the safety system is 6.296E-8/yr, and the CDF increase rate is 1.5%.

As an example, Figure 1 shows the PDS-ET model for the event tree of SLOCA (-1.0 in), which is the initial event having the highest core damage contribution.

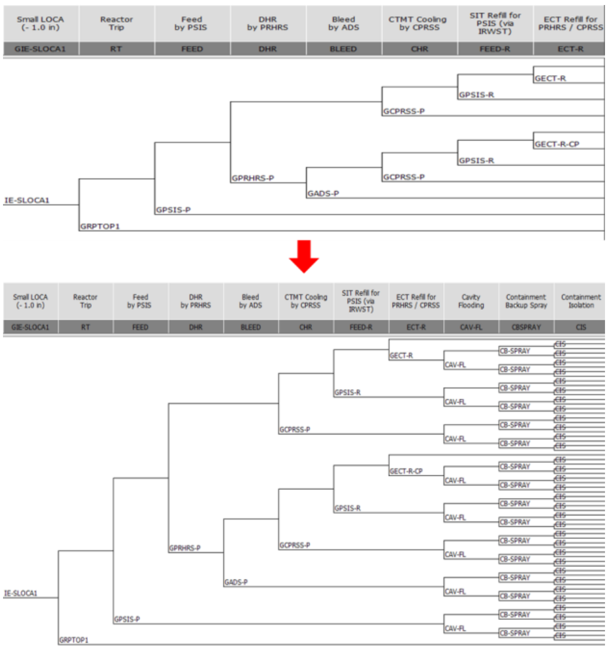

Fig. 1. SLOCA (-1.0 in) Event Tree and PDS-ET

2.2 Plant Damage State (PDS) Quantification

The purpose of the classification of all accident sequences using PDS logic diagram is to reduce the number of accident analysis required while retaining the essential spectrum of probable accident progression. This can be accomplished by grouping the relatively large number of core damage sequences into a small set of states, each representing a similar plant status at the time of core damage.

The defined PDS-ET accident sequences are classified into 10 specific PDSs by 5 variables (BYPASS, CONISO, RCSP, CFS, CSPRAY), as shown in the PDS logic diagram (See Fig. 2).

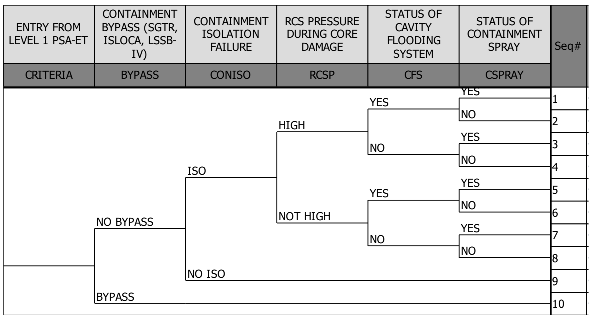

Fig. 2. Plant Damage State (PDS) Logic Diagram

Table I shows the results of PDS quantification, and Table II shows the fraction results by PDS variable.

The total frequency of PDS for SMART-100 internal events is 6.30E-8/yr, and #PDS-1 and #PDS-5 account for the majority, about 92%. The success probability of CFS and Backup Spray corresponds to 98.7% and 94.3%, respectively, of the total accident sequences. Conversely, the frequency of #PDS-4 and #PDS-8, which both CFS and Backup spray fail, is very low, less than 0.1%. In addition, in the case of #PDS-9, it has a very low value of 1.31E-12/yr as the accident sequence of isolation failure.

In the case of SMART-100 internal events, it can be expected that the containment will be integrated in analyzing the integrity of the containment because both CFS and Backup Spray are available, such as #PDS-1 and #PDS-5, and most of the accidents achieve all the purposes of cooling the outer wall of the RV, and preventing UCA overpressure.

Table I: Results of PDS Quantification

PDS	Frequency (/yr)	Fraction (%)
#PDS-1	3.61E-8	57.39%
#PDS-2	2.17E-9	3.44%
#PDS-3	4.88E-10	0.78%
#PDS-4	2.92E-11	~0.0%
#PDS-5	2.22E-8	35.2%
#PDS-6	1.35E-9	2.14%
#PDS-7	2.98E-10	0.47%
#PDS-8	1.80E-11	~0.0%
#PDS-9	1.31E-12	~0.0%
#PDS-10	3.13E-10	0.5%
Total	6.30E-8	100.0%

Table II: Fraction Results by PDS variable

PDS variable	Branch (#)	Frequency (/yr)	Fraction (%)
BYPASS	NO BYPASS (1-9)	6.26E-8	99.5%
	BYPASS (10)	3.13E-10	0.5%
CONISO	ISO (1-8)	6.26E-8	100.0%
	NO ISO (9)	1.31E-12	0.0%
RCSP	HIGH (1-4)	3.88E-8	62.0%
	NOT HIGH (5-8)	2.38E-8	38.0%
CFS	YES (1-2, 5-6)	6.18E-8	98.7%
	NO (3-4, 7-8)	8.34E-10	1.3%
CSPRAY	YES (1, 3, 5, 7)	5.91E-8	94.3%
	NO (2, 4, 6, 8)	3.56E-9	5.7%

2.3 Containment Event Tree (CET) Quantification

CET is quantified to analyze the behavioral characteristics of the containment, such as phenomena that can occur during a severe accident, the condition of the containment, and the type of damage to containment.

A total of 8 severe accident headings (BYPASS, CONISO, RCSFAIL, RVFAIL, DCF, ECF, LCF, BMT) are considered, and all severe accident scenarios, that is, the number of CET termination points, are 20 (see Fig. 3).

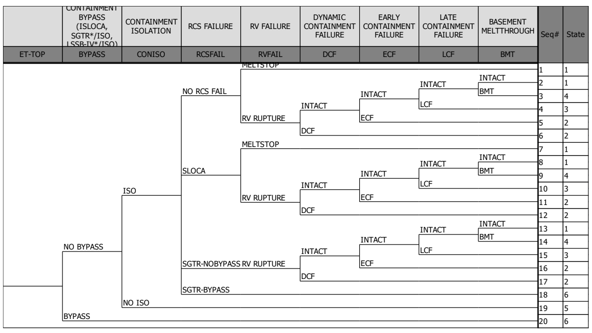

Fig. 3. Containment Event Tree (CET)

Table III shows the results of CET quantification, and Table IV shows the quantification by the type of containment damage.

#CET-1 and #CET-7 are cases in which the corium is cooled by injection by CFS and cooling of the outer wall of the RV in the RV, accounting for about 53% of the total. In addition, #CET-2 was damaged by the high pressure of the RV despite the injection of CFS, but the containment was not damaged early and late by CFS and Backup Spray, and BMT did not occur, accounting for about 31%.

Table III: Results of CET Quantification

CET	Damage Type		Frequency (/yr)	Fraction (%)
#CET-1	MELT STOP	NO RCS FAIL	2.12E-8	33.6%
#CET-2	INTACT (RV FAIL)		1.94E-8	30.7%
#CET-3	BMT		5.66E-10	0.9%
#CET-4	LCF		6.43E-11	0.1%
#CET-5	ECF		9.44E-11	0.2%
#CET-6	DCF		5.51E-11	0.1%
#CET-7	MELT STOP	SLOCA	1.21E-8	19.2%
#CET-8	INTACT (RV FAIL)		1.33E-9	2.1%

#CET-9	BMT		1.79E-10	0.3%
#CET-10	LCF		1.15E-11	~0.0%
#CET-11	ECF		2.86E-12	~0.0%
#CET-12	DCF		1.52E-12	~0.0%
#CET-13	INTACT (RV FAIL)	SGTR-NOBYPASS	7.49E-9	11.9%
#CET-14	BMT		1.12E-10	0.2%
#CET-15	LCF		1.94E-11	~0.0%
#CET-16	ECF		3.93E-11	0.1%
#CET-17	DCF		2.31E-11	~0.0%
#CET-18	SGTR-BYPASS		7.76E-11	0.1%
#CET-19	NO ISO		1.31E-12	~0.0%
#CET-20	BYPASS		3.13E-10	0.5%

Table IV: Quantification by Type of Containment Damage

Damage Type	Frequency (/yr)	Fraction (%)
INTACT (RV INTACT)	3.32E-8	52.8%
INTACT (RV FAIL)	2.82E-8	44.7%
BMT	8.57E-10	1.4%
DCF & ECF	2.16E-10	0.3%
LCF	9.52E-11	0.2%
NO ISO	1.31E-12	0.0%
BYPASS	3.90E-10	0.6%
Total	6.29E-8	100.0%

2.4 Source Term Category (STC) Quantification

The end points of the CET represent the outcomes of possible accident sequences. These end points describe complete severe accident sequences from initiating event to releasee of radioactive materials to the environment.

To distinguish the source term, it is quantified into 7 STCs using 4 main variables (BYPASS, CONISO, MELTSTOP, CF-TIME) (see Fig. 4).

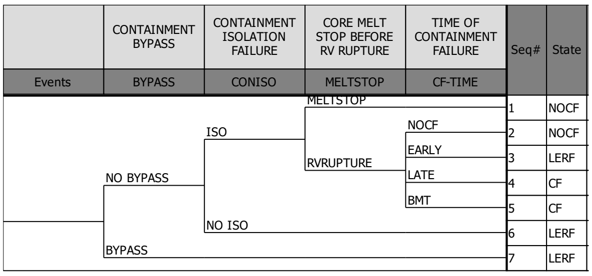

Fig. 4. Source Term Category (STC) Logic Diagram

NPPs must meet the probabilistic safety goals for operation, which include that the total frequency of accident scenarios where the emission of Cs-137 exceeds 100TBq must be less than 1.0E-6/yr.

Table V shows the results of STC quantification. Cases in which the emission of Cs-137 exceeds 100TBq correspond to #STC-4, #STC-5, and #STC-6, and the total of those cases is 9.53E-10/yr, which is lower than the regulatory standard value.

In addition, cases of LERF correspond to #STC-3, #STC-6, and #STC-7, and the total of those cases is 6.08E-10/yr, which also meets the regulatory standard value.

Table V: Results of STC Quantification

STC		Frequency (/yr)	Fraction (%)
#STC-1	RV INTACT	3.32E-8	52.8%
#STC-2	RV FAIL	2.82E-8	44.7%
#STC-3	DCF + ECF	2.16E-10	0.3%
#STC-4	LCF	9.52E-11	0.2%
#STC-5	BMT	8.57E-10	1.4%
#STC-6	NO ISO	1.31E-12	0.0%
#STC-7	BYPASS	3.90E-10	0.6%
Containment Damage Freq. (STC-3 + STC-4 + STC-5 + STC-6 + STC-7)		1.56E-9	2.5%
LERF (STC-3 + STC-6 + STC-7)		6.08E-10	1.0%
Total		6.29E-8	100.0%

3. Conclusions

Based on the Level 2 PSA results for SMART-100 internal events, PDS, CET, and STC results were quantified. The frequency of accident sequences exceeding 100TBq of Cs-137 release is 9.53E-10/yr, and LERF is 6.08E-10/yr, indicating that they are below the regulatory standard value, respectively.

In the case of CFS, Backup spray, and CIS, which are severe accident mitigation systems for developing PDS-ET, subsequent uncertainty analysis is required due to uncertainty in design.

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