CONSOLIDATED APPROACH TO IDENTIFY ACCIDENT SEQUENCES OF A LOSS OF COOLANT ACCIDENT IN A PSA

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In a Conventional risk model using PSA for a NPP, loss of coolant accident (LOCA) are usually treated as fixed event groups by using break size. Most of PSA models divide this accident into small, medium, and large LOCA. In each group, safety function/systems are treated as applicable in the whole range of the break spectrum. Since many safety systems/functions are considered simultaneously in a single LOCA group, it is not possible to exactly find the applicable break spectrum in a single event tree. Present paper proposes new methodology for accident sequence analysis of LOCA. We suggest an integrated single ET construction for LOCA by incorporating a safety system/function and its applicable break spectrum into the ET.

I. INTRODUCTION

Conventional risk model using PSA (probabilistic Safety Assessment) for a nuclear power plant (NPP) considers two types of internal accident initiators, LOCA (Loss of Coolant Accident) and transient event such as Loss of electric power, Loss of cooling, and so on. Traditionally, a LOCA is divided into three initiating event (IE) categories depending on the break size, small, medium, and large LOCA. In each IE group, safety functions or systems modeled in the accident sequences are considered to be applicable regardless of the break size within the group. However, since the safety system or functions are not designed based on a break size, there exist lots of mismatch between safety system/function and an IE, which may make the risk model conservative or in some case optimistic.

Present paper proposes new methodology for accident sequence analysis for LOCA. We suggest an integrated single ET construction for LOCA by incorporating a safety system/function and its applicable break spectrum into the ET.

II. METHODS AND RESULTS

In this section overall method and the results are described. In Section 2.1 basic idea of the present paper is introduced. Section 2.2, 2.3, 2.4, and 2.5 explain the process to construct the integrated ET for LOCA. Finally, the results based on Boolean form of accident sequence are compared with the conventional result in section 2.6.

II.A. Basic Idea for Integrated LOCA ET Construction

The basic idea of the present paper is that all the safety system/function should be described with their applicable break range from the entire break spectrum. To apply this idea, a LOCA should be treated in an integrated environment. That is, LOCA should be treated in a single ET instead of separation. When LOCA spectrum is separated intentionally, the applicable range of safety system/functions can be missed or exaggerated.

If many safety system/function is defined with its specific success criteria and its applicable break spectrum, variety of subset of the entire break spectrum will be presented in the accident sequence which may make the analysis complex. However, simple Boolean algebra can treat this matter easily (see section 2.4). Also, although the inclusion of break spectrum for each safety system/function make the ET more complex, well ordered break spectrum may not increase the accident sequence exceedingly (see section 2.6).

II.B. Safety Function and Its Break Set Point

Based on the OPR-1000 [1] PSA, the safety functions related to a LOCA are composed of three categories, reactor trip, inventory make-up, and decay heat removal. Each safety function/system and related break set point is explained below

II.B.1. Reactor trip (RT)

In a LOCA scenario, reactor trip is assumed to be needed when a break size is not sufficiently large. In case of a LOCA with sufficiently large break size, the reactor is assumed to be shut down by void effect. For this safety function, one break set point may be used to discriminate the accident sequences which need reactor trip from the whole accident sequences

II.B.2. Inventory make-up (IM)

Two types of inventory make-up (IM) are provided depending on the RCS pressure, high pressure safety injection and low pressure safety injection in OPR 1000. A safety function used in a LOCA scenarios related to IM is shown in table 1. For the safety system/function of inventory make-up, we assigned six kinds of break set points [2] as shown in table 3.

TABLE I. Safety function/system used as Inventory make-up for LOCA scenarios

LOCA	Safety function	description
Small LOCA	HPI	High pressure safety injection
	DP	RCS depressurization for Low pressure injection when HPI not available
	SIT	Injection using Safety injection tank
	LPI	Low pressure safety injection
Medium LOCA	HPI	High pressure safety injection
	HNC	Hot and cold leg injection to prevent boron deposition
Large LOCA	SIT	Injection using Safety injection tank
	LPI	Low pressure safety injection
	HNC	Hot and cold leg injection to prevent boron deposition

II.B.3 - Decay Heat Removal (DR)

Decay heat removal (DR) can be accomplished by energy release to the break or S/G in a LOCA. Table 2 shows the safety function related to DR. For the safety function, DR, we assigned one break point [2] as showed in table 3.

TABLE II. Safety function/system used in the decay heat removal

LOCA	Safety function	description
Small LOCA	S/G	Decay heat removal via S/G
	BL	Bleeding to SDS valve when S/G is not available
	HPR	Recirculation using HPI
	LPR	Recirculation using LPI
Medium LOCA	HPR	Recirculation using HPI
	CSR	Recirculation Cooling
Large LOCA	HPR	Recirculation using HPI
	CSR	Recirculation Cooling

For the determination of the break set point, detailed analysis for OPR-1000 was not performed. However, brief analysis for several break set points has been performed [2]. Based on the performed results and the engineering judgment, seven break set points were given for the LOCA. Table 3 shows the overall description of the break set points. In the table, the number is given depending on the break size. For example, break set point 7 is larger than break set point 6.

TABLE III. Break set point for safety function

Set point	Safety function	description
1	IM	A break point below which RCS can be depressurized using S/G
2	IM, DR	A break point below which RCS cooling via S/G is needed(insufficient energy release to break)
3	RT	A break point below which Reactor trip is required
4	IM	A break point above which SIT and LPSI are allowable without depressurization
5	IM	A break point above which hot and cold leg injection is required to prevent flow path blocking from boron deposition
6	IM	A Break point below which one HPSI pump can perform inventory make-up function
7	IM	A break point below which two HPSI can supply coolant

II.C. Integrated ET Construction for LOCA

The heading used in the ET is as follows

- S1: Break set point for depressurization
- S2: Break set point for RCS energy balance
- S3: Break set point for reactor trip
- S4: break set point for LPSI with depressurization
- S5: break set point for hot and cold leg injection
- S6: break set point for one HPSI operation
- S7: break set point for two HPSI operation
- RT: reactor trip
- HPI2: two HP pump operation
- HPI1: one HP pump operation
- DP: depressurization of RCS using S/G
- SIT: success of injection using SIT
- LPI: success of LP pump
- HNC: hot and cold leg injection
- BL: bleeding operation
- RC: recirculation
- CC: containment cooling

The following two rules are used to construct LOCA ET.

- A branching for a safety system(heading) follows the branching of a break set point of the safety system if it exists
- When one makes a branching at a break set point, one should investigate the effect of preceding branching of a break set point.

The first rule means that a safety system/function should be related to its applicable break range. For example, it is meaningless to ask S/G to be used in a large break size. The second rule says that depending on the preceding branching, it may be needless to make other branching. For example, if an accident sequence has a branching at a small break set point (if it is success), it is no need to make branching at a larger one. This rule significantly contributes to reduce the total number of scenarios. Figure 1 shows the resulting integrated ET for LOCA. This event tree has 51 accident scenarios including one scenario of failed reactor trip which is transited to ATWS (Anticipated Transient without Scram) sequence. 39 scenarios are related to core damage.

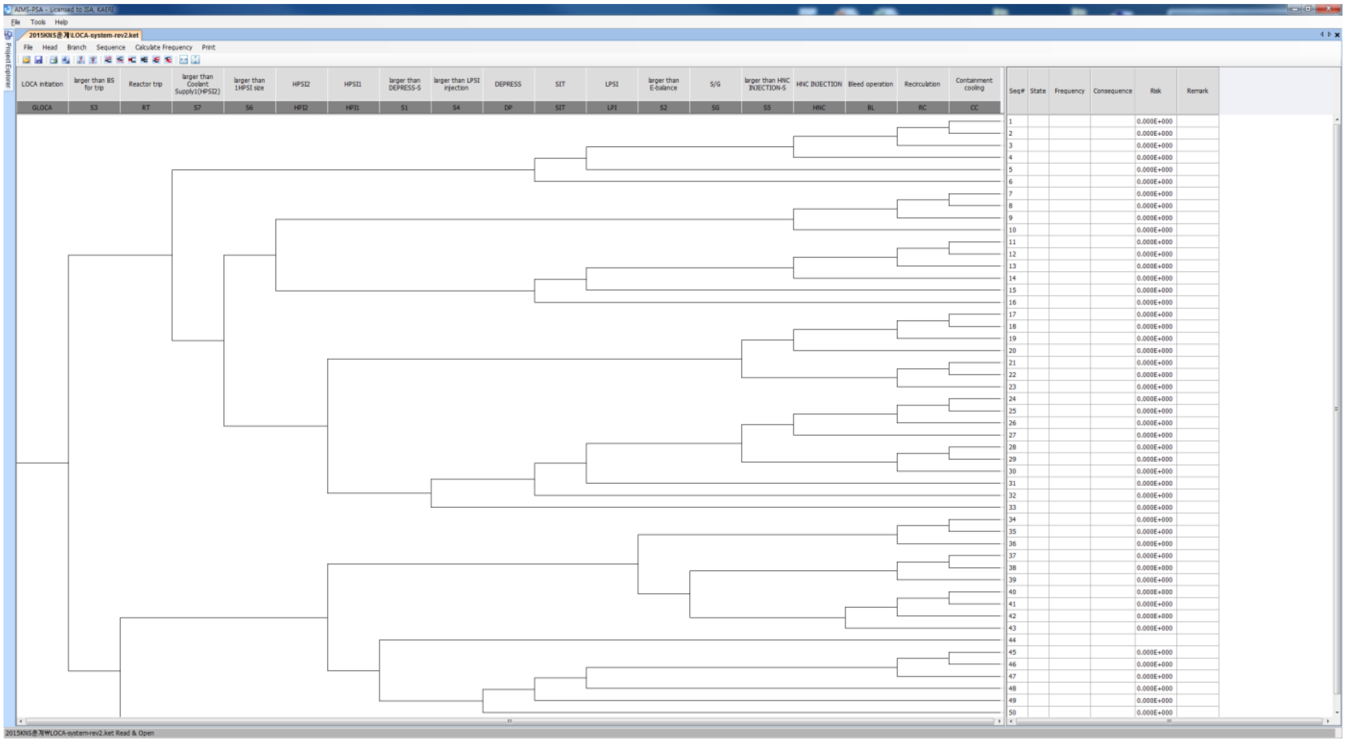

Fig. 1. . Integrated Event Tree for LOCA

II.D. Boolean Algebra with Break Set Point

Since many break size are used in the accident sequence analysis, to quantify the final accident sequence, Boolean algebra is needed to simplify the result. In an ET sequence, Boolean multiplications among break size are frequently presented. The following definitions are used and calculation rules are induced from Boolean algebra

- Definition

a. Si: an event that the break size is smaller than set point, i
b. /Si: an event that the break size is larger than set point, i
c. Sij : an event that the break size is larger than a break set point i and smaller than set point j. "i" should be smaller than "j".

- Calculation rules

For j>i, Si*Sj= Si, /Si*/Sj=/Sj
For j>i, Sj*/Si = Sij
For i>j Sj*/Si = 0

For j>i>k, Sij*Sk = 0
For j>k>i, Sij*Sk = Sik
For k>j>i, Sij*Sk = Sij

For j>i>k, Sij*/Sk = Sij
For j>k>i, Sij*/Sk = Skj
For k>j>i, Sij*/Sk = 0

II.E. LOCA Frequency Estimation

In the conventional approach for LOCA, its occurrence frequency is estimated based on the three categories, small, medium, and Large LOCA. To apply the present method, a continuous distribution for LOCA frequency is required since each accident sequence may have different band in the entire break spectrum. We used the recent estimation for LOCA frequency using expert elicitation and the probabilistic fracture mechanics [3] Table IV shows the LOCA frequency.

TABLE IV. LOCA initiating event frequency

LOCA Category	gpm	Effective Diameter (in)	Mean Value
1	>100	0.5	1.90E-03
2	>1500	1.625	4.20E-04
3	>5000	3	1.60E-05
4	>25k	7	1.60E-06
5	>100k	18	2.00E-07
6	>500k	31	2.90E-08

To obtain a break frequency at a specified point, an interpolation is needed. Since the frequency of break have a tendency of exponential decrease with the break size, a power law fits is applied [3] as follows:

$$y = a \cdot x^b \qquad (1)$$

Where ‘y’ and ‘x’ are occurrence frequency and break size respectively. The constant ‘a’ and ‘b’ is determined by two neighboring points in Table 1. The occurrence are finally compensated for the critical reactor year of the plant. We used 90% of the reactor critical year.

II.F. Major Accident Sequences

Table 4 shows the entire accident sequences for LOCA. For the comparison with the conventional LOCA scenarios, all the accident sequences are divided into three groups which are not exactly compatible with the conventional LOCA categories. As shown in the table, in a group, the safety system/functions in the accident sequence are different depending on the break spectrum. All the accident sequences have their specified break range which is the applicable of the safety system.

TABLE IV. Major Accident Sequences of LOCA from the Present Method

Size	Accident Sequence
Small	S2 /RT /HPI1 /SG /RC CC S2 /RT /HPI1 /SG RC S2 /RT /HPI1 SG /BL /RC CC S2 /RT /HPI1 SG /BL RC S2 /RT /HPI1 SG BL S13 /RT HPI1 S1 /RTHPI1 /DP /SIT /LPI /RC CC S1 /RT HPI1 /DP /SIT /LPI RC S1 /RT HPI1 /DP /SIT LPI S1 /RT HPI1 /DP SIT S1 /RT HPI1 DP
Mid	S35 /HPI1 /RC CC S35 /HPI1 RC S34 HPI1 S23 /RT /HPI1 /RC CC S23 /RT /HPI1 RC S45 HPI1 /SIT /LPI /RC CC S45 HPI1 /SIT /LPI RC S46 HPI1 /SIT LPI S46 HPI1 SIT

Large	/S7 /SIT /LPI /HNC /RC CC /S7 /SIT /LPI /HNC RC /S7 /SIT /LPI HNC /S7 /SIT LPI /S7 SIT S67 /HPI2 /HNC /RC CC S67 /HPI2 /HNC RC S67 /HPI2 HNC S67 HPI2 /SIT /LPI /HNC /RC CC S67 HPI2 /SIT /LPI /HNC RC S67 HPI2 /SIT /LPI HNC S67 HPI2 /SIT LPI S67 HPI2 SIT S56 /HPI1 /HNC /RC CC S56 /HPI1 /HNC RC S56 /HPI1 HNC S56HPI1/SIT/LPI/HNC/RC CC S56 HPI1 /SIT /LPI /HNC RC S56 HPI1 /SIT /LPI HNC

II. CONCLUSIONS

Integrated accident sequence analysis in terms of ET for LOCA was proposed in the present paper. Safety function/system can be properly assigned if its applicable range is given by break set point. Also, using simple Boolean algebra with the subset of the break spectrum, final accident sequences are expressed properly in terms of the Boolean multiplication, the occurrence frequency and the success/failure of safety system. The accident sequence results show that the accident sequence is described more detailed compared with the conventional results.

Unfortunately, the quantitative results in terms of MCS (minimal Cut-Set) was not given because system fault tree was not constructed for this analysis and the break set points for all 7 point were not given as a specified numerical quantity. Further study may be needed to fix the break set point and to develop system fault tree.

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