DEVELOPMENT OF ASP METHODOLOGY AND ITS APPLICATION TO THE SIGNIFICANT ACCIDENT PRECURSORS

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The purpose of ASP (Accident Sequence Precursor) analysis is to evaluate operational accidents in full power and low power operation using PRA (Probabilistic Risk Assessment) technology. In 1979, the ASP analysis was performed in the United States for the first time. And, the SPAR (Standardized Plant Analysis Risk) program has been developed to support ASP programs since 1992. In U.S., 80 SPAR programs were developed from 100 nuclear power plants in 2013 and they have expanded its research and development range until now. In Korea, the methodology for ASP analysis has been developed.

Recently, the awareness of the importance of the ASP analysis has been on rise. In this paper, two case studies in full power and low power operation were performed for the ASP analysis using SAREX program. Also, we suggest the ASP regulatory system in the conclusion.

I. Introduction

The ASP analysis is a method to evaluate safety significance of target events in nuclear power plants quantitatively. In the ASP analysis, the precursors have to be selected from quantitative criteria, and conditional risk associated with the target event is evaluated using a developed PRA model. It reflects characteristics of the reference nuclear power plant. The main results of the ASP analysis are fault tree and event tree modeling that were modified to reflect the target event into the existing PRA model. A precursor means inappropriate core cooling or an event which can lead to it. And, a precursor is selected by quantitative criteria that CCDP (Conditional Core Damage Probability) of target events is below 1.0×10^{-6}. A research for ASP analysis methodology development, based on the methodology of US, has been performed in Korea. But, most researches focus on precursors occurred in full power operation. Precursors occurred in low power operation also need evaluation and management of conditional risk. In this study, the methodology for ASP analysis in full power and low power operation has been developed. We applied the methodology into the target accidents occurred in full power and low power operation. In addition, we suggest an applicable proposal to Korea for regulating ASP analysis.

II. A Methodology for ASP analysis

There are four steps to perform ASP analysis as follow: understanding potential risk, relating an event to a PRA model, modifying a PRA model for reflecting the event into the PRA model, quantifying the modified PRA model and obtaining considerations from it. The PRA model consists of fault trees, event trees, frequencies of initiating event, failure rate, human error probabilities, recovery probabilities and uncertainty parameters. We can modify these factors to describe the event in the PRA model. When an initiating event or a malfunction of safety system occurs, it’s appropriate to use CCDP as conditional risk measure. When the initiating event occurs, CCDP is used. When the malfunction of safety system occurs, ΔCDP is used.

II.A. ASP analysis in full power operation

ASP analysis in full power operation is a methodology for evaluating conditional risk of an accident occurred in full power operation. We reviewed an applicable methodology by referring to the methodology of NRC and KINS. Based on it, we suggest that ASP analysis consists of selection of a precursor, quantification, review, final selection of a precursor and documentation.

II.A.1. Selection of a precursor

A precursor could be inappropriate core cooling or an event which leads to it. Precursors are divided into 2 groups; initiating event and condition event. You can distinguish exclusive events and non-exclusive events from precursors. It is shown in TABLE I.

TABLE I. Exclusive events and non-exclusive events

Type	Detailed events
Exclusive events	A hardware failure without loss of redundancy
	Temporary loss of redundancy in a system
	An event before initial criticality
	A relatively small error of design and quality than expected
	An ineffective event to safety system
	An event that only affects core damage
Non-exclusive events	A failure of safety systems or components
	Loss of redundancy of safety systems
	Failure of coolant systems, instrument air systems
	Loss Of Offsite Power (LOOP), Steam Generator Tube Rupture (SGTR), Small Loss Of Coolant Accident (SLOCA)
	An event leading to shut-down or Loss Of Feed Water (LOFW) by malfunction of a component
	Unexpected accidents

II.A.2. Quantification

There are 2 types of quantification in accordance with type of precursor. Quantification process could be understood by the next example. There is an event tree of it in Fig.1. Sequence 3, 5 and 6 have core damage state. Each core damage frequency can be calculated as below.

$$CDF(IE) = F(Seq.3) + F(Seq.5) + F(Seq.6) \tag{1}$$

$$F(Seq.3) = F(IE)(1 - P(A \mid IE))P(B \mid IE, \overline{A})P(C \mid IE, \overline{A}, B) \tag{2}$$

$$F(Seq.5) = F(IE)P(A \mid IE)(1 - P(B \mid IE, \overline{A})P(C \mid IE, A, \overline{B}) \tag{3}$$

$$F(Seq.6) = F(IE)P(A \mid IE)P(B \mid IE, A) \tag{4}$$

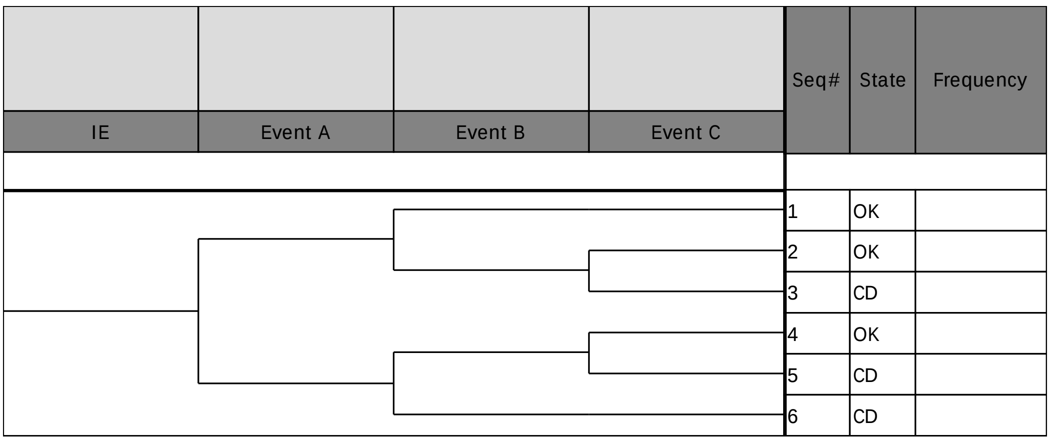

Fig. 1. Event tree example

If a precursor is the initiating event, CCDP is obtained as below.

$$CCDP = (1 - P(A \mid IE)P(B \mid IE, \overline{A})P(C \mid IE, \overline{A}, B) + P(A \mid IE)(1 - P(B \mid IE, A))P(C \mid IE, A, \overline{B}) + P(A \mid IE)P(B \mid IE, A) \tag{5}$$

If a precursor is component failure, ΔCDP is obtained as below.

$$\Delta CDP = P(CD \mid A) - P_{CD} \tag{6}$$

The basic event related to component failure is logically changed from ‘false’ to ‘true’.

II.A.3. Review

A result of preliminary precursor is sent to operator or professional institutions. And, they scrutinize accuracy of technical analysis, modeling assumptions and appropriateness of analysis model. After review, it’s re-quantified if necessary. The final precursor is selected if CCDP or ΔCDP is more than 1.0×10^{-6}.

II.A.4. Documentation

The result of the precursor is documented and managed separately. Precursor, which is difficult to be quantified such as degradation of the system, is analyzed by applying conservative assumption. Its result is documented. Special precursor, which CCDP or ΔCDP is less than 1.0×10^{-6}, is separately documented and classified as interest case; it interfere with the continuous core cooling, it is not related to normal failure mode. In addition, it is documented separately that the precursor includes containment failure.

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II.B. ASP analysis in low power operation

Accidents occurs in full power operation period as well as low power operation period. This period means the duration from reactor shutdown to restart after fuel replacement. POSs (Plant Operational State) are classified with operating parameters. A possible accident for each POS is also varied. There are possibilities of core damage that an accident, occurred in other period except for fuel replacement period, induced loss of loaded fuel cooling.

In Korea, there are no cases or results that ASP analysis applies into an accident in low power operation. But, many people acknowledge the necessity to manage conditional risk in low power operation by performing ASP analysis. Applicable methodology to Korea by referring RASP handbook is described.

II.B.1. Selection of a precursor

Criteria of precursor in low power operation includes an event to induce loss of shutdown cooling. Non-exclusive events in precursors are shown in TABLE II.

TABLE II. Non-exclusive events

Type	Detailed events
Non-exclusive events	Loss of shutdown cooling capability
	Loss of coolant inventory
	Loss of alternative power
	LOOP, SLOCA
	An event only occurred in low power operation

II.B.2. Plant Operational State

It is necessary to determine POS of the selected precursor. POS of PWR in NUREG/CR-6144 is shown in TABLE III. POS is classified by 6 operational mode in operating technical specification. Also, Many factors is considered such as reactor power, coolant level, temperature, pressure, whether open of reactor coolant system or not. We used the POS of OPR1000 (Ref.7) in our application.

TABLE III. Classification of POS

POS	Description
1	Low Power Operation and Reactor Shutdown • Turbine and Rx power levels are decreased to low power levels w/out causing Rx trip or loss of power conversion system (PCS) • Power at 10-15% • RCS temp (T_{ave}) is 547°F
2	Cooldown with SGs to 345°F • Cooldown from 547°F and 2235 psig to RCS temp～345°F and press～345 psig
3	Cooldown with RHR to 200°F • Cooldown of Rx from 345°F to ≤ 200°F by controlled main turbine steam bypass (while maintaining SG pressure) • RHR is placed in service during hold • All engineered safeguard pumps (except one charging pump) is placed in pull-to-lock (PTL) • RCS pressure is maintained at 345 psig with a bubble in the pressurizer • Once RHR is in service SG steaming and RHR cooling is used to cooldown RC until SG pressure decreases to 5 to 15 psig (RCS temp 220 - 250°F)
4	Cooldown to Ambient Temperature (using RHR) • RCS is cooled down from 195 to 140°F by RHR heat exchangers flow control • RCS pressure is maintained at 345 psig with a bubble in Pressurizer
5	Draining the RCS to Mid-Loop • Starting at 140°F with a bubble, the one operating RCP and pressurizer heaters are secured • The RCS is depressurized by spray down of the pressurizer and filling it
6	Mid-Loop Operations • RCS at mid-loop, may be vented, the RC loops may be isolated
7	Fill for Refueling • The Rx head is de-tensioned, unbolted, and removed • The water level is raised to flood the Rx • The upper internals are removed and stored underwater
8	Refueling • With Rx head removed and refueling cavity flooded, the spent fuel assemblies are removed from the Rx core
9	Draining RCS to Mid-Loop after Refueling • The Rx head bolts are tensioned
10	Mid-Loop Operations after Refueling
11	Refill RCS Completely • Water level is raised using CVCS • RCS is brought solid
12	Heat-up Solid and Draw a Bubble • The solid RCS is pressurized to ～345 psig
13	Heat-up to 350°F • Pressurizer ～345 psig, temperature controlled by RHR heat exchanger flow at 195°F
14	Heat-up with SGs available • The RCS and secondary systems continue the unit heat-up within heat-up rate limits
15	Rx Startup and Low Power Operation • RCS pressure at 2235 psig, temperature at 547°F • Rx brought critical and power increased (<10%) to warm-up

II.B.3. Quantification

PRA models for quantifying precursors in low power operation are modeled in accordance with POS. Each PRA model has different initiating events, event trees and fault trees. If a precursor is an initiating event or a condition event, the following contents are necessary for quantification. It is shown in TABLE IV.

TABLE IV. Classification of precursors

Precursor	Description
Initiating events	The type of initiating event
	Faulty component or unavailable component
	Whether the correction of operator performance is needed or not
	Plant shutdown time
	Whether an event occurred in the period of component failure or overhaul
Condition events	Define the POS associated with the event
	Total time of each POS
	Unavailable component
	The start time for Mid-loop operation

III. Application and results

We performed ASP analysis in full power and low power operation. We select the LOKV in Hanbit (Ref. 8) and SGTR in Hanul (Ref. 9). And, we used SAREX program (Ref. 4) to modify PRA model and quantify it.

III.A. Application of ASP analysis in full power operation

The operational accident occurred in full power operation is 'Loss of a 4.16kV AC bus and running of EDG by running of a ground fault protection relay in Hanbit unit 4. The accident proceeded as follow: running start-up transformer and a ground fault protection relay (251 GNA), opening of a switchyard circuit breaker (PCB 7900, 7971), a 4.16kV AC bus circuit breaker, loss of voltage and running emergency diesel generator and supplying power to 4.16kV AC bus.

Full power PRA model of Hanbit nuclear power plant (unit 3, 4) was used as base model. The event tree is shown in Fig. 2. And, two kinds of fault trees were changed due to unavailability of 01SA and running of EDG which are shown in Fig. 3 and Fig. 4.

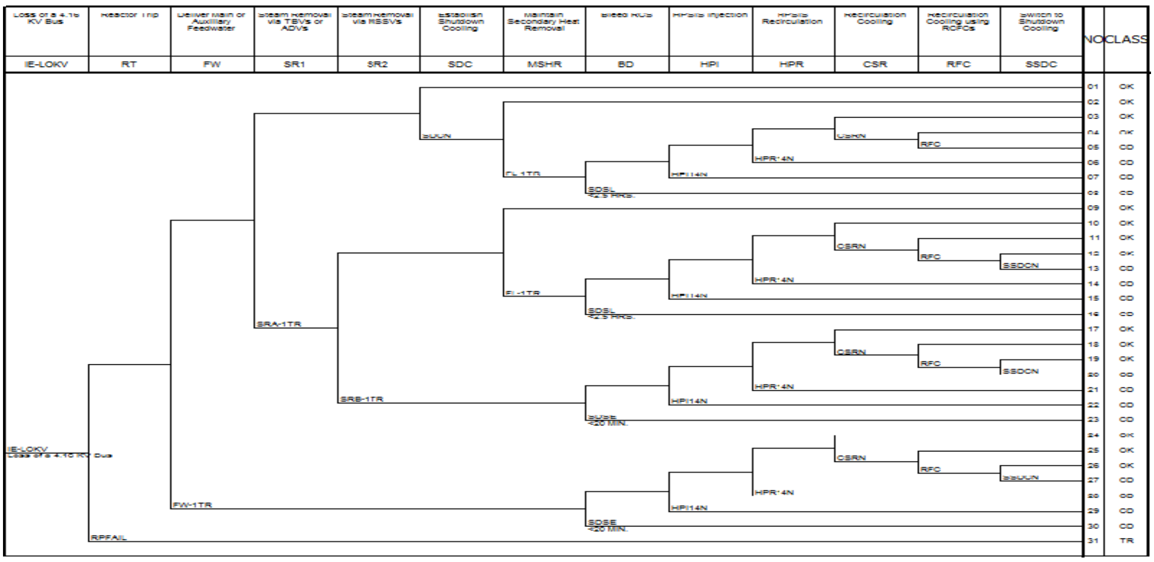

Fig. 2. Event tree of LOKV.

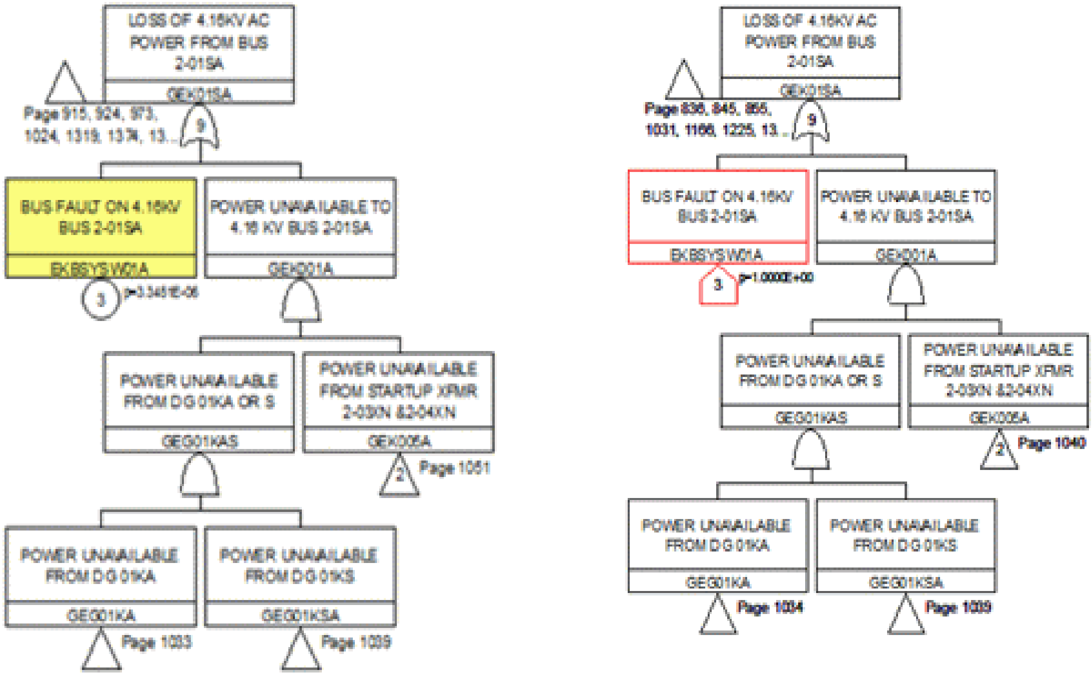

Fig. 3. Modified fault tree by unavailability.

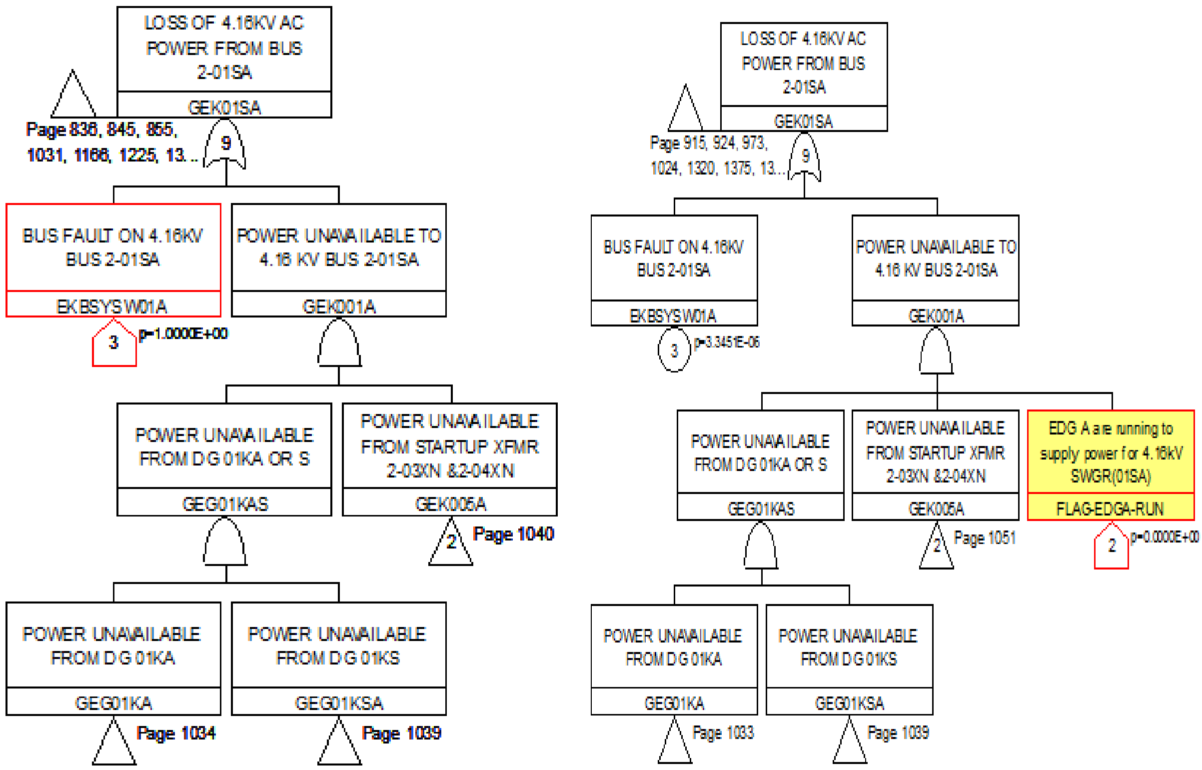

Fig. 4. Modified fault tree by running EDG.

The quantification results is shown in TABLE V. The net result of CCDP is 1.195×10^{-6}. It means the Precursor and White in color coding of NRC (Ref. 5).

TABLE V. Result of quantification

Model	Value	Per (%)	Cut-off
Base model	$2.267\ x10^{-9}$	-	$1.0x10^{-12}$
%IE = 1	$1.195\ x10^{-6}$	-	$1.0x10^{-9}$
Modified model 1	$1.195\ x10^{-6}$	0	$1.0x10^{-9}$
Modified model 2	$1.195\ x10^{-6}$	0	$1.0x10^{-9}$

III.B. Application of ASP analysis in low power operation

The operational accident in low power operation is 'Safety injection by Steam Generator Tube rupture in Hanul unit 4. It is as below (Ref. 6). The accident proceeded as follow: shutdown for overhaul, drawing-down of level during hot stand-by mode, an alarm for high reactivity in steam generator blow down line occurs, recognizing tube rupture in steam generator B, isolating steam generator B and pressure equilibrium by steam generator A.

This accident occurred in POS 2. Full power PRA model of Hanul nuclear power plant (unit 3, 4) was used as a base model. The event tree in Fig. 5 was changed by deleting the heading of RT (Reactor Trip), DPI (Depressurize RCS for LPSIS Injection) and LPI (LPSIS Injection).

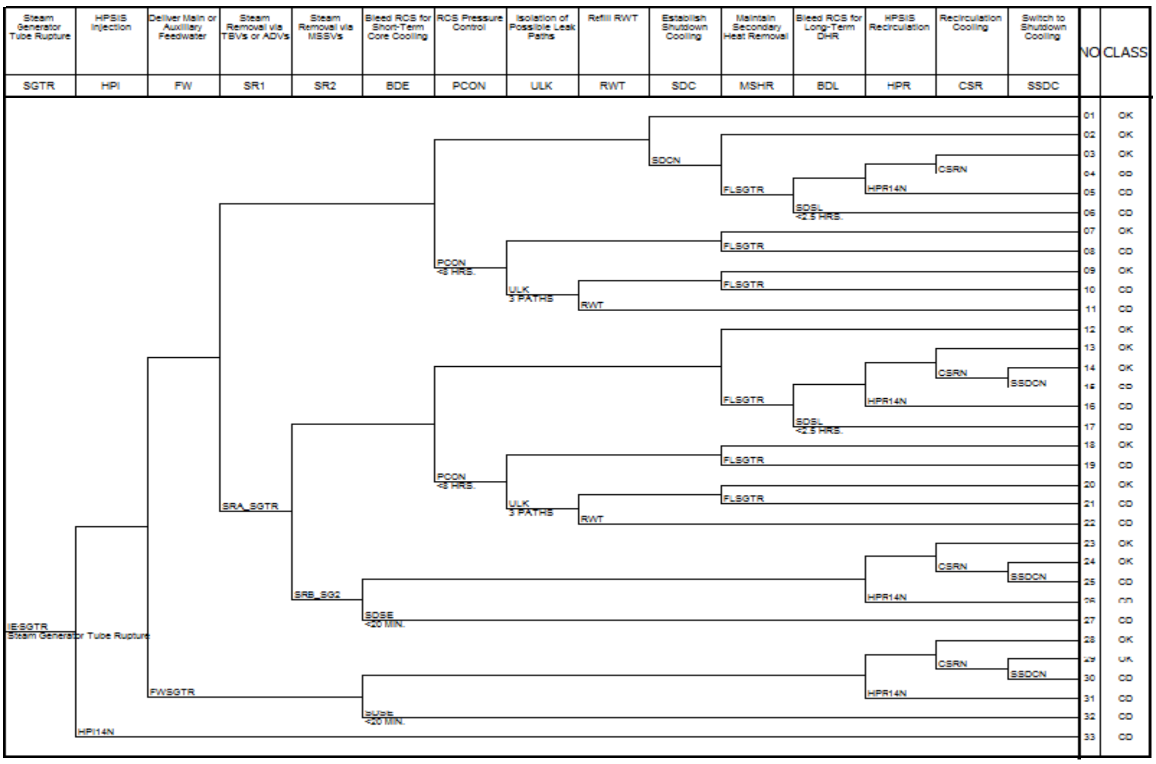

Fig. 5. Modified event tree by deleting headings of RT, DPI and LPI.

There are 3 types of modified fault trees because of a loss of electrical grid by turbine trip couldn't occur, delete of auto reset and human error that a manager, at that time, opened MSIBV to prevent leaking out of radioactive materials. Those are shown in Fig. 6, Fig. 7 and Fig. 8.

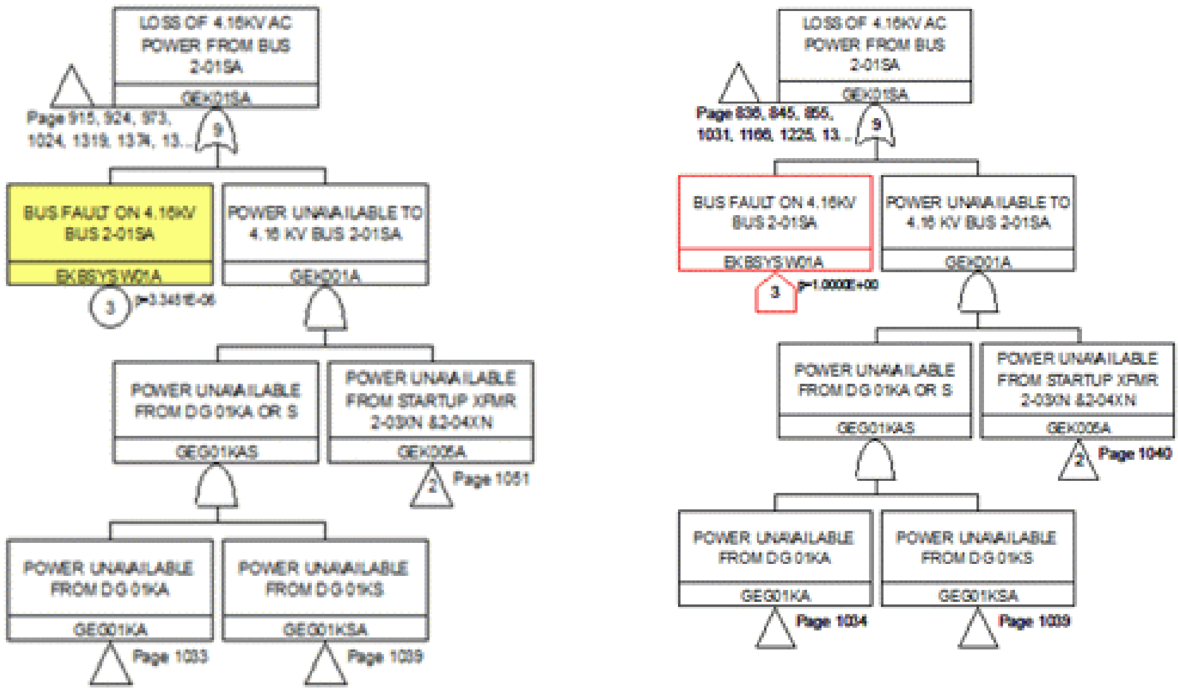

Fig. 6. Modified Fault Tree by unavailability.

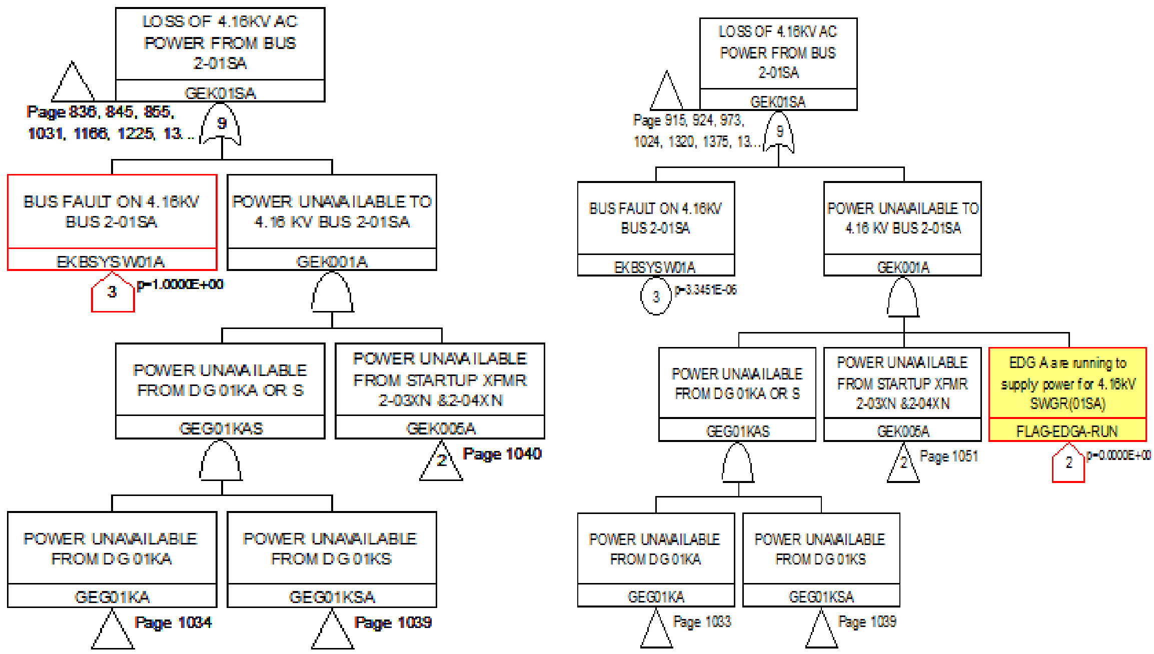

Fig. 7. Modified Fault Tree by running EDG.

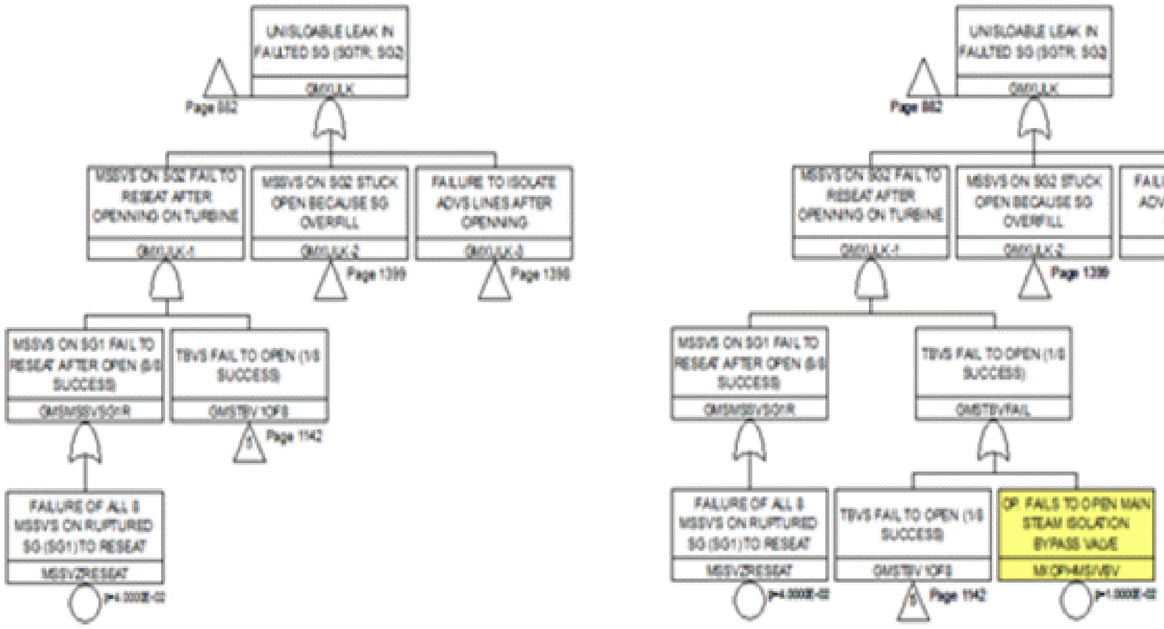

Fig. 8. Consideration of MSIVBV.

The quantification results is shown in Table VI. The net result of CCDP is 2.261×10^{-3}. It means the Precursor and RED in color coding of NRC.

TABLE VI. Result of quantification

Model	Value	Per (%)	Cut-off
Base model	5.195 x10^{-7}	-	1.0x10^{-12}
%IE = 1	1.159 x10^{-4}	-	1.0x10^{-10}
Modified model 1	1.134 x10^{-4}	-2	1.0x10^{-10}
Modified model 2	2.289 x10^{-3}	1,875	1.0x10^{-10}
Modified model 3	2.261 x10^{-3}	1,851	1.0x10^{-10}
Modified model 4	2.261 x10^{-3}	1,851	1.0x10^{-10}

IV. CONCLUSIONS

In this study, we reviewed previous researches for ASP analysis, and applied the methodology of ASP into nuclear power plant in Korea. We quantified CCDP of these 2 cases; 1.195×10^{-6} for full power operation and 2.261×10^{-3} for low power operation, respectively. The ASP analysis is essential to analyze and manage conditional risk. It is that significant accidents actually occurred in nuclear power plant can be described in PRA model.

Up to now, there is no enforced regulation for the ASP analysis in Korea. The ASP analysis could detect the conditional risk by assessing the operational accidents. The ASP methodology might contribute to improving the safety of nuclear power plant by detecting, reviewing the operational accidents and finally removing conditional risk. In the future, this study might contribute to systematize a regulatory basis of ASP analysis in Korea. We suggest the regulatory system of ASP program in Fig. 9. In the suggested regulatory system, operator has to notify regulatory institute of operational accident before recovery work for the accident. After follow-up accident, they have to check precursors in data base to find similar accident. And, probabilistic risk assessment and deterministic review of the accident are performed. Based on this information, regulatory institute takes appropriate actions to check and evaluating licensee for this precursor.

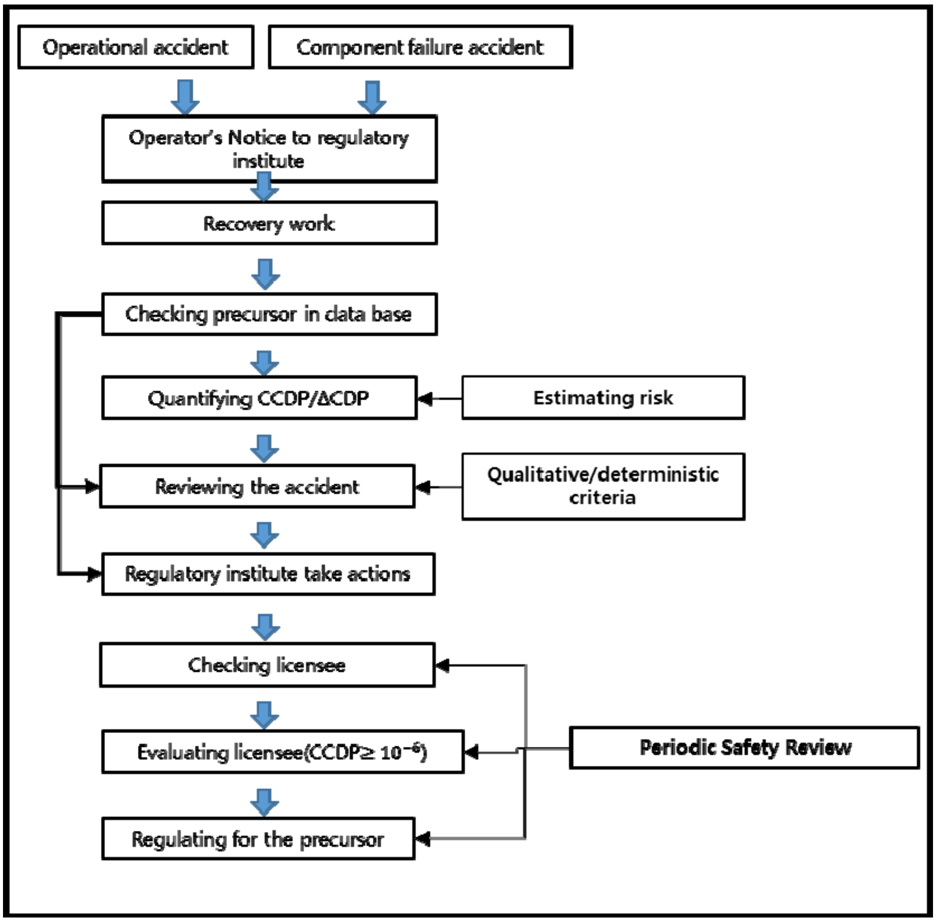

Fig. 9. Regulatory system of ASP.

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