Development of Level 3 PSA Event Tree Model for Probabilistic Assessment of the Offsite Alarm Time

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Abstract: This paper presents a new approach to Level 3 Probabilistic Safety Assessment (PSA) by developing an event tree model. Conventional Level 3 PSA focuses primarily on consequence analysis following severe accidents, often considering of the weather, atmospheric dispersion, and countermeasures such as sheltering and evacuation. Meanwhile, this study evaluates the offsite consequence probabilistically by developing a Level 3 PSA Event Tree model. This paper describes the methodology for constructing the event tree. Offsite alarm time (OALARM) used in MELCOR Accident Consequence Code System (MACCS) is determined by Level 3 PSA Event Tree model. Headings were identified by considering events expected to occur until an offsite alarm is declared. Level 3 PSA Event Tree originally uses a fault tree to determine the probability of success/delay/failure heading branches like the conventional PSA analysis method, but in this study, simply determined branch probability was used to derive preliminary results. Representative accident scenario was selected as initial source term category to simulate the MACCS code. The MACCS code then inputs each OALARM time determined from the event tree to calculate the offsite consequence, thereby deriving the final risk. This study provides a framework for developing a Level 3 PSA Event Tree model. This study also provides preliminary results for reference site based on a newly developed event tree model. Preliminary results show population-weighted cancer fatality risk distribution by frequency. Furthermore, key factors that significantly influence the offsite consequence outcomes can be derived after the fault tree is developed and reflected in the Level 3 PSA Event Tree model.

Keywords: Level 3 PSA Event Tree, Offsite Alarm, Emergency Response, Risk Assessment

1. INTRODUCTION

Much research has been done on Level 3 Probabilistic Safety Assessment (PSA), which evaluates the offsite consequences of a hypothetical accident in nuclear power plant [1]. When conducting a Level 3 PSA, it is important to develop an appropriate emergency response model that reflects realistic conditions. Simulation codes are typically used to calculate the impact on human health and the environment through atmospheric dispersion modeling, and the health impact is mainly related to weather conditions and countermeasures such as evacuation and sheltering. Therefore, the Level 3 PSA and the radiation protection fields are working closely together to design a Level 3 PSA simulation code and model.

In particular, as a starting point for emergency response in the event of a nuclear accident, it is important to properly estimate the time for nearby residents to be notified of evacuation order. This time is an input to the emergency response model in the simulation code. Previous studies have used simple assumptions to determine this time, while in reality, this time is determined by a series of different events. This time, which is called offsite alarm time, is a very important factor because it is directly related to when residents begin their emergency response. Since it has a significant impact on the results of offsite impact analysis, it is necessary to develop a new method that overcomes the limitations of the existing method and reflects a more realistic situation by applying the offsite alarm time.

To overcome these limitations, this paper discloses the development of a Level 3 PSA event tree model that aims to correct these shortcomings by introducing a framework for Level 3 Event Tree model. This model provides an improvement over existing methods by integrating event tree and fault tree analysis to probabilistically estimate offsite alarm time.

The term Level 3 PSA Event Tree was first used in a research report by VTT, which performed deterministic and probabilistic safety assessment (IDPSA) as a pilot-study of the Fukushima accident [2]. The goal of the report was to analyze whether the low fatality rate in the Fukushima accident was probabilistic or coincidental. The paper used deterministic methods for the analysis of atmospheric distribution and population dose, and probabilistic method for analysis of wind/precipitation and sheltering/evacuation. It was developed as an event tree, and the ARANO code [3] was used to analyze offsite results, but it has the limitation of using overly simplistic values for the probability of sheltering/evacuation from expert judgment.

To analyze the impact of various variables affecting Level 3 PSA results, the U.S. The Nuclear Regulatory Commission (NRC) analyzed the impact of various uncertainty parameters used in SOARCA Level 3 PSA software interpretation [4, 5]. It includes 21 MELCOR variables and 350 (20 groups) MACCS variables, and their values have a distribution. The distribution of variables such as delay to evacuation and evacuation speed used triangular distribution based on the evacuation time and speed calculation report. This study evaluated which parameters are important factors for offsite consequence analysis.

Level 2 PSA predicts the progress of an accident by designing an event tree for the phenomenon, but an attempt was made to incorporate the response of the Severe Accident Management Guideline (SAMG) [6]. This study modeled the SAMG event tree and fault tree, and combined them with Plant Damage State - Event Tree (PDS-ET) to update each Minimal Cut Set with a new PDS number. Through this, the frequency of Source Term Category(STC) was quantified again and the risk was assessed. This study showed that applying SAMG can reduce risk by 44% compared to the existing method, and risk-significant factors were evaluated through the Fussell-Vesely importance measure.

The purpose of this study is to evaluate risk and derive risk-significant factors through the development of a Level 3 PSA Event Tree model. In this study, newly devised Level 3 PSA Event Tree model outlines the sequence of events leading to the offsite alarm, categorizing them into stages such as emergency declaration, evacuation recommendation, evacuation decision, and evacuation order, with further subdivisions into outcomes of success, delay, and failure. The emergency response considered in Level 3 PSA varies from offsite-alarm to long-term evacuation and relocation, but Level 3 PSA Event Tree in this study only models the offsite alarm and does not model sheltering and evacuation. This study only considers internal events, and among them, one early release scenario was selected as a representative scenario. As a result of this study, offsite consequence for representative scenario was derived through Level 3 PSA Event Tree method. The offsite consequence is calculated for each branch of the Event Tree reflecting emergency response, and the risk is obtained by multiplying the frequency with which each branch occurs. In the future, when the fault tree is refined, key factors that have a significant impact on offsite consequence can be derived through cut set analysis. The biggest advantage of Level 3 PSA Event Tree model is that it reduces uncertainty and increases reliability by probabilistically considering values that were considered as single values. In addition, another important value in this study is that it can identify risk-significant factors among emergency responses. Through this, it is expected that risk insights can be obtained and used for emergency response decision making.

2. CONCEPT OF LEVEL 3 PSA EVENT TREE

Figure 1 conceptually shows the PSA analysis method from Level 1 to Level 3 [7]. The top image in Figure 1 shows the process from Level 1 Initial Event (IE) to Level 3 final risk derivation using a typical PSA analysis method. Level 1 PSA calculates the Core Damage Frequency (CDF) from the Initial Event (IE) through the event tree and through success criteria analysis. Level 2 PSA classifies events in which CDF occurs by Plant Damage Status (PDS) and uses them as initial values, and obtains the source term of each scenario and its probability through an event tree for the phenomenon. Level 3 PSA analysis uses the STC, which is the result of Level 2 PSA, as input and uses simulation code to derive offsite consequences. The simulation code derives offsite consequences using deterministic emergency response-related analysis variables for each source term category, and obtains risk by multiplying this by the STC frequency. Level 3 calculation codes typically consider annual weather conditions, cohort characteristics, sheltering and/or evacuation times, etc., but currently the only statistical considerations applied to Level 3 PSA studies are meteorological data.

The bottom image of Figure 1 shows the concept of the Level 3 Event Tree presented in this study. This concept uses an event tree like Level 1 and Level 2 PSAs to perform probabilistic analysis based on emergency responses. Each STC branches into various scenarios following the Level 3 PSA Event Tree. Each scenario obtained along the Level 3 Event Tree is simulated by MACCS code [8]. Final risk can be obtained by multiplying the offsite consequence of each scenario by the frequency of occurrence of that scenario. Therefore, the Level 3 PSA Event Tree model must be properly interfaced with the offsite consequence analysis code MACCS. The main parameters of the MACCS code for emergency phase modeling over time are presented in

Figure 2. Among various parameters, Offsite Alarm (OALARM) is one of the most important interpretation parameter because it is the point at which the response of the residents begins, and all subsequent response (sheltering/evacuation) times are affected. This study only addresses the assessment of OALARM time, the first step in Figure 2. As future work, more comprehensive and inclusive event tree can be designed to cover further emergency responses such as sheltering and evacuation.

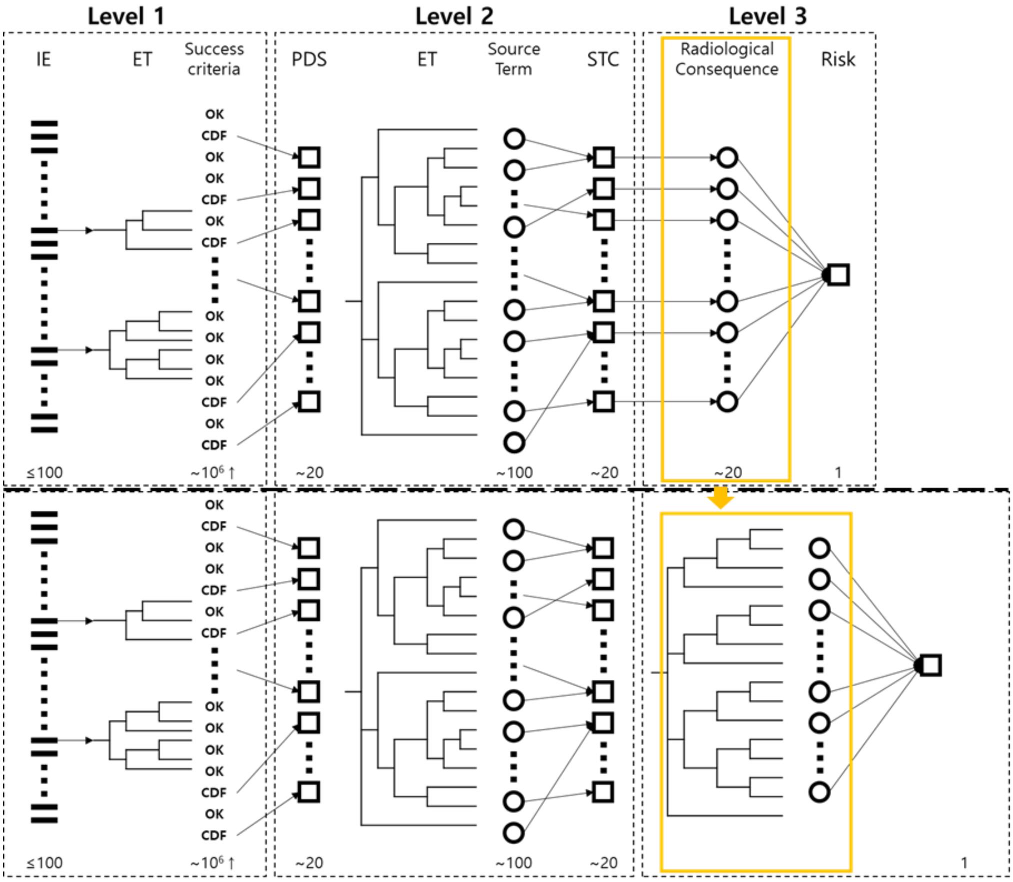

Figure 1. Concept of Level 3 PSA Event Tree Model

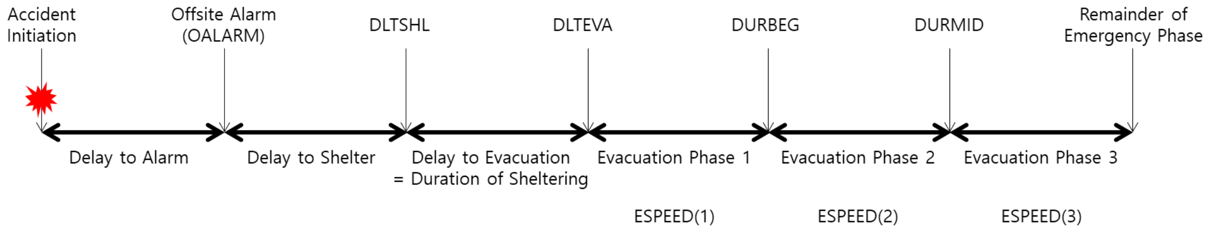

Figure 2. Emergency response related parameters used in MACCS

3. DEVELOPMENT OF LEVEL 3 PSA EVENT TREE MODEL

3.1. Framework

Figure 3 shows a framework of how to develop a Level 3 PSA Event Tree model. Conventional Level 3 PSA calculates risk by obtaining offsite consequences from STCs as shown in the procedure on the left side of Figure 3. The process of applying the Level 3 PSA Event Tree Model is explained in steps ① ~ ③ of designing the Level 3 PSA Event Tree Model, and steps ④ ~ ⑥ of assessing risk.

First of all, in order to develop Level 3 PSA Event Tree Model from ① to ③, the headings are selected by referring to various emergency response manuals[9]. Since the event tree is basically organized in time sequence, it is essential to understand the emergency response procedures. More information on this is provided in Section 3.2. After headings are designed, the event tree is branched to comprehensively reflect various emergency response scenarios resulting from the success and failure of headings (Section 3.3). Once the headings and branches of the event tree are constructed, a fault tree is designed to determine the probability of each branch (Section 3.4). After the event tree and fault tree structures are established, the characteristic of each STC, which is the initial input for the Level 3 PSA Event Tree, is identified. Here, the time from the accident initiation to exceed GE (general emergency) Level is calculated, and this value is used in the OALARM calculation. A detailed explanation is provided in Section 3.5.

The following ④ to ⑥ are the parts that interpret the results from Level 3 PSA Event Tree. In the first step, the OALARM values from each branch of the Level 3 PSA Event Tree are inputted into the Level 3 PSA simulation code, and calculations are performed on all OALARM values. Then, the risk is derived by multiplying the offsite consequence by the frequency at which each OALARM branch occurs (Section 4.1). Finally, each cut set of the Level 3 PSA Event Tree is analyzed to evaluate risk-significance (Section 4.2).

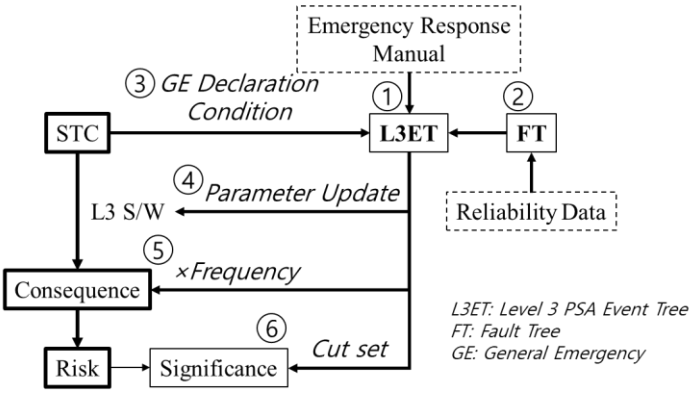

Figure 3. Level 3 PSA Event Tree Model Framework

3.2. Headings

To design Level 3 PSA Event Tree headings, standardization of emergency response procedures is necessary. To standardize the procedure, as shown in Table 1, the response behavior and target time of each organization were investigated when alert, site area emergency(SAE), and general emergency (GE) situations occur [10].

The presented time used the shortest value among the literature investigated, and for further details, refer to Lee et al. [9]. Practical actions and decisions related to evacuation are performed after a GE occurs, and in alert and site area emergency situations, preparations are made to respond to the actions required during a GE. It can be concluded that the success/failure of the GE response in required time determines the success/failure of the entire emergency response.

Table 1. Preparedness for a Nuclear Emergency for Licensee and Government

	Alert	**Site Area Emergency**	**General Emergency**
Licensee	Onsite ERO* & EOF** operation *1 hr*		Evacuation Recommendation *30 min after GE Declaration*
Central Government	Preliminary Offsite ERO (Command Center) *6 hr*	Offsite ERO (Command Center)	Evacuation Decision *15 min after Recommendation*
Local Government	Offsite ERO (Local Headquarters) *6 hr*	Preparedness of Public Protective Action	*Evacuation Order* *15 min after Decision*

*ERO: Emergency Response Organization
**EOF: Emergency Operation Facility

Therefore, the headings of this Level 3 PSA Event Tree are designed as a response for GE, and the role of each organization and its response procedures are schematized in Figure 4. Standardized emergency response procedures are as follows. When Emergency Action Level(EAL) exceeds, it consists of four headings: GE declaration & notification (30 minutes), evacuation recommendation (15 minutes), evacuation decision (15 minutes), and evacuation order (15 minutes). In the procedures, the GE declaration (15 minutes) and notification (15 minutes) procedures are separated, but since the two responses have the same subject and can proceed simultaneously, they are used under one heading. The subject of evacuation recommendation is Onsite ERO, and the subject of evacuation decision and order is central and local offsite ERO, respectively. Since the responses of alert and site area emergency situations affects the success/failure of responses of GE, they are developed as a fault tree and reflected in the event tree.

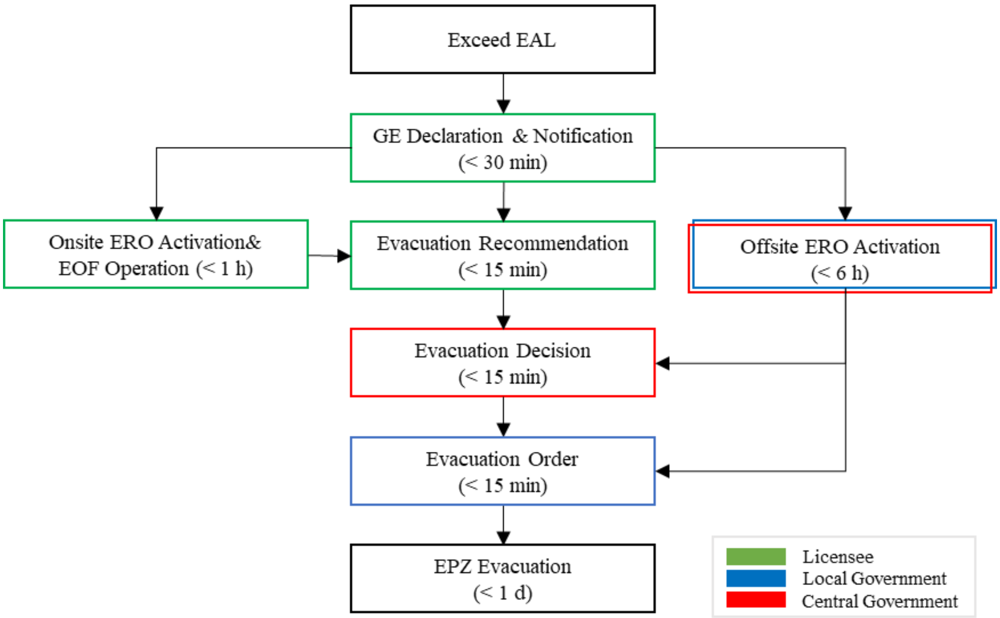

Figure 4. Standard procedures and time objectives during general emergency

There are two important rules: First, the progression of the accident scenario is not affected by emergency response. Therefore, the exceed EAL timing does not change depending on the emergency response of the headings, and the progress of the accident follows only the results of the accident simulation code. Second, emergency response headings occur independently. Therefore, the time required to perform each heading is cumulative rather than overlapping.

3.3. Level 3 PSA Event Tree

The event tree is designed to realistically reflect emergency response scenarios through the four headings [10]. Each heading is divided into three: succeed, delay, and fail, so a total of 81 sequences occur. Since there may be overlap in the result (OALARM time), the number of cases is less than this.

The time taken to succeed, delay and fail of each heading determines the OALARM time derived from the event tree. Therefore, the time required for succeed, delay and fail of each heading was designed to reflect the reality of emergency response and have a meaningful difference in offsite consequences.

Figure 5 shows the results of sensitivity analysis for OALARM to offsite consequence. Sensitivity analysis was carried out using the MACCS code, and an early release accident case selected as a representative accident scenario was simulated. Because this study was a pilot study on a reference site, absolute values were not indicated. As shown in the figure, it was observed that the consequences of the general public cohort and the tail cohort increased rapidly between about 300 and 400 minutes, and continued to increase gently after about 600 minutes. Therefore, this study designed the required time for each heading so that the branching of the event tree reflects the section where consequences change rapidly.

Figure 6 is part of the designed Level 3 PSA Event Tree, and the required time for each heading is indicated. Each heading firstly branches into succeed and not succeed, and not succeed branches again into delay and fail. The success criterion for each heading is to complete the execution of the heading within the required time (Figure 4). For conservative analysis, Level 3 PSA Event Tree assumes that there is no completion earlier than the required time, and therefore, when emergency response is successful, the required time of the heading is considered to be fully used.

Considering the reality of emergency response and OALARM sensitivity test results, the delay time for each heading was designed to be 60 minutes, and the fail time was designed to be 120 minutes. Required time are accumulated as it passes through each heading. The accumulated time passing through all headings is called the cumulative emergency response time, and sequences with the same cumulative emergency response time have the same offsite consequence. And the cumulative emergency response time plus the time from accident initiation to exceed GE Level is called OALARM. The time from accident initiation to exceed GE Level for a representative accident scenario in this study is approximately 120 minutes, which is covered in Section 3.5. Figure 7 shows the OALARM time distribution of the designed Level 3 PSA Event Tree sequences. OALARM was designed to have many sequences between 300 and 600 minutes through required time design.

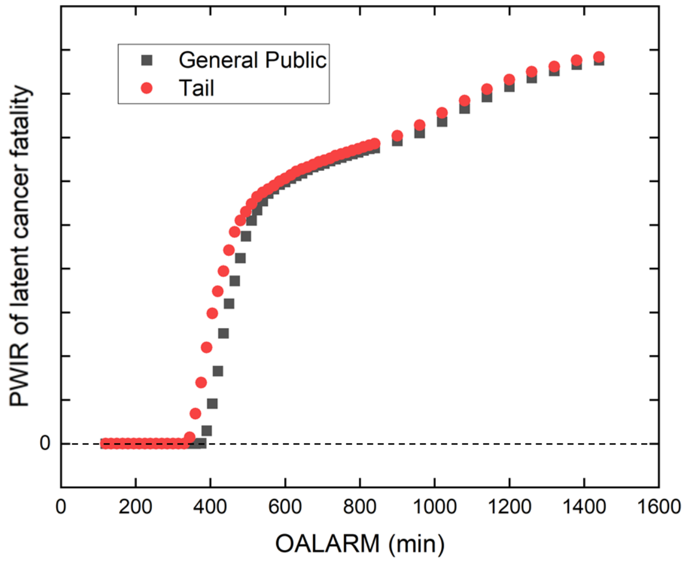

Figure 5. OALARM Effect on Population-Weighted Individual Risk (PWIR) of Latent Cancer Fatality

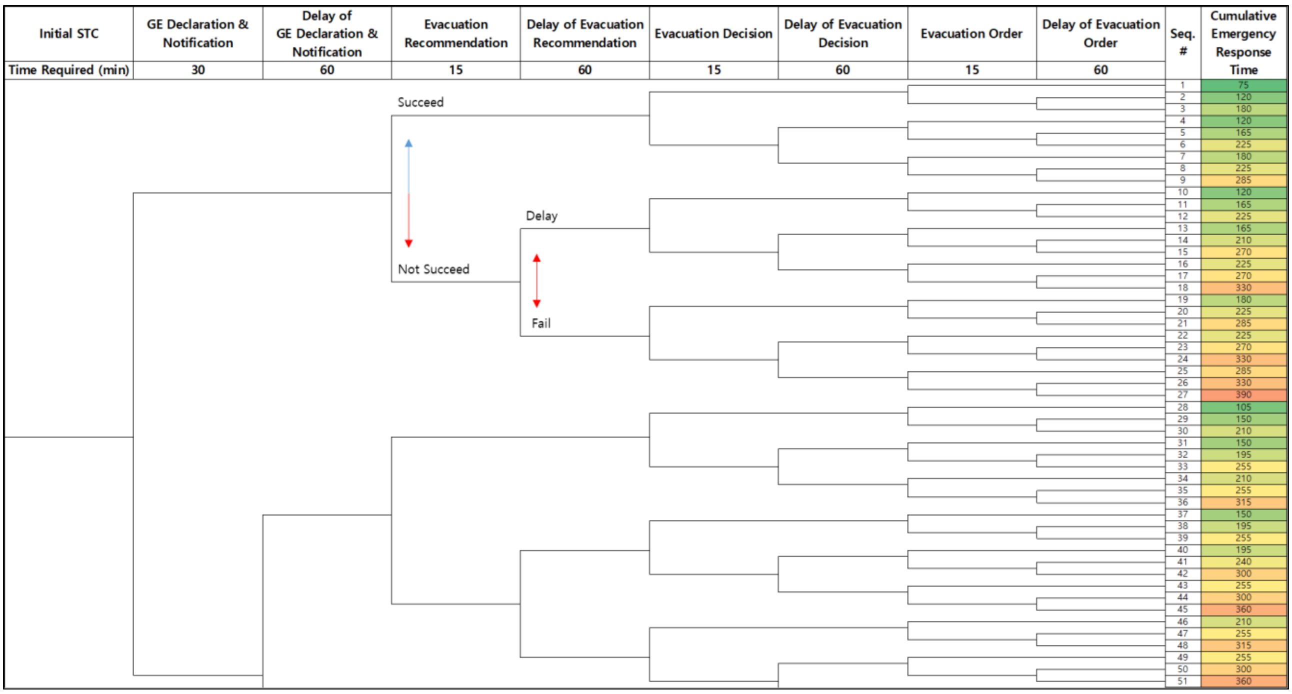

Figure 6. Designed Level 3 PSA Event Tree

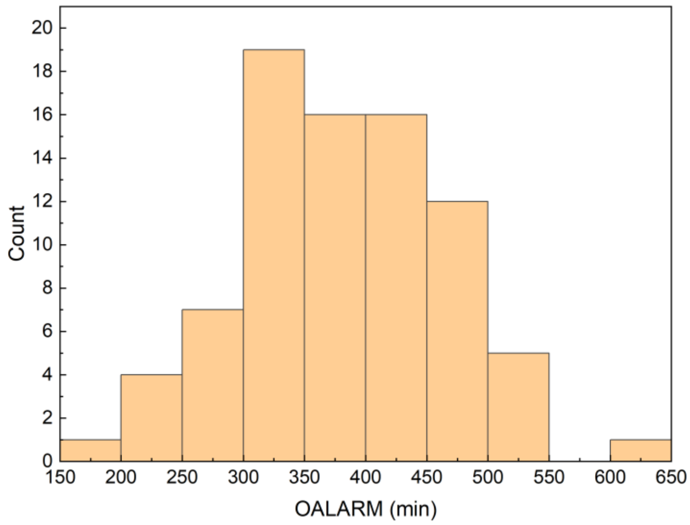

Figure 7. OALARM Histogram in Designed Level 3 PSA Event Tree

3.4. Level 3 PSA Fault Tree

The use of the fault tree is the biggest advantage and most meaningful part of the Level 3 PSA Event Tree model. Risk assessment using a concrete and reliable fault tree allows deriving risk-significant factors and ultimately provides risk insight.

The fault tree should be designed considering all possible factors that affect the success/delay/failure of emergency response heading, such as organization activation, human error, and measurement and communication systems failure. All basic events in a fault tree must have probability values derived based on reliable data. Designing fault trees and obtaining probability values is a very challenging task. This paper is still an ongoing study, and design and verification of the fault tree are still required. Therefore, event tree analysis through the fault tree was not carried out in this study. In the future, the fault tree should be designed and verified through reliable sources such as power plant data, Fukushima accident data, and expert judgment.

3.5. Initial Source Term Category

The source term category (STC), which is the first input to the Level 3 PSA Event Tree, is called initial source term category (ISTC). The main purpose of this ISTC analysis is to calculate the time from accident initiation to exceed GE Level. This is because, as previously explained, the OALARM time is the sum of the cumulative emergency response time and the time from accident initiation to exceed GE Level.

Since late release STCs takes a very long time to release radioactive materials after an accident initiation, the sensitivity analysis shows that the difference in late release STCs' offsite consequence according to the OALARM range designed in this study will be meaningless. It is expected that a Level 3 PSA Event Tree reflecting the time required for succeed, delay and fail of each heading should be developed separately for late release STCs. Therefore, in this study, representative incident scenarios were selected considering symbolism and impact among the early release ISTCs. The accident scenario is as follows: Entry into SBO, core damage after about 2 hours due to TD-AFW (Turbine Driven Auxiliary Feed Water pump) initial startup failure, and containment failure due to hydrogen explosion about 3 hours later (failure to operate all safety systems).

As a result of analyzing the EAL of the GE, it was determined that the GE Level would be exceeded when the core exit temperature (CET) reached 354.4℃ for the selected representative ISTC. Accordingly, by applying the results of thermal hydraulic analysis, it was determined that the GE Level would be exceeded approximately 120 minutes after accident initiation.

The time from accident initiation to exceed GE Level is determined as one value for each ISTC, and the cumulative emergency response time is displayed as a distribution according to the Level 3 PSA Event Tree. Therefore, the OALARM time distribution of representative ISTC can be obtained by adding the time from accident initiation to exceed GE Level (120 minutes) to the cumulative emergency response time distribution in Figure 6.

4. RISK ASSESSMENT – A CASE STUDY RESULTS

Through Chapter 3, the development of the Level 3 PSA Event Tree has been partially completed. The reason for using the expression “partially” is as follows.

- In this study, using the Level 3 PSA Event Tree model, which has not yet been completely developed, the author conducted a pilot trial of the entire process from model development to risk assessment.
- As this is a pilot study on a reference site, absolute values are meaningless. To avoid misunderstanding, only relative values were expressed by dividing all consequences by the maximum consequence value.
- Since a concrete and reliable fault tree design has not been completed, fault tree analysis was not performed to avoid misunderstanding. To demonstrate the process of deriving the result, the probability of each branch were assumed to be upper branch 0.7 and lower branch 0.3. In this case, the probabilities of success, delay, and failure for each heading are 0.70, 0.21, and 0.09, respectively.

Therefore, this study is intended to demonstrate the process and method of assessing risk using the Level 3 PSA Event Tree, and remember that the values presented in this paper themselves have no meaning.

4.1. Offsite Consequence Analysis

For the representative early ISCT selected for this study, the MACCS code derived PWIR (Population-Weighted Individual Risk) value by changing the OALARM value. Table 2 shows PWIR-cancer and its frequency in the general public and tail cohort. Normalized PWIR value is normalized to the maximum PWIR value among the derived results.

Table 2. Normalized population-weighted cancer fatality risk distribution for representative ISTC

General Public			Tail		
Normalized PWIR-Cancer	Frequency	Normalized Risk	Normalized PWIR-Cancer	Frequency	Normalized Risk
0.00%	91.84%	0.00%	**0.00%**	80.08%	0.00%
0.00%	0.20%	0.00%	0.01%	6.20%	0.00%
0.15%	2.50%	0.00%	2.38%	5.56%	0.13%
4.85%	2.02%	0.10%	11.32%	0.20%	0.02%
15.12%	1.19%	0.18%	23.00%	2.50%	0.58%
27.39%	0.33%	0.09%	36.30%	2.02%	0.74%
41.58%	1.07%	0.45%	49.17%	1.19%	0.59%
52.81%	0.36%	0.19%	57.43%	0.33%	0.19%
69.97%	0.21%	0.15%	65.02%	1.07%	0.70%
78.22%	0.15%	0.12%	72.94%	0.36%	0.26%
84.16%	0.05%	0.04%	84.16%	0.21%	0.18%
91.42%	0.06%	0.06%	87.46%	0.15%	0.13%
98.68%	0.01%	0.01%	90.43%	0.05%	0.05%
			94.72%	0.06%	0.06%
			100.00%	0.01%	0.01%
	Sum=	1.38% of max. value		Sum=	3.62% of max. value

The sum of the frequencies of each cohort in the table is 100%, and the risk can be derived by multiplying each PWIR by the frequency. Using the assumptions of this study (upper branch 0.7, lower branch 0.3), PWIR-

Cancer can be expected to be 0 with a probability of about 92% for General public and about 80% for Tail. It can be seen that the higher the PWIR-cancer, the smaller the probability.
The actual risk should be multiplied by the Core damage frequency (CDF) and the probability of each STC. As explained above, this study only presents methodology and the values themselves are meaningless.

4.2. Risk-significant Factors

In the future, as the fault tree design is refined, the fault tree can be used to determine the branching probability of the event tree. The importance of emergency response related basic event can then be assessed through risk importance measures such as Fussel-Vesely.

5. DISCUSSION

The greatest value of the Level 3 PSA Event Tree method is the probabilistic risk assessment that reflects emergency response scenarios and the derivation of risk significant factors through Fault Tree analysis.
The following tasks remain to complete this study.

- By developing a comprehensive and reliable Fault Tree, risk insight can be drawn. This can be used for nuclear emergency response strategy development and decision making.
- Site risk can be quantified through all ISTC analyses.
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The following studies can be additionally conducted in the future.

- Currently, analysis is limited to the Offsite Alarm point (OALARM), but can be expanded to include sheltering and evacuation.
- It can be expanded to external events and multi-unit.
- Level 3 human reliability analysis (HRA) studies related to emergency response can be performed.

6. CONCLUSION

This paper suggested a new concept of Level 3 PSA Event Tree and systematically presents a method for developing the model. This paper provides an overall process to develop a Level 3 PSA Event Tree model according to the proposed framework and evaluate risk for a pilot site. Since this paper presents pilot results using a limited scope and model, the value itself is meaningless, but the Level 3 PSA Event Tree model has the following important meanings. (1) A probabilistic risk assessment considering various emergency response scenarios can be made. (2) Emergency response basic events can be analyzed, and risk-significant factors can be derived and used for risk management.

Acknowledgements

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