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DEVELOPMENT OF AN INTEGRATED RISK ASSESSMENT FRAMEWORK FOR INTERNAL/EXTERNAL EVENTS AND ALL POWER MODES

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From the PSA point of view, the Fukushima accident of Japan in 2011 reveals some issues to be re-considered and/or improved in the PSA such as the limited scope of the PSA, site risk, etc. KAERI (Korea Atomic Energy Research Institute) has performed researches on the development of an integrated risk assessment framework related to some issues arisen after the Fukushima accident. This framework can cover the internal PSA model and external PSA models (fire, flooding, and seismic PSA models) in the full power and the low power-shutdown modes. This framework also integrates level 1, 2 and 3 PSA to quantify the risk of nuclear facilities more efficiently and consistently. We expect that this framework will be helpful to resolve the issue regarding the limited scope of PSA and to reduce some inconsistencies that might exist between (1) the internal and external PSA, and (2) full power mode PSA and low power-shutdown PSA models. In addition, KAERI is starting researches related to the extreme external events, the risk assessment of spent fuel pool, and the site risk. These emerging issues will be incorporated into the integrated risk assessment framework. In this paper the integrated risk assessment framework and the research activities on the emerging issues are outlined.

KEYWORDS : Integrated Risk Assessment, OCEANS, External Event PSA, Spent Fuel Pool, Site Risk

1. INTRODUCTION

The Probabilistic Safety Assessment (PSA) is a useful tool to assess the risk of nuclear facilities, and to identify the design and operational vulnerabilities of them. The PSA has been widely used in many countries to improve the safety of nuclear facilities for several decades [1]. The PSA can cover all risk contributors beyond design basis accidents (DBA), e.g. an earthquake over the design criteria and related possible accident scenarios. The PSA consists of levels 1, 2 and 3, whose scopes are illustrated in Fig. 1. Basically, the PSA should cover all risks from all power modes and all hazards as shown in Table 1.

The results of the PSA have been used in risk-informed decision making to improve the safety of nuclear facilities. However, in most risk informed decision making, only the results of level 1 (Core Damage Frequency: CDF) and limited level 2 PSA (Large Early Release Frequency: LERF) for the full power operation mode have been used [2]. Due to such practice, the Fukushima accident of Japan in 2011 reveals some issues to be re-considered and/or improved in the PSA.

Such issues can be classified into two groups. The first group is related to the incompleteness of the current PSA practice, and the second group is related to the combined hazards. Some of those issues are listed below:

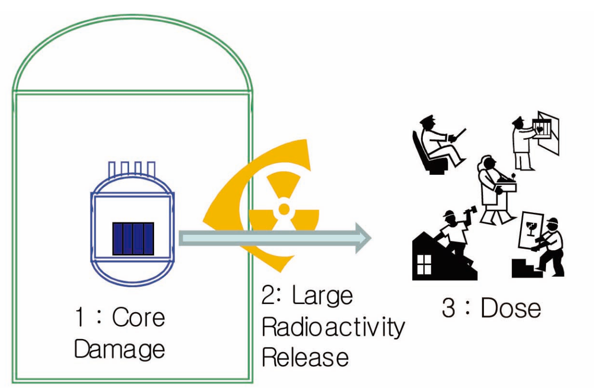

Fig. 1. Scopes of Level 1, 2 and 3 PSAs

Table 1. Modes & Hazards to be Analyzed in PSA

Mode	Hazards \ Level	Level 1	Level 2	Level 3
Full Power	Internal	CDF	LRF	Dose
	External (Fire, Flood, Seismic, etc)	CDF	LRF	Dose
Shutdown	Internal	CDF	LRF	Dose
	External (Fire, Flood, Seismic, etc)	CDF	LRF	Dose

- Incompleteness
  - Limited scope of PSA
  - Coverage of external hazards
  - Risk of spent fuel pool
  - Site risk
  - Hydrogen behavior
- Combined Hazards
  - Combined external hazards, e.g. earthquake and tsunami as at the Fukushima
  - External hazard-caused internal events, e.g. seismic induced fire

Those issues should be resolved to use the results of the PSA appropriately in future risk-informed decision making processes. From now on, we expect that a more holistic risk-informed, performance-based regulatory approach will be required [3]. We should focus on the risk itself, rather than just frequency, and we have to try to cover all risk contributors appropriately as far as possible. However, we need considerable time, efforts and international cooperations to resolve all issues. Now, KAERI (Korea Atomic Energy Research Institute) is performing research to resolve some issues related to incompleteness. Results of this research will be presented in this paper.

KAERI is trying to solve the issues regarding the limited scope of the PSA. Since the PSA requires a lot of resources, in many cases, only the limited scope of the PSA is performed, that is, the internal level 1 and limited level 2 PSA for full power mode. Furthermore, the low power-shutdown (LPSD) PSA requires much more resources than the full power PSA, since the LPSD PSA consists of many PSA models developed for different plant statuses of a nuclear power plant (NPP) during the overhaul. So, there are a limited number of LPSD PSAs in the world. In addition, since the external PSA framework is not well established compared to the internal PSA framework, only some external level 1 PSAs have been usually performed.

However, such a limited scope of the PSA might fail to provide appropriate insights with some risk-informed decision makings and/or sometimes result in too excessive conservatism. For example, the risk-informed emergency preparedness requires not the CDF/LERF but the site specific risk information. In some cases, a limited level 2 PSA has used conservative approaches to simplify the estimation process of the LERF and/or source terms.

In order to solve the issues regarding the limited scope of the PSA, KAERI has developed a framework to integrate level 1, 2 and 3 PSAs, which can quantify the risk of nuclear facilities more efficiently and consistently. In addition, we have developed a method to generate the basic LPSD and external PSA models automatically from the full power PSA model, in order to reduce the necessary resources for performing the LPSD and external PSA.

We expect that this framework will be helpful to resolve the issues regarding the limited scope of the PSA, and to reduce the required resources. In addition, we can reduce some inconsistencies that might exist between (1) the internal and external PSA, and (2) full power mode and LPSD PSAs, which have arisen from the manual modification process of the internal PSA models for developing the external and/or LPSD PSA models. In Section 2, we will explain the framework for the integrated risk assessment of (1) internal and external events, (2) the full power and LPSD modes, and (3) level 1, 2 and 3 PSA.

In order to solve some incompleteness issues, we are also starting research on extreme external hazards, risk assessment of the spent fuel pool and site risk. These are the emerging issues after the Fukushima accidents. The external event is a site specific issue, so each NPP should check the external event for its own site. The site risk issue is a very important one, especially in Korea, since we have from 4 to 6 units per site. We will outline our approach to resolve these emerging issues in Section 3. These will be incorporated into the developed framework in order to handle all possible risk contributors and their effects consistently and efficiently within one framework, i.e. in more holistic way. For instance, in the future, the site risk including internal and external hazards will be required rather than just the risk of a unit. The developed framework will be useful to handle such problems. In Section 4, the brief conclusions will be presented.

2. DEVELOPMENT OF AN INTEGRATED RISK ASSESSMENT FRAMEWORK

In the developed framework, we used the mapping technique to generate the basic LPSD and external PSA models automatically from the full power PSA model. Some PSA tools are also developed to support such automation and integration of various PSA models. In subsection 2.1, we will explain our basic approaches for the integrated risk assessment of internal/external events and all power modes. The developed PSA tools will be described in subsection 2.2.

2.1 Basic Approach for the Integrated Risk Assessment of Internal/External Events and All Power Modes

2.1.1 Basic Approach for the Integrated Risk Assessment of Internal/External Events

Representative external events which are currently under consideration in Korea are fire, flooding, and seismic activity. Most of the external event modeling, in view of the PSA, starts from an internal event PSA model. Since the internal event PSA model includes most accident sequences and system models in terms of event tree (ET) and fault tree (FT), external events are mapped into the internal event PSA model under the condition that the accident progressions are similar to the internal event accident sequence. When an external event shows a different accident progression, it is general to develop the external event model separately from the internal event model.

When an external event shows similar accident sequences with those of the internal event, one can use the same ET. In this case, the initiator of the ET should be replaced with the external initiator, by mapping internal initiators into them. Also, since an external event may invoke simultaneous failure of several components of a system, the effect of external events on a system should be considered. Such effects can be reflected by mapping system failures by external event into the system FT used in the failure modeling of an internal event.

For a simple example, let's look at the ET of Fig. 2.

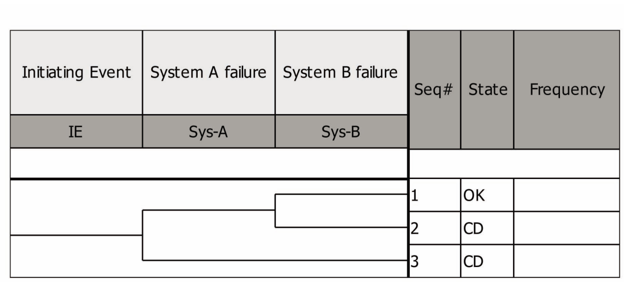

Fig. 2. Example of an Event Tree

From this, one can obtain the following accident scenarios in the sense of Boolean algebra:

IE*/Sys-A*/Sys-B (1)

IE*/Sys-A*Sys-B (2)

IE*Sys-A (3)

where notation "/" means a negation of an event. Since the failed sequences are needed to describe a risk of an entire system such as an NPP, scenario (2) and (3) are modeled in a PSA.

The system FT of Sys-A and Sys-B are shown in Fig. 3.

The PSA modeling method, which is widely used in the current PSA, is to link the ET and the system FT. By linking these, a single one-top FT is generated, which has all accident sequences along with its system failure model. By linking the system FT in Fig 3 with the ET in Fig. 2, the entire system FT is generated as shown in Fig. 4.

By Boolean operation and applying delete-terming approximation, the following minimal cut-sets can be obtained from the FT in Fig. 4.

IE*VALVE-1 (4)

IE*VALVE-2 (5)

IE*PUMP-1*PUMP-2 (6)

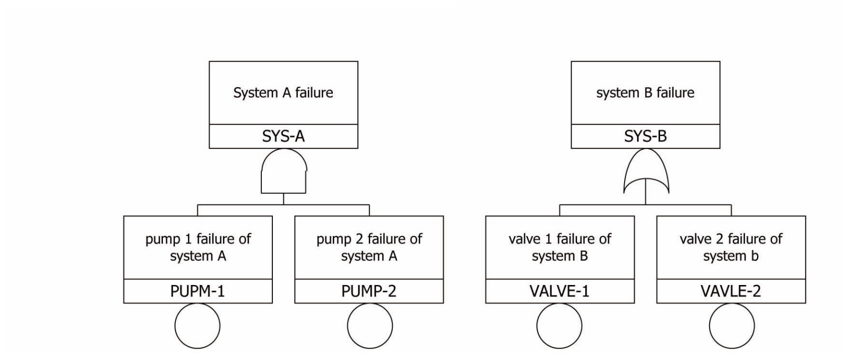

Fig. 3. Examples of FT

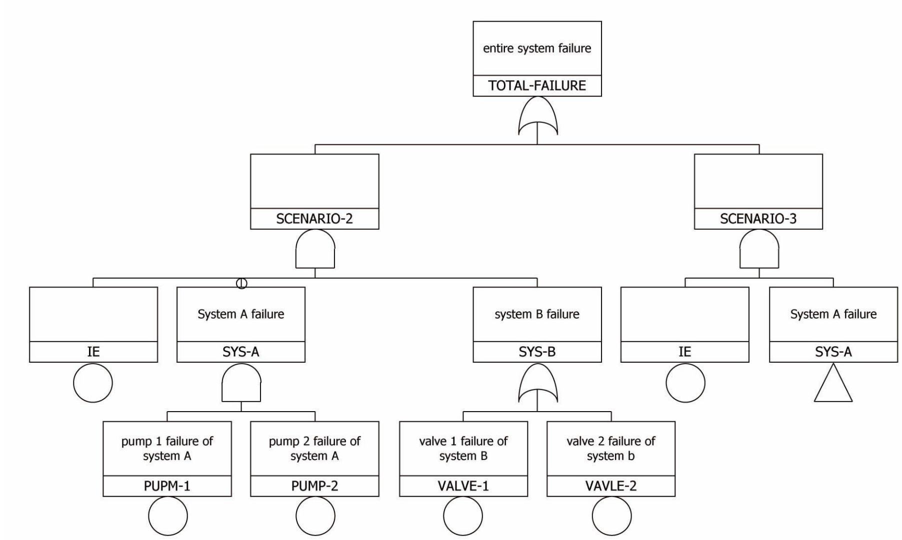

Fig. 4. Integrated FT for Entire System Failure

Assuming an external event follows the same accident sequences in Fig. 2 and systems have an additional failure event caused by the external event, this external event can be modeled by the following mapping:

$$\text{IE} \rightarrow \text{EE} \quad (7)$$

$$\text{PUMP-1} \rightarrow \text{PUMP-1} + \text{PUMP-1\_EX} \quad (8)$$

$$\text{PUMP-2} \rightarrow \text{PUMP-2} + \text{PUMP-2\_EX} \quad (9)$$

$$\text{VALVE-1} \rightarrow \text{VALVE-1} + \text{VALVE-1\_EX} \quad (10)$$

$$\text{VALVE-2} \rightarrow \text{VALVE-2} + \text{VALVE-2\_EX} \quad (11)$$

Where "EE" represents an external initiating event and "_EX" represents a component failure caused by an external event. Mapping Eq. (7) to (11) into the FT in Fig. 4, the FT for an external event is obtained as shown in Fig. 5.

In the case that one to one mapping between an internal event scenario and an external event is maintained, the method of simple mapping explained above can be used to construct an basic external event PSA model. This is the basic approach of the external event modeling method. However, there are some differences in external event modeling methods in order to reflect the specific features that depends on the characteristics of an external event. The detailed methods of external event modeling are explained in the following subsection.

■ The method of fire/flooding event modeling

There are many places in which a fire/flooding event can occur. A fire/flooding risk analyst usually divides an entire area into hundreds of compartments. A fire/flooding event is assumed to occur in a compartment. Generally, the entire fire area is composed of more than 200 fire compartments in a Korean PSA.

To model fire risk using a simple mapping method, a fire risk analyst should perform routine iterative process using an internal PSA model. To avoid this massive iterative resource consuming process, new fire/flooding risk modeling and quantification methods are used in the developed framework [4-5].

The new method mainly uses the exclusiveness among initiating events in different fire compartments. For example, there are two different fire events in two fire compartments, respectively, as shown in Fig. 6. For simplicity, the two fire event is assumed to follow the accident sequences in Fig. 2. It is also assumed that System A and B are located in these compartments and can be damaged by a fire event.

For multiple fire initiating events, as shown in Fig. 6, the following mapping method is used to model the fire event in a single FT.

$$\text{IE} \rightarrow F_1 + F_2 \quad (12)$$

$$\text{Pump-1} \rightarrow \text{Pump-1} + F_2 {*} CF_{21}, \text{ Pump-2} \rightarrow \text{Pump-2} + F_2 {*} CF_{22} \quad (13)$$

$$\text{Valve-1} \rightarrow \text{Valve-1} + F_1 {*} CF_{11}, \text{ Valve-2} \rightarrow \text{Valve-2} + F_1 {*} CF_{12} \quad (14)$$

Where F_i represents the frequency of the fire event in the compartment i, and CF_{ij} means a conditional failure of component j by F_i. Inserting Eq. (12) to (14) into the FT

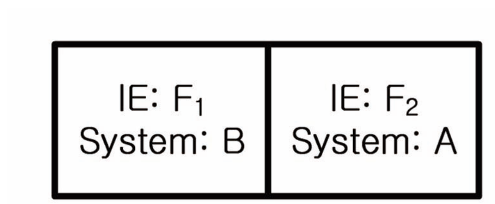

Fig. 6. Example of Two Fire Compartments

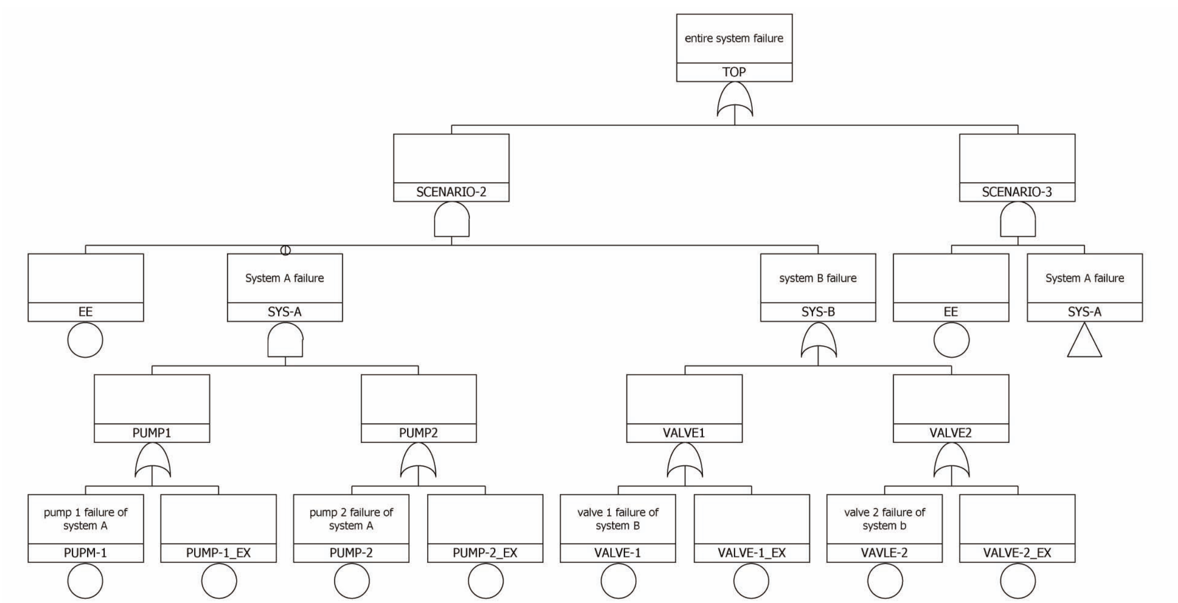

Fig.5. External Event FT Generated by Mapping Event

in Fig. 5, we can obtain the following minimal cut-set:

$$\begin{aligned}\text{Total Failure} = & (F_1 + F_2)*(\text{Pump-1} \\ & + F_2*CF_{21})*(\text{Pump-2} + F_2*CF_{22}) \\ & + (F_1 + F_2)*(\text{Valve-1} + F_2*CF_{11}) \\ & + (F_1 + F_2)*(\text{Valve-2} + F_2*CF_{12})\end{aligned} \quad (15)$$

Assuming exclusiveness among fire initiating events ($F_1*F_2=0$ in Eq. (15)), Eq. (15) can be simplified as follows

$$\begin{aligned}\text{Total failure} = & (F_1 + F_2)*\text{Pump-1}*\text{Pump2} \\ & + F_2*(CF_{21}*\text{Pump-2} + CF_{21}*F_2*CF_{22}) \\ & + (F_1 + F_2)*\text{Valve-1} + (F_1 + F_2)*\text{Valve-2} \\ & + F_2*CF_{11} + F_2*CF_{12}\end{aligned} \quad (16)$$

Since current FT quantification programs, such as FTREX, usually use the exclusiveness rule among their initiating events, there is no problem in the quantification of the generated FT for fire risk [5-6]. The same approach can be used for the flooding PSA as well.

■ The method of seismic event modeling

A seismic event is assumed to have a different accident progression from that of an internal event. Independent accident sequences are to be developed to model seismic event. Although an independent ET is developed for seismic events, the system failure modeling is based on that of an internal event.

Since a seismic event can have a wide spectrum of magnitude, the entire seismic magnitude range is divided into several sections. In one section, a separated seismic PSA model is developed to obtain risk in this range. The simple mapping method explained above is used to develop an individual seismic PSA model in all ranges of magnitude. After developing each seismic PSA model in each range, the total risk by seismic event is simply the sum of each risk from its seismic magnitude ranges.

2.1.2 Basic Approach for the Integrated Risk Assessment of Full Power and LPSD PSA Models

During the LPSD period of an NPP, the NPP will have different thermal-hydraulic characteristics and system configuration conditions, compared to at-power condition. Usually, an accident during this period has the LPSD specific scenarios for which an accident sequence, in terms of ET, is to be independently developed. It is mainly due to the fact that the reactor decay heat is lower, and other parameters, such as pressure and water level of the reactor coolant system, are different, from those of at-power conditions.

Also, since the decay heat and other conditions change continuously, the concept of a time window, called a POS (Plant Operating Status), is used to reflect the variance of the NPP status during the LPSD period. In an LPSD PSA, usually more than 10 POS are used to describe the LPSD status, and an independent PSA model is constructed for each POS of the LPSD period.

However, the safety function and system used in the LPSD PSA are almost identical with those of at-power conditions, except the gravity feed function, which is normally available in the atmospheric conditions of a reactor vessel. As in the case of external event modeling, most of the system failure models of the LPSD PSA start from the system modeling of at-power conditions.

Since various maintenance activities that makes a system unavailable are performed, a risk analyst should consider such unavailability. Furthermore, configurations of systems are changed frequently, by which, components of a system should be treated appropriately depending on a their current condition.

To consider such a variation of the systems, the following changes of the FT should be possible to model the LPSD PSA.

- Change of systems' availability
- Status change of a system (from running of standby or vice versa)
- Changes of an event's failure probability
- Manipulation of unrealistic events

For the case of "change of systems' availability", the following way can be used to denote the availability of a system in a PSA model.

$$\text{system failure} = \text{true} \quad (17)$$

Most systems in maintenance can be treated as in Eq. (17). When a system may experience its status change, such as standby state to running state, or running state to standby, some existing events in the full power model may be changed into the unnecessary event and/or some additional events need to be added to the full power model. For the change from running state to standby state, the following mapping is used.

$$S_r \rightarrow S_s + S_r \quad (18)$$

where S_r and S_s represent the running failure event, and the standby failure, respectively.

When the standby system is in running state, the starting failure of a system should be eliminated. The following mapping is used.

$$S_s + S_r \rightarrow S_r \quad (19)$$

The mapping of Eq. (18) and (19) can also be applied to the gate of an FT, when a specified system by a gate has experienced status change.

Frequently, it is necessary to change the probability of an event or to delete an event. For instance, when a human error probability should be changed or deleted from the system FT of at-power PSA model, the following mapping rule can be used

$$S_a \rightarrow S_L \quad (20)$$

where S_a and S_L represent the failure event for at-power and at LPSD state, respectively.

By applying the above mappings, the basic LPSD FT can be generated from the full power PSA model.

2.1.3 Basic Approach for the Integrated Risk Assessment of Level 1, 2 & 3 PSA

The basic interfaces among level 1, level 2 and level 3 PSA are shown in Fig. 7.

▪ Linkage of Level 1 PSA with Level 2 PSA

Although the level 2 PSA starts from the result of an level 1 PSA, it is difficult to directly link the Boolean information obtained from the level 1 PSA (in term of minimal cut-sets) with the logic of the level 2 PSA. When linking the level 1 PSA result with the level 2 PSA, it is difficult to quantify the overall result since the structure of the FT becomes too complex. Also, the frequent uses of negation in the level 2 PSA make it difficult to use the approximation of “delete-terming”. To exactly solve the FT with negation, we may need another quantification method such as BDD (binary decision diagram). However, current state of art technology of BDD cannot handle the big FT used in the current PSAs of NPPs.

To avoid such difficulties, in the developed framework, the level 2 PSA uses only the ET information of the level 1 PSA in linking the level 1 PSA result with the level 2 PSA. Using the information of the ET of the level 1 PSA, PDS (plant damage state) logic is constructed to classify similar PDS groups from the level 1 PSA accident scenarios. The classified PDS groups then progress with the CET (containment event tree).

The final results of the CET are then fed back to the level 1 PSA results to describe the containment failure fraction in each minimal cut-set of the level 1 PSA. Also, the source term category groups are classified in the level 2 PSA frame, in order to generate the information required in the level 3 PSA.

▪ Linkage between Level 2 and Level 3 PSA

In the development of the level 3 PSA, two main inputs from the level 2 PSA are needed: the source term category frequencies and the contents of the source term. A simple data-linking program called SARA (Severe Accident Risk Analyzer) was developed to facilitate the data linkage between level 2 PSA information and the level 3 PSA, which is described in Section 2.2 [10].

2.2 Development of an Integrated Risk Assessment Tools

KAERI has been developing a more systematic and efficient PSA platform, called OCEANS (On-line Consolidator and Evaluator of All mode risk for Nuclear System), for the risk assessment of all power modes and all hazards [7], for the purpose of improving PSA technology and supporting PSA analyses. The basic approach of OCEANS is to store all information in databases in structured format, and to use pre-defined procedures to automate some basic work required in the PSA. The overall information flows in OCEANS are shown in Fig. 8.

The AIMS-PSA (Advanced Information Management System for PSA) [8] plays a key role in OCEANS, which takes charge of the ET and FT analysis. The AIMS-PSA is a fully redeveloped version of KIRAP (KAERI Integrated Reliability Analysis Package) [9] using the recent software technology. The project explorer is introduced to provide the means to do most work, such as browsing each PSA model, quantifying the PSA, and viewing the results.

The integrated approach implemented in the AIMS-PSA enables the user to finish the quantification of a PSA by executing just those two menus in the project explorer in very short computation time. It takes less than 10 seconds for most level 1 internal PSAs with the FTREX quantification engine [6]. Traceability and reproducibility are enhanced greatly. Fig. 9 shows an example screen of the AIMS-PSA.

As an example of how OCEANS works, let’s review the fire PSA case. A typical fire PSA is usually constructed

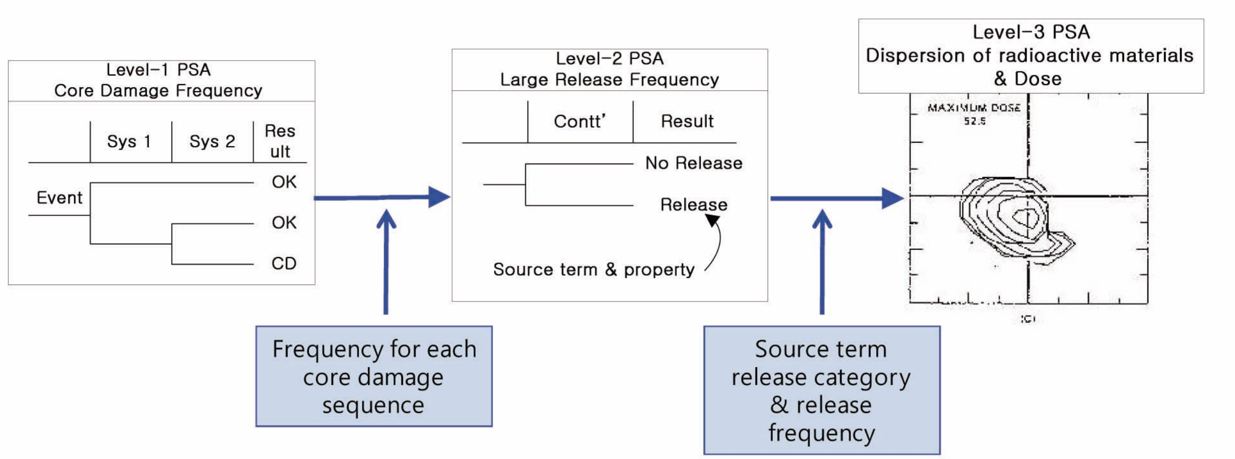

Fig.7. Concept of Level 1, 2 and 3 PSA Interface

by modifying the PSA model affected by a fire event. In the fire PSA, the conditional core damage probability (CCDP) is calculated by incorporating the fire propagation, and suppression factors of the fire event. This process was repeated for all of fire zones. The quantification for fire zones may require a huge amount of manual work, as

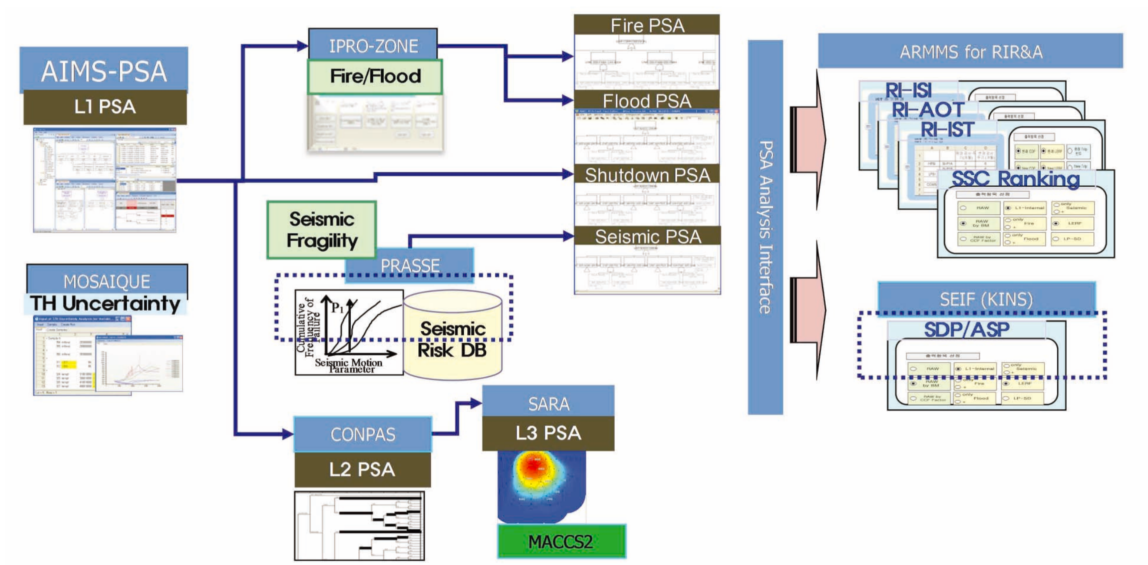

Fig. 8. Overview of an Integrated PSA Tool, OCEANS

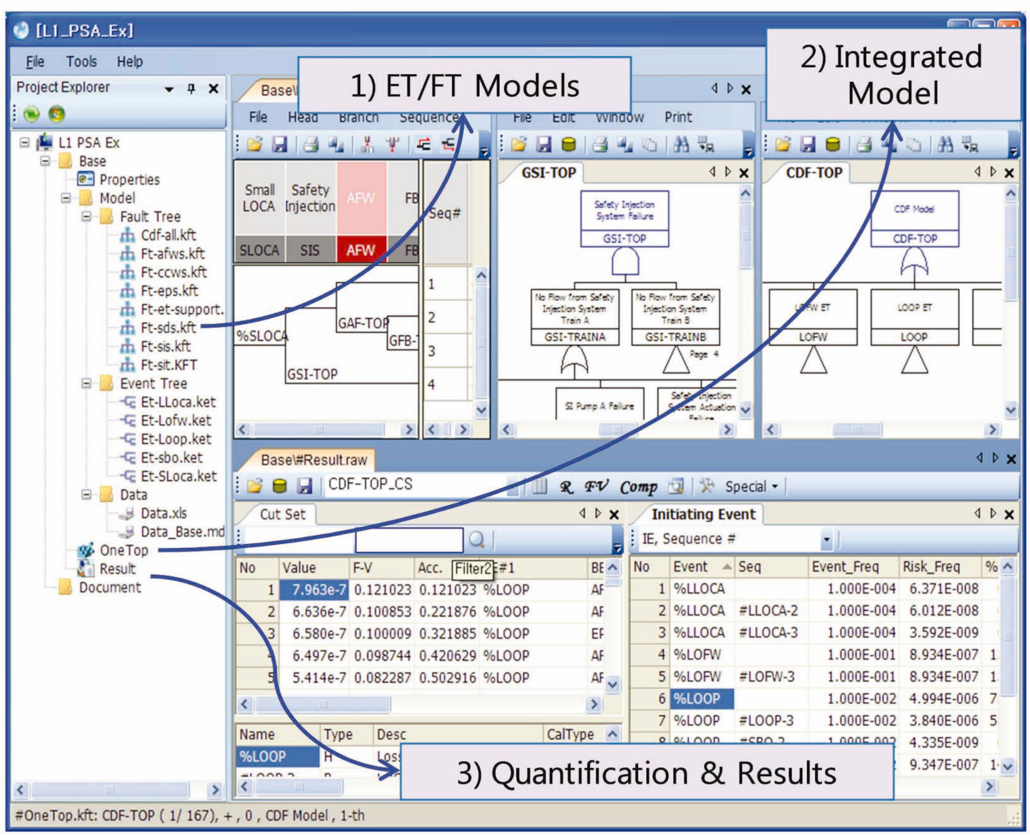

Fig. 9. Example Screen of AIMS-PSA

well as a combined knowledge of PSAs and fire analysis.

In OCEANS, the necessary information is categorized systematically and stored in a database. Then OCEANS generates and quantifies the fire PSA model automatically. Fig. 10 illustrates how OCEANS handles a fire PSA.

The information stored in the database comes from the fire hazard analysis. This basic information is generated by an expert in fire analysis. This kind of approach enables the PSA analysts to save time and effort on the fire PSA. The seismic and flood PSAs and the LPSD PSA can also be automated in similar ways.

The level 2 and level 3 PSAs are conducted with CONPAS (CONtainment Performance Analysis System) [11] and SARA [10], respectively, as shown in Fig. 8. The frequency and fraction of large release for each PDS are the interface between the level 1 and level 2 PSA models. The level 1 PSA provides the frequency and the level 2 PSA provides the fraction for the PDS. This is used in OCEANS to integrate the level 1 and level 2 PSA models. A similar way is used for the level 2 and level 3 PSA interface. The essential information from the level 2 PSA, such as accident sequences and radiological source terms are transferred to SARA.

OCEANS has been being developed to integrate level 1, level 2 and level 3 PSAs, internal and external PSAs, and full power and LPSD PSAs. The development of OCEANS provides a more systematic and efficient framework for the risk assessment of all power modes and all hazards.

3. NEW ISSUES IN THE PAS AFTER THE FUKUSHIMA ACCIDENT

As mentioned earlier, we are starting research on some topics that have been emphasized after the Fukushima accident: extreme external hazards, risk assessment of the spent fuel pool and site risk. We will outline our approach to resolve the coverage of external hazards, site risk, and risk of spent fuel pool issues in this section. We plan to integrate these topics into the developed framework explained before.

3.1 Risk Assessment of Extreme External Events

Since the Fukushima accident, in which a catastrophic earthquake was followed by great tsunami greater than the design basis, extreme external events have emerged as significant risk contributors to NPPs. This accident shows that extreme external events have the potential to simultaneously affect redundant and diverse safety systems, and thereby induce common cause failure or common cause initiators.

Some standards set forth requirements for external-event PSAs used to support risk-informed decisions for commercial NPPs, and prescribe a method for applying these requirements for specific applications [12-13]. External events covered within these standards include both natural external events and man-made external events. Most of the external events generally included within an external-events PSA are listed in the appendix of these standards, which is adapted from NUREG/CR-2300 [14].

It is essential to identify the extreme external events that can potentially affect the safety of NPPs for the evaluation of the site specific external hazards and risks. Various external events that can cause damage to an NPP have been reviewed for the site evaluation during the design stage. The natural and man-made hazards have been considered as design basis events for the design of Korean NPPs. Most of the extreme external hazards had been screened-out due to the low probability of occurrence estimated by deterministic and probabilistic hazard

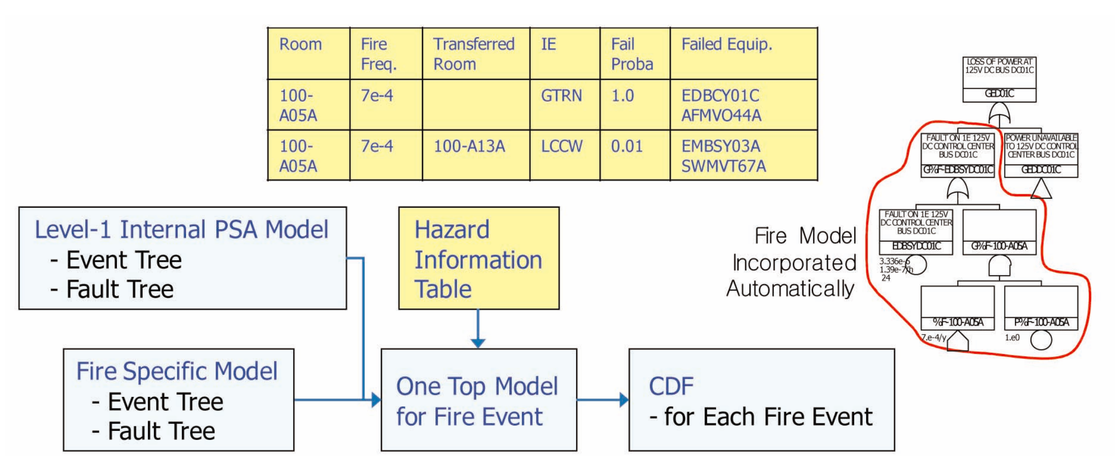

Fig.10. Concept of Automating a Fire PSA

analysis in and nearby the NPP sites. So, up to now, only seismic risk has been considered as an extreme external event in Korean PSA. (Even though, the internal fire and flooding PSA have been regarded as the external PSAs in some cases.)

In the seismic PSA, a realistic seismic hazard evaluation is one of the most important tasks, and a significant source of uncertainty to the seismic risk of a plant. KAERI has reviewed and estimated the historical earthquake data in historical documents, and performed the PSHA (probabilistic Seismic Hazard Analysis) for Korean NPPs site based on the reevaluated historical earthquake data to reduce the uncertainty of the PSHA results. Several area sources have been used in the PSHA to consider the seismicity. However, the identification of active faults, including unknown and hidden active faults, which have a potential to generate large earthquakes, became very important to secure the safety of NPPs against the beyond design earthquake level. For this reason, it is emphasized to make an active fault map of the Korean Peninsula for a realistic seismic hazard evaluation [15].

A tsunami that follows a great earthquake became a big issue after the Fukushima accident. The Korean peninsula has historically experienced tsunami several times, and most of them hitting the east side of the peninsula. Most of the tsunamis were induced by earthquakes on the west side of Japan. For the realistic tsunami hazard analysis and reduction of the uncertainty in the tsunami hazard of a plant site, it is very important to identify the tsunamigenic sources, and investigate the characteristics.

An example study on the tsunami PSA of Korean NPPs was performed [16]. The tsunami hazard curve was determined for a PSA by using the historical tsunami data recorded before 1900 in the historical documents, and some instrumental tsunami data records by tidal gauge after 1900. The target site selected was units 5 and 6 of Ulchin NPP, which is located on the east coast of Korea. For the evaluation of the tsunami return period, the east coast of the Korean peninsula was considered as one region. The power-law, upper-truncated power law and exponential function were considered for the evaluation of the return period of a tsunami.

To get more accurate results of the tsunami PSA, we plan to perform research on the tsunami hazard, tsunami fragility and system analysis. For the realistic assessment of a tsunami hazard curve, we are going to especially analyze the probabilistic tsunami hazard considering the tsunamigenic sources between the Korean peninsula and Japan.

The realistic evaluation of seismic safety, based on the realistic seismic capacity and responses, is important for the operating plants, especially for the older ones. In order to develop a realistic evaluation of the seismic safety of a plant, the potential effects of age-related degradation of structures, systems, and components within an NPP should be considered. We have performed research on the aging-related degradation of NPP components, since the degradation of the components affects not only their seismic capacity, but also their response [17]. The structural degradations are expected to be an important factor as plants age, and are important to plant safety when extreme environmental demands, such as large earthquakes, are considered.

3.2 Risk Assessment for Spent Fuel Pool

An assessment of the accidental risk of the spent fuel pool (SFP) against both internal events and external hazards is one of the emerging issues required to be integrated into the aforementioned integrated risk assessment framework. This issue was identified as one of the lessons learned from the Fukushima accident, and relevant activity is currently progressing worldwide.

From the DBA point of view, the major safety-related issues for the SFP are closely related to (1) controlling the configuration of fuel assemblies in the pool without loss of pool coolants, (2) ensuring the pool storage space is enough to prevent fuel criticality due to chain reactions of fission products, and the ability for neutron absorption to keep the fuel cool.

Just after the 11th September 2001, the US NRC issued orders to plant operators requiring several measures aimed at mitigating the effects of a large fire, explosion, or accident that might severely damage an SFP from a beyond design basis event (BDBE) point of view. These were means to deal with the aftermath of a terrorist attack or plane crash; however, they would also be effective in responding to natural hazards such as tornadoes, earthquakes or tsunami. Even for the foregoing activities to ensure SFP-related safety, several additional issues were also raised from a safety and security point of view [18-19]. The Fukushima accident has stimulated the need for in-depth research to enhance the safety of spent fuels stored in the SFP, and related regulation requirements.

Although the underlying accident phenomena and progressions in an SFP are different from the reactor case subject to high pressure and temperature, a similar framework with the reactor case can be formulated to assess accidental risk from the PSA point of view [20-21]. The accidental risk in SFP can be assessed by (1) specifying the initiating events and relevant accident sequences leading to the uncovery of spent fuel, making significant contributions to SFP risk (similar with the level 1 PSA in the reactor case), (2) assessing key phenomena leading to a severe damage of spent fuels [22] and relevant severe accident progression in an SFP (similar with the level 2 PSA in the reactor case), and finally (3) assessing the accidental risk based on the radiological source terms released to the SFP outside (similar with the level 3 PSA

Table 2. KAERI Framework for Accidental Risk Assessment on SFP

Level 1 PSA on SFP	Level 2 PSA on SFP	Level 3 PSA on SFP
• Specification of Initiating Events and Frequency Analysis - Loss of pool cooling system (LOPC) - Loss of coolant inventory (LOCI) - Loss of offsite power (LOOP), due to plant-centered and grid-related events, and severe weather like typhoon - Station blackout (SBO) - Cask drop caused by human error, - SFP structural failure, due to seismic events (including concurrent tsunami) - Internal fire, due to pool structural failure and seismic initiator, cask drop, etc. - Man-made external attack such as aircraft impact, external fire and explosion • Analysis of Accident Sequences Leading to Spent Fuel Uncovery - Based on conventional Event Tree/Fault Tree (ET/FT) Analysis - Level 1 risk surrogate metric: Frequency of Spent Fuel Uncovery	• Key Accident Phenomena - Spent fuel rods (decay heat sources with time, fuel heat-up and uncovery, severe damage, zirconium oxidation/ignition, fuel melting, etc.) - Spent fuel assembly (radial heat transfer, fire propagation, fuel assembly collapse, etc.) - Spent fuel storage rack - Downcomer next to the edge of the pool - Base region beneath the racks (cooing air ingression into the fuel assembly, molten corium-concrete interaction, etc.) - Spent fuel storage buildings (hydrogen burn, etc.) - Effect of accident mitigation strategies • Severe Accident Progression Analysis Leading to SFP Building Failures and Radiological Source Term Releases - Base tool: MELCOR SFP version [23] - Supporting tool: MAAP5 SFP analysis model [24] • Probabilistic Accident Progression Analysis - Based on Accident Progression Event Trees (APETs) - Level 2 risk surrogate metric: Large Release Frequency (LRF)	• SFP Risk Analysis - Based on MACCS2 [25] and multi hazards (risk sources, reactor, containment and SFP) - Level 3 risk metric: offsite risk due to SFP

in the reactor case), successively. Table 2 summarizes a basic framework of KAERI for the accidental risk assessment on an SFP which is currently being performed as a part of an integrated risk assessment and key technical elements.

3.3 Site Risk Assessment for Multi-unit Accidents

Concurrent reactor accidents at a site have been ignored in most of the current PSAs, because they were performed with the assumption that the event leading to core damage can only occur in one reactor at a time. Following the Fukushima accident, however, the issue of site risk is spreading over all the multi-unit sites, composed of two or more operating reactors. It is the reason that the independent risk for one reactor can be significantly underestimated by some missing scenarios associated with multi-unit site risk. This issue was raised with the problem on the past interpretation of quantitative health objective (QHO) during the process of developing a risk-informed technology-neutral framework for licensing new reactors, especially, modular reactors [3, 24].

Even though we have some difficulties in developing a level 3 PSA model for even a single unit, the multi-unit site risks can be ideally evaluated by the site-wide level 3 PSA models that include concurrent initiating events; so-called single-caused-multiple events (SCMEs), dependences and common cause failures between multi-units, and so on. K. Flemming [27] proposed an approach to develop level 3 PSA models, including three types of initiating events (IEs): (1) IEs impacting both units (loss of offsite power, seismic events, external flooding, tornado and wind, or a truck crash in switchyard), (2) IEs impacting both units under certain conditions (loss of condenser vacuum, loss of service water, and turbine missile), and (3) IEs impacting each unit independently (loss of coolant, general transients, loss of component cooling, loss of one DC (Direct Current) bus, internal fire and flooding, and aircraft crashes), based on the results of the previous Seabrook PRA [28]. S. Arndt suggested a simplified method for assessing the risks associated with multi-unit sites in his Ph.D. thesis [29]. T. Hakada also proposed a seismic PSA methodology for multi-unit sites with the actual examples using the CORAL-reef code [30].

As mentioned earlier, the site issue is a very important one, especially in Korea, since Korean sites have from 4 to 6 units per site. We plan to perform research with the following two goals [31]:

- Development of site risk assessment methodology and models, including the extremely complicated multi-unit accidents.
- Development of Korean site risk profile, based on all power modes, all hazard level 1/2/3 PSA, including the extreme risk factors.

4. CONCLUSIONS

After the Fukushima accident, in many countries, various measures against severe accidents are being introduced, such as movable EDGs (Emergency Diesel Generators), fire engines, etc. It is important to prepare such measures in case a severe accident occurs in nuclear facilities.

However, we also need to find a more complete way to prevent a disaster like the Fukushima accident. For this, we need a more holistic risk-informed, performance-based approach that enables us to estimate the risk of nuclear facilities more accurately, and to find ways to prevent the disaster more effectively and efficiently. In this paper, we describe our approach to resolve some issues related to the PSA that have arisen after the Fukushima accident. We developed a framework for the integrated risk assessment that covers the followings:

- Internal Event PSA model
- External Event PSA models (fire, flooding & seismic),
- Full power and LPSD PSA models
- Level 1, 2, 3 PSA models

We expect that this framework will be helpful to resolve the issues regarding the limited scope of PSAs, and to reduce the required resources for the PSA. In addition, we think this framework can enhance the consistency of PSA results.

KAERI has also started the research on extreme external hazards, risk assessment of the spent fuel pool and site risk. These issues are to be resolved in order to use the results of the PSA appropriately in future risk-informed decision making processes. The results of this research will be incorporated into the developed platform, OCEANS, at a later stage, in order to build a more holistic risk-informed, performance-based framework.

We expect that our research is helpful to solve the incompleteness issues described earlier. However, there are still many issues to be resolved in the PSA, like topics related to unanticipated scenarios: the combined external hazards of the earthquake and tsunami in Fukushima, external hazards causing internal events, such as seismic induced fire, and hydrogen behavior, etc. These topics are to be resolved for the complete risk profiles of nucrear facilities in the future. However, we expect that the developed integrated framework will be the effective basis for future research on the above topics, as well.

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