Insights from PSA for the operating Nuclear Power Plants in Korea

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KHNP has recently completed the project of upgrading and developing PSA models for the operating NPPs in Korea. In this project, we have upgraded Level 1 internal PSA models considering the requirements of ASME PRA Standard, and updated seismic/flooding PSA models and Level 2 PSA models for full power operations. For fire PSA, we have firstly applied the new methodology of NUREG/CR-6850 for a pilot plant. We have also developed LPSD (Low Power and ShutDown) Level 1 PSA models based on NUREG-6144. For developing LPSD SAMG (Severe Accident Management Guideline), one of the post-action items as near term Fukushima accident measures, LPSD Level 2 PSA models have been developed for a pilot plant. We identified different CDF (Core Damage Frequency) characteristics according to the reactor types, and derived different safety improvements according to each unit. As the portion of CDF from SBO (Station Black Out) and Loss of UHS (Ultimate Heat Sink) was estimated higher, we identified that the portion of CFF (Containment Failure Frequency) increased as well. We also identified the CDFs from external events were relatively higher than the CDFs from internal events. For LPSD PSA, maintenance schedules, procedures and conservative assumptions were identified as the most important factors to CDFs. As for LPSD Level 2PSA, the opening condition of equipment hatch was the most important factor to large early release frequency. As KHNP operates various types of NPPs, we have experienced several challenges on standardizing modeling methods and balancing PSA results. This paper presents the risk insights from PSA for various types of NPPs, which are Westinghouse, Framatome, CANDU and OPR1000 typed reactors. This paper also compares the results of PSA for all types of NPPs, identified the safety improvements according to the reactor types. From this project, we identify the fields to be improved in near term plan, with respect to overall risk profile, which can be conservative assumptions and uncertainty especially for external events analysis and containment integrity assessment to improve the quality of the PSA models.

I. INTRODUCTION

KHNP (Korea Hydro & Nuclear Power) presented the paper of "An Implementation Strategy of Low Power Shutdown PSA for KHNP NPPs" at PSAM12 conference.[1] Subsequently, this paper is to introduce the results of the implementation of the PSA (Probabilistic Safety Assessment) project for all the operating NPPs (Nuclear Power Plants) in Korea, and to present overall insights from various types of reactors.

KHNP has recently completed the project of upgrading and developing PSA models for the operating NPPs in Korea. In this project, we have upgraded Level 1 internal PSA models considering the requirements of ASME PRA Standard, and updated seismic/flooding PSA models and Level 2 PSA models for full power operations. For fire PSA, we have firstly applied the new methodology of NUREG/CR-6850[2] for a pilot plant. We have also developed LPSD Level 1 PSA models based on NUREG-6144.[3] In addition, for developing LPSD SAMG, one of the post-action items as near term Fukushima accident measures, LPSD Level 2 PSA models have been developed for a pilot plant. To get a technical adequacy for internal Level 1 PSA, KHNP reflected the major results of the peer reviews in the previous projects for two types of plants, and standardized the methodology of CCF (Common Cause Failure) and HRA (Human Reliability Analysis) which are the most influential factors to risk measures of NPPs.

For the scope of LPSD PSA, KHNP has developed Level 1 PSA models for Westinghouse, Framatome and CANDU typed reactors, and upgraded the models for OPR1000 typed reactors based on standard outage maintenance practices and Plant Operational Status (POS). LPSD Level 2 PSA models also developed for two types of pilot plants, one for PWR and the other for PHWR (Pressurized Heavy Water Reactor).

II. MODELING METHODS AND QUALITY IMPROVEMENT OF PSA ELEMENTS

II.A. Internal Level 1 PSA on Full Power Operations

To ensure the quality of full power PSA models, we applied the insights of the peer reviews which were performed by domestic and foreign experts for two types of plants. The expert panels identified the findings and observations from two peer reviews, 198 lists from WH type and 50 lists from OPR1000. One of the main findings and observations was whether the latest reliability data were applied or not. So, we updated IE (Initiating Event) frequencies as well as component failure data based on new generic database (NUREG/CR-6928).[4] Another was about applying the latest references as for RCP seal failure modeling, SGTR ET (Event Tree) modeling, and so on. The other recommendations were that the more T/H analyses should be performed in details to increase the quality of HRA, and that the test schemes should be considered when estimating CCF factors.[1]

As for the CCF analysis, one of the most important factors on risk measures, KHNP had used MGL parameter method assuming only staggered test scheme. Assuming staggered tests only is, however, underestimating the risk as a factor of redundancy multiplication in CCF modeling. So, we reflected the test schemes of components on estimating CCF parameters and applied Alpha Factor method because of convenience in uncertainty analysis and combining the latest international research results or data for CCF events.

Several HRA methodologies such as ASEP (Accident Sequence Evaluation Program), THERP (Technique for Human Error Rate Prediction) and HCR (Human Cognitive Reliability) had been applied to the existing PSA models in Korea, but some differences between models and some technical issues were identified through the peer reviews. Therefore, we applied standardized HRA methodology (K-HRA),[5] which provides detailed instruction to maintain the consistency of analysis through consensus among HRA experts in Korea.[1] K-HRA methodology, based on ASEP and THERP methodology, was validated through participation in various programs of NRC and OECD/NEA in order to secure the international confidences.

Initiating event analysis including data estimation was identified as the other PSA element which needed improving. The emphasizing point was the documentation about classification bases, grouping of initiating events, and FMEA (Failure Mode and Effect Analysis) on supporting systems. In case of initiating event frequencies, we used new data from NUREG/CR-6928 for LOCA (Loss of Coolant Accident) group and the Korean specific operating experiences for transient group.

As for the component reliability data analysis, KHNP had applied ALWR URD (Advanced Light Water Reactor Utility Requirement Document) database as the generic data.[6] It could not, however, reflect the latest component failure characteristics and “As-is, As-operated” status of a basic concept of PSA. Therefore, we used NUREG/CR-6928 data which were generated from the recent operating power plants in US. Component reliability of NUREG/CR-6928 has following major differences as compared to conventional ALWR URD data; 1) Provides normally running, normally standby data for 9 major components 2) Provides fail to load and run data for normally standby system 3) Demand failure data is beta distribution and running failure data is gamma distribution.

PRinS (Plant Reliability Data Information System), developed for the Korean specific database generation by KHNP, was also updated according to the revised PSA model. We reviewed, compared and evaluated the newly revised PSA model and database to apply NUREG/CR-6928. The specific data were produced from failure history of 16 PWRs in Korea. It was identified that the Korean specific failure rates of DG and AFW pump were decreased, but, those of fans and chillers were increased.

II.B. Modeling Method of the Other Scopes

For other scopes of PSA, we updated PSA models through basically reflecting internal Level 1 PSA models and database. Comparing the existing method, we newly applied EPRI TR for estimating the flooding event frequencies instead of the old reference which provides rough assumption to the flooding region. However, we could not apply the new methodologies of analyzing flooding propagation. And, we reflected the reinforcement activities of seismic fragility for some major components as post Fukushima actions.

As for Fire PSA, we applied the new methodology of NUREG/CR-6850 for a pilot plant. According to NUREG/CR-6850, we additionally performed the tasks of cable selection, circuit analysis, circuit failure analysis, fire HRA, fire modeling, and so on.

In early 2000’s, KHNP firstly performed LPSD PSA only for Mid-Loop operation for two pilot plants, and we developed LPSD Level 1 PSA models for all plant operational status for constructing NPPs. In this project, we developed LPSD Level 1 PSA models for all the operating plants. Although we had not performed LPSD Level 2 PSA prior to this project, we developed LPSD internal Level 2 PSA models for the first time in Korea. It was because one of the post Fukushima actions was to develop LPSD SAMG. In LPSD Level 2 PSA, we performed containment accident sequence analysis for each POS and source term analysis. And, the risk information from LPSD Level 2 PSA was utilized to develop Specific LPSD SAMG.

III. RISK PROFILES AND SAFETY IMPROVEMENTS OF NUCLEAR POWER PLANTS IN KOREA

III.A. Risk Profiles and Safety Improvements for Westinghouse and Framatome typed reactors

KHNP has been operating six units of Westinghouse typed reactors and two units of Framatome typed reactors. As for Westinghouse typed reactors, two units have the capacity of around 600 MWt, which are the first NPPs in Korea, and the four units have the capacity of about 950MWt. As for the first two units, the risk measures, such as CDF (Core Damage Frequency), were estimated relatively high, and showed a little different risk profiles from other Westinghouse typed reactors.

However, the two units of Framatome typed reactor with the capacity of about 950MWt have the similar risk profiles to the four units of Westinghouse typed reactors, so we would present the risk profiles of the six units except the first two units in this paper. Fig. 1 shows the CDF distributions of each PSA scope except fire PSA for the six units. The results of seismic PSA on full power operation were identified up to twice higher than those of internal PSA, and CDFs of flooding PSA were estimated lower than any others. The results of LPSD PSA showed lower than those of PSA on full power operations, but CDFs of LPSD internal PSA were estimated quite high. It is considered that the differences from 'level of details' between PSA models on full power operation and LPSD PSA models caused relatively high CDFs on low power and shutdown operation.

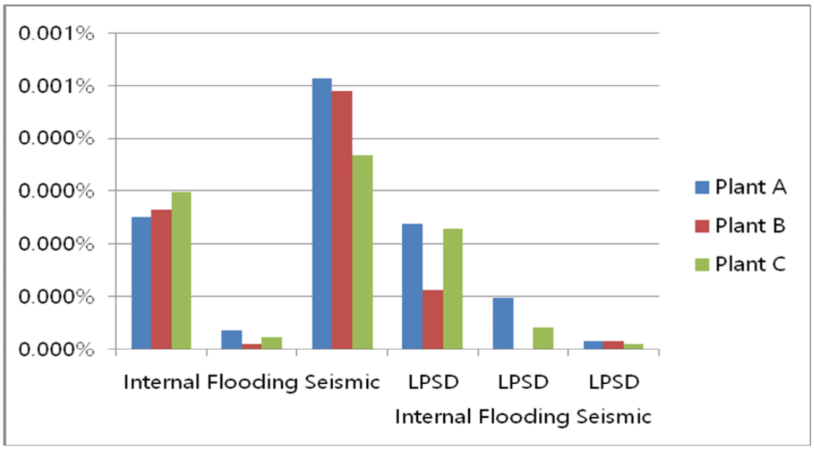

Fig. 1. Risk Profiles of Westinghouse and Framatome Typed Reactors

As a result of performing PSA for Westinghouse and Framatome typed reactors, we derived the following safety improvements. They should be, however, reviewed in view of field application and cost/benefit analysis.

- Improving safety of RCP (Reactor Coolant Pump) seal
  - Installing an improved backup seal such as Westinghouse Shutdown seal (Gen III)
  - Changing seal type from static to dynamic
  - Design changes related to supplying substitute cooling water to charging pumps
  - Design changes of making auxiliary charging pump started automatically when loss of seal cooling
- Enhancing recovery actions (procedure, portable equipments, etc.) in case of loss of HVAC in 1E SWGR room
- Increasing battery capacity
- Changing O/H maintenance schedules of EDG, CS, ECW, CS
- Changing the door of 1E SWGR room into Watertight door

Although CDFs of flooding PSA were estimated low, all the accident sequences turned into containment failure sequences. So the last safety improvement in the above list is important to the view of the results of Level 2 PSA.

III.B. Risk Profiles and Safety Improvements for OPR1000 typed reactors

KHNP has operating twelve units of OPR1000 typed reactors, which have a capacity of 1000 MWt. The first two units of OPR1000 typed reactors were designed based on System 80+ of Combustion Engineering. And, the design of the other ten units has been continuously modified and improved unit by unit, especially for an auxiliary feed water system, component cooling water system, and digital instrument & control system, etc. Fig. 2 shows the CDF distributions of each PSA scope except fire PSA for the twelve units. Although the CDFs were estimated much lower than those of Westinghouse typed reactors, the overall risk profiles showed similar to those of Westinghouse typed reactors.

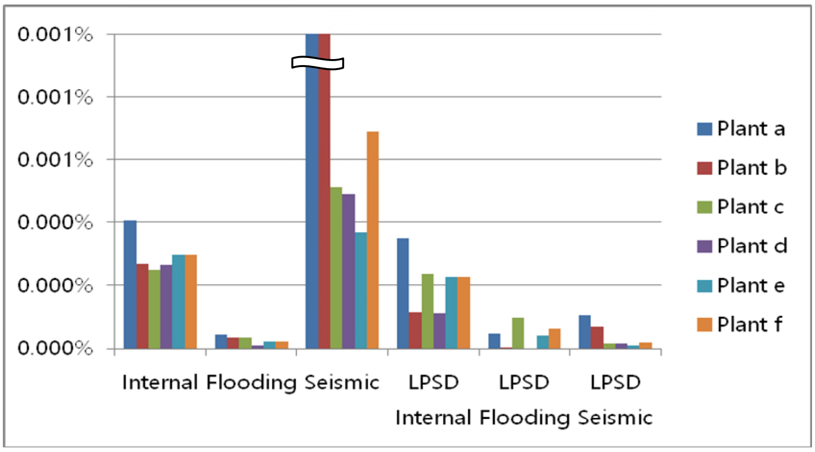

Fig. 2. Risk Profiles of OPR1000 Typed Reactors

As a result of performing PSA for OPR1000 typed reactors, we derived the following safety improvements. They should be, however, reviewed in view of field application and cost/benefit analysis. As for OPR1000 typed reactors, we need to put more efforts into a study on seismic hazard analysis and seismic fragility analysis, and apply new and realistic methodologies to modeling because the results of Seismic PSA were estimated much higher than those of internal PSA. Also, we should ensure the quality of Level 2 PSA more because we identified that the conditional CFF (Containment Failure Frequency) were over 40% under the core damaged condition.

- Enhancing recovery actions (procedure, portable equipments, etc.) in case of loss of HVAC in 1E SWGR room and the safety related pump rooms
- Increasing battery capacity or developing load shedding operation
- Enhancing the seismic capacities of essential power equipments and sump discharge MOV for recirculation operation
- Installing severe accident mitigation system such as CFVS (Containment Filtered Vent System) or ECSBS (Emergency Containment Spray Backup System)

III.C. Risk Profiles and Safety Improvements for CANDU typed reactors

KHNP has operating four units of CANDU typed reactors, which have a capacity of 700 MWt. CANDU PSA was performed based on Generic CANDU PSA – Reference Analysis in the mid 2000's.[7] In this project, however, we performed CANDU specific FMEAs for initiating event analysis and accident sequence analysis based on T/H analysis, and so forth.

The first unit of CANDU typed reactors got the permission of 10 year life extension in 2015. Although the first unit was the older designed reactor, the first unit showed the lower risk measures through lots of design changes for the life extension including the post Fukushima actions such as PAR (Passive Autocatalytic Recombiner), CFVS. Fig. 3 shows the CDF distributions of each PSA scope except fire PSA for the four units. As for the first unit, the result of seismic PSA is not shown in Fig. 3 because the first unit performed SMA (Seismic Margin Analysis). We identified that CDFs during low power and shutdown operation were estimated higher than those on full power operations. As a result of performing PSA for CANDU typed reactors, we derived the following safety improvements for LPSD PSA. They should be, however, reviewed in view of field application and cost/benefit analysis.

- Ensuring additional bleeding path for bleeding operation
- Modification of automatic actuation signals for emergency core cooling and aggressive cooling operation
- Enhancing procedure and training for operator actions
- Reducing the period of mid-loop operation

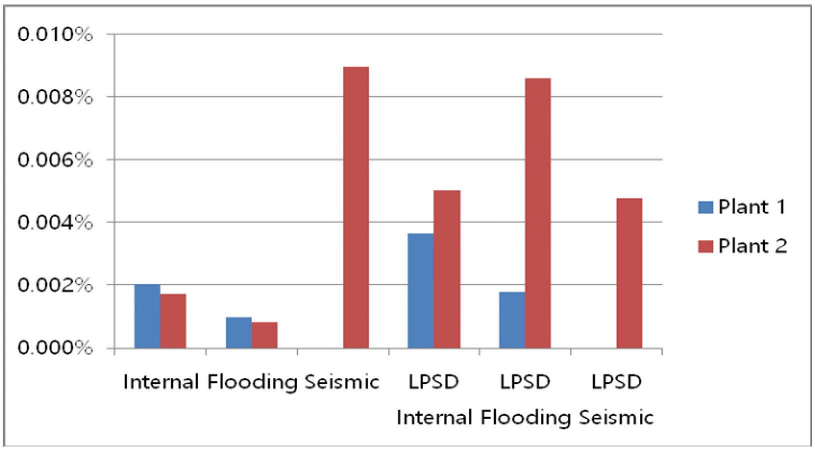

Fig. 3. Risk Profiles of CANDU Typed Reactors

IV. CONCLUSION

KHNP has recently completed the project of upgrading and developing PSA models for the operating NPPs in Korea. In this project, we have upgraded Level 1 internal PSA models considering the requirements of ASME PRA Standard, and updated seismic/flooding PSA models and Level 2 PSA models for full power operations. And, we have developed LPSD Level 1 PSA models based on NUREG-6144. In addition, for developing LPSD SAMG, one of the post-action items as near term Fukushima accident measures, LPSD Level 2 PSA models have been developed for a pilot plant.

To get a technical adequacy for internal Level 1 PSA, KHNP standardized the methodologies of CCF and HRA, and applied the latest operating experiences as well as the new generic database of NUREG/CR-6928 to reliability database. While upgrading Level 1 internal PSA models, we could not improve the quality of the PSA models of the other scopes, such as seismic hazard analysis, new flooding propagation analysis, latest severe accident phenomena, and so on. So, we need to be care of risk aggregation, and put more efforts into realistic analysis against conservative assumptions for other scopes of PSA. As a result of performing PSA, we identified that CDFs from seismic PSA were generally estimated relatively higher than those of other scopes. RCP seal integrity was identified as the weakest points in Westinghouse typed reactors. As for OPR1000 typed reactors, it is considered that containment integrity should be improved through installing severe accident mitigation systems. And, we identified that safety improvements could be required during low power and shutdown operations for CANDU typed reactors.

Recently, KHNP is using the PSA models, developed in this project, when performing PSR (Periodic Safety Review) projects. We plan to update these models according to the schedules of PSR, and upgrade Level 2 PSA models, external event PSA, and LPSD PSA models considering regulatory requirements in near future.

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