Importance Analysis of SAMG related basic events using Level 2 PSA

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1. Introduction

After Fukushima accidents, there has been significant interest in the severe accident and mitigation strategies. Nuclear Safety Act (NSA) of Republic of Korea revised in 2015 is requiring nuclear power plants (NPPs) to satisfy a new safety goal of "*the total frequency of the accident with the release of more than 100 TBq of radionuclide Cs-137 should be less than 1.0E-6/year*" [1]. The probabilistic safety assessment (PSA) provides a systematic approach to estimate the risk of NPPs. Level 2 PSA quantifies the containment failure frequency and the amount of radionuclide release to the environment after containment failure. One of the key issues in enhancing the current Level 2 PSA model includes the systematic modelling of severe accident mitigation guidance (SAMG) strategies and analysis framework [2]. Furthermore, in order to effectively manage and control the plant risk from SAMG execution, the importance analysis of SAMG strategies must be conducted using Level 2 PSA model.

The aim of this paper is to analyze the importance of SAMG-related components and activities on overall plant risk. In this study, two importance measures, Fussel-Vesely (FV) and Birnbaum measures, were estimated for each SAMG-related basic events. For the calculation of FV and Birnbaum, the amount of Cs-137 radioactive material release was used as a measure of NPP risk. The relationship between the two importance measures for each SAMG-related basic events was analyzed to provide important insights on risk management as well as the information on allocating risk control methods intended to reduce the plant risk.

2. SAMG modeling in Level 2 PSA

In the SAMG, several plant parameters such as water levels, temperatures, and pressures are specified in the diagnostic flow chart (DFC) to be sequentially and continually monitored. These parameters are used by the main control room (MCR) and technical support center (TSC) staffs to determine which severe accident guideline (SAG) should be executed. The SAG represents a set of recovery or mitigation actions that could bring the plant to a controlled safe state.

Table I lists the mitigation strategies and related safety systems described in OPR-1000 SAMG [3]. As shown in Table I, SAG-1 to 3 for OPR-1000 are concerned with in-vessel mitigation strategies, whereas SAG-4 is related to in-vessel retention of a molten core through cavity flooding. SAG-6 to 7 are focused on the ex-vessel mitigation which aims to maintain the integrity of containment and prevent radionuclide release.

Table I: Mitigation strategies in OPR-1000 SAMG

Strategy	Fixed System	Portable System
Inject into SG (SAG-1)	- Feedwater pump - SG depressurization valve	- Portable pump
Depressurize RCS (SAG-2)	- Safety depressurization valve	N/A
Inject into RCS (SAG-3)	- High-pressure safety injection pump	- Portable pump
Inject into containment (SAG-4)	- Containment spray pump	- Portable pump
Control containment condition (SAG-6)	- Containment spray pump	- Portable pump
Control containment hydrogen (SAG-7)	- H_2 igniter	N/A

In the authors' previous research [4], the SAMG-event-tree/fault-tree (ET/FT) model was developed based on OPR-1000 SAMG as shown in Figures 1 and 2. The SAMG-ET model was developed based on the SAG sequence in the DFC. The specific logic of each SAG branches in SAMG-ET model was developed in the form of FT model. In the SAMG-FT model, the mitigation systems and a set of human actions required for each SAG was modeled. The SAMG-FT model is then integrated into the PDS-ET where the top event is restructured to include SAMG strategy and the PDSs are reassigned to evaluate a new STC. The detailed modeling and quantification framework for SAMG-FT/ET is provided in the reference [4].

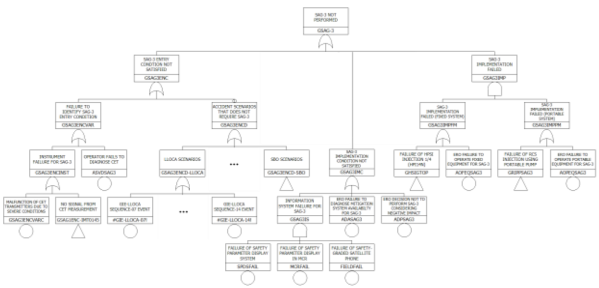

Fig. 1. SAMG-FT model for SAG-3 strategy of OPR-1000

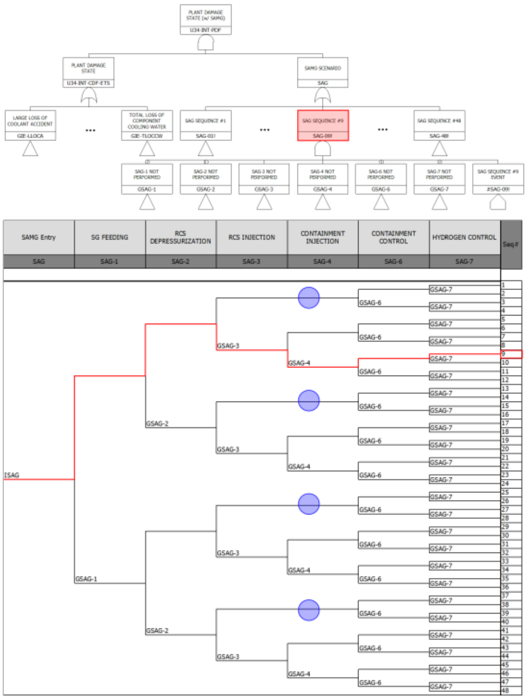

Fig. 2. SAMG-ET model of OPR-1000

3. Importance Analysis of SAMG-related Events

In this study, two risk importance measures, FV Birnbaum [5], were estimated for each SAMG-related basic event to analyze its contribution to the plant risk. The risk is defined as the product of likelihood and consequences. For the purpose of this analysis, likelihood is represented by the probability of each minimal cutset (MCS) derived from the SAMG-FT/ET developed in the preceding section. The consequences are represented by the Cs-137 radioactivity calculated from the new STC reassigned by SAMG for each MCS.

The FV (risk reduction potential) measure indicates how much each component or system contributes to the overall risk due to its failure. The FV is calculated by determining how much the risk could be reduced if the component is assumed to be always available. The value for FV ranges from 0 to 1, the former indicating that the component contributes nothing to the risk and the latter indicating that if a component is available all the time it would reduce all of the risk. The components having a high FV are those for which the most effective control methods must be applied to reduce the total risk.

The Birnbaum measure represents a risk increase potential which indicates how sensitive risk is to the reliability of a component. It measures how much each component could potentially contribute to overall risk if the component is allowed to degrade in reliability. The Breflects how much the current risk would increase if the component is assumed to be completely unreliable. The value for Birnbaum also ranges from 0 to 1, the former indicating that the risk would not increase at all if a component is unavailable and the latter indicating that if the component is completely unavailable, the system would not function. The components that has high Birnbaum value are the candidate component for assuring high reliability, requiring more effective control methods compared to other components.

In this study, the relationship between the two importance measures are analyzed and represented as a scatter plot of component importance to provide important insights on risk management as well as additional information on allocating risk control methods intended to effectively reduce the overall risk. The estimated importance measures of component failure and human error related to SAG strategies are shown as in Figure 3. The insights regarding the contributors to the overall risk are derived as follows:

- **(Region A - a high risk increase potential and a high risk reduction potential)** The basic events related to SAG strategy in this portion includes the malfunction of DFC parameter transmitters due to severe condition (*GSAGnENCVARC*) and the failure of operator to identify mitigation system availability during each SAG (*ADASAGn*). Since risk is most sensitive to changes in reliability or effects of failure of these events, most effective control methods must be provided by improving their reliability. For example, the installation of the redundant DFC instrumentation that is highly reliable in extreme condition and the operating practice review and education for plant operators will play a significant role in managing the additional risk from SAMG operation.
- **(Region B - a high risk increase potential and a low risk reduction potential)** The SAMG-related basic events in this portion includes the failure of operator to diagnose DFC parameter (*ASVSAGn*) and the decision of TSC not to perform SAG considering its negative impact on the plant (*ADPSAGn*). Although they are low in risk reduction potential due to their inherent high reliability or existing operating practices, the overall risk could significantly increase if these events are allowed to degrade in reliability. In this case, the existing computerized supporting system for severe accident progression can be further developed for operators' decision making during SAMG operation to minimize the impact of human error may be beneficial in managing the risk.
- **(Region C - a low risk increase potential and a high risk reduction potential)** The basic events in this portion includes the mechanical failure of Multi-barrier Accident Coping Strategy (MACST) equipment such as portable diesel pump (*DDPPR2SAGn*) and the failure of field operators to operate MACST equipment (*AOPEQSAGn*) for

SAG-1 strategy. The events in this region contribute significantly to risk but would not have a significant additional impact on risk even if they degrade in reliability. Therefore, more reliable or improved operation methods for flexible and portable equipment may be helpful for managing the risks from this portion.

- **(Region D - a low risk increase potential and a low risk reduction potential)** The SAMG-related basic events in this portion includes the failure of MCR operators to operate fixed mitigation systems in NPP such as safety pumps and valves (*AOFEQSAGn*) for SAG-1, 3, and 4 strategies and the mechanical failure of MACST equipment for SAG-1 strategy. While improving the reliability of the events would have little benefits to overall risk, any control methods that would simply provide for replacement or repair of components after their failure should be evaluated for its cost-effectiveness.

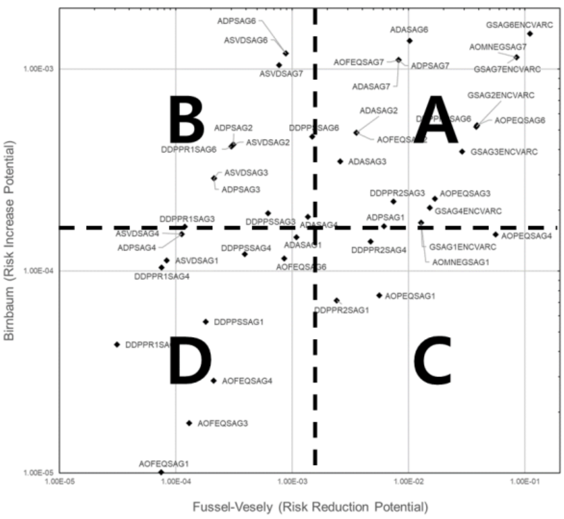

Fig. 3. SAMG-related basic event importance based on SAMG-FT/ET model

4. Conclusion

After Fukushima accidents, there has been significant interest in NPP severe accident and SAMG is considered to play an important role in mitigating severe accidents in NPPs. In order to manage and reduce the risk from SAMG, the importance analysis for SAMG strategies can be conducted to derive the most effective control method for components or systems.

In this study, FV and Birnbaum measures were estimated for each SAMG-related basic event to analyze its contribution to Cs-137 risk of NPP. As a result, the failure modes of components and operator action that have high value in terms of risk management were identified. Based on the result, proper control methods for the identified basic events can be implemented to reduce the Cs-137 risk of OPR-1000.

ACKNOWLEDGEMENT

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REFERENCES

[1] K.T. Kim, “Recent changes of safety regulation in Korea”, *In Proc. IAEA Technical Meeting on Novel Design and Safety Principles*, Vienna, Austria, Oct. 3-6, 2016.

[2] J.Kim and J.Cho, “Technical Challenges in Modeling Human and Organizational Actions under Severe Accident Conditions for Level 2 PSA,” *Reliability Engineering & System Safety*, 194, 106239 (2020).

[3] KAERI, *Development of Accident Management Guidance for Korean Standard Nuclear Power Plant*, KAERI/RR-1939/98 Rev.01, 2000.

[4] S. H. Lee, J. Cho and J. Kim, Development of SAMG-FT/ET Model for Level 2 PSA of OPR-1000 NPPs, *International Topical Meeting on Probabilistic Safety Assessment and Analysis (PSA 2021)*, Columbus, OH, Aug. 29-Sept. 3, 2021 *(Accepted)*.

[5] M. C. Cheok, G. W. Parry and R. R. Sherry, “Use of Importance Measures in Risk-informed Regulatory Applications”, *Reliability Engineering & System Safety*, 60(3), pp. 213-226, 1998.