Quantification of Risk Importance Measure using Cs-137 Radioactive Risk

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1. Introduction

Cs-137 is a dangerous fission product because of its high yield during fission, moderate half-life, high-energy decay pathway, and chemical reactivity; it is accordingly a major contributor to the total radiation released during nuclear accidents. In particular, in response to the Fukushima accident, the Republic of Korea (ROK) revised its Nuclear Safety Act (NSA) in 2015. The new NSA requires that both existing and new commercial nuclear power plants (NPPs) must satisfy the following stated environmental safety goal: "The total frequency of accidents with a release of more than 100 TBq of radionuclide Cs-137 should be less than 1.0E-6/year" [1].

The system, structures, and components (SSCs) in NPPs are modelled as basic events in Level 1 probabilistic safety assessment (PSA). Such basic events comprise hardware failures, human errors, and common cause failures; among them, hardware failures refer to component unreliability (fail to start, fail to run, fail to operate) and component unavailability due to test or maintenance. Regarding the risk of SSCs, risk importance measures (RIMs) such as Fussell–Vesely (FV) importance, risk reduction worth (RRW), and risk achievement worth (RAW) have traditionally been used to quantify the risk importance of basic events [2]. These days, quantifying the RIMs of basic events in Level 1 PSA is essential to obtain NPP risk insight.

Objects of this study are 1) to propose a new approach for RIM quantification using the radioactivity of Cs-137, and 2) to verify the effectiveness of the developed approach by applying it to the OPR-1000 full-power internal event PSA model. The use of actual risk in RIM quantification will allow us to manage NPP risk with plentiful risk information, and further, the identification of risk-significant basic events can help to satisfy national nuclear regulations, such as the new Korean NSA Cs-137 rule.

2. Methods and Results

To quantify RIM using actual risk, such as Cs-137 risk, three steps were proposed. The first step, *frequency quantification*, identifies all accident scenarios and quantifies their related frequencies. To do so, this study used a Level 1 and 2 PSA linked model.

The second step, *consequence quantification*, quantifies the consequence of all accident scenarios. Here, this study suggests using Cs-137 radioactivity as the consequence of Cs-137. In addition, any weighting factor can be applied as the accident scenario consequence; for example, weighting factors of early fatalities or latent cancer fatalities can be used for each source term category (STC). In this study, the MAAP5 code was used to calculate the radioactivity of Cs-137 for all STCs.

The third step, *RIM quantification*, obtains the actual risk of all accident scenarios by the product of the frequency and consequence from previous steps and then quantifies the RIMs of the basic events.

2.1 Frequency quantification

The likelihood function between plant damage states (PDSs) and STCs can be identified. STC containment failure modes include no containment failure, early containment leak failure, and containment isolation failure. Thus, each accident sequence contains the likelihood that every containment failure mode occurs, which means that we can calculate the probabilities of every containment failure mode given the occurrence of one accident sequence. In this paper, the likelihood functions of every accident sequence are called the "mapping fraction". The lower section of Fig. 1 shows a schematic of the Level 1 and 2 PSA linked model using mapping fractions of PDS-STC. Each minimal cut set can be extended to an STC by using simple multiplication by mapping fractions.

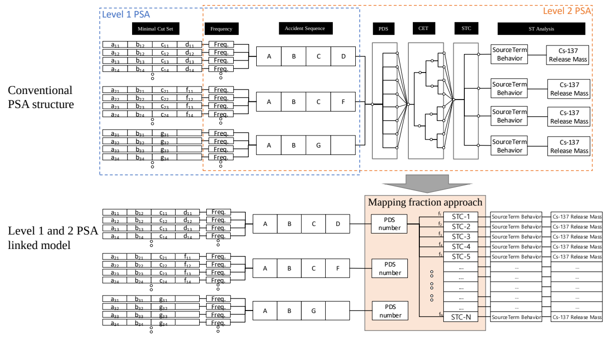

Fig. 1. Conventional PSA structure (upper) and Level 1 and 2 PSA linked model using mapping fractions (lower).

The OPR-1000 Level 1 and 2 PSA models are taken from a multi-unit PSA methodology study by the Korea Atomic Energy Research Institute [3, 4]. The OPR-1000 full-power internal event Level 1 PSA has 644,536 minimal cut sets with a cut-off frequency of 1.0e-14. All the minimal cut sets are made up of 16 initiating events and 1,563 basic events. In the Level 2 PSA model, there are 39 PDSs, 100 end states of CETs, and 21 STCs. Each of the 39 initial conditions has a likelihood of undergoing 100 severe accident scenarios, with the 100 accident scenarios grouped into 21 containment failure modes. From the PDS-STC relationship, a mapping fraction table putting the 39 PDSs into 21 STCs was obtained.

2.2 Consequence quantification

For the accident scenarios defined in the 21 STCs, MAAP5 code analyses were performed to obtain the source term behavior of each STC. The MAAP5 outputs consist of the release fractions of 18 groups of radioactive compounds as a function of time. Among the 18 groups, three groups (groups 2, 6, and 16, corresponding to CsI, CsOH, and Cs2MoO4) contain cesium [5]. The radioactivity of Cs-137 released into the environment as a function of time was obtained for all STCs, as shown in Fig. 2. The cumulative final value was used as the consequence of Cs-137 in the risk calculation of each STC.

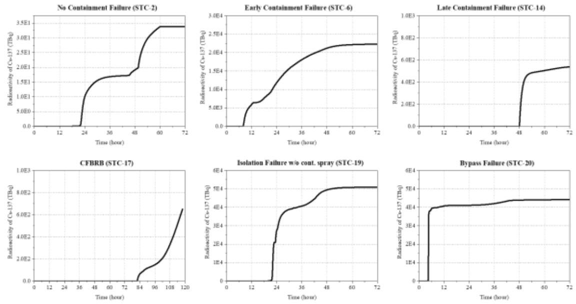

Fig. 2. Radioactivity of Cs-137 in major STCs.

2.3 Risk importance measure quantification

The left panels of Fig. 3 show the occurrence frequency and radioactivity of Cs-137 for each STC, respectively; multiplying them gives the Cs-137 risk for each STC, as in the right panel. Fig. 3 provides the information about which STC should be noted considering Cs-137 risk. This information showed that there are 13 STCs that exceed the 100 TBq Cs-137 radioactivity limit defined in the recent NSA in the ROK. Among them, the risk from STC-21 (steam generator tube rupture, SGTR) has the highest Cs-137 risk.

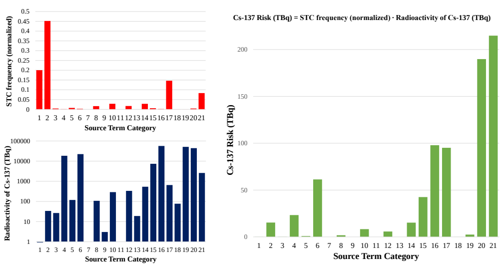

Fig. 3. Cs-137 risk for all STCs.

Table I shows the top 10 basic events in terms of FV importance, and RRW using Cs-137 risk.

Table I: Top 10 basic events in FV importance and RRW by Cs-137 risk.

Rank	BE	Description	FV	RRW	Major accident sequences
1	CWCUK4Q-1A2A1B2B	Running CCF – ECW chiller unit 01A & 02A & 01B & 02B fails to run	0.107	1.119	SGTR-13, SGTR-21, (PDS-39)
2	RCPSEAL_2S	RCP seal LOCA	0.050	1.053	SBOR-38, SBOS-38 (PDS-35)
3	FSXRWX1234S2	CCF of interface relay/contact X-1, 2, 3 & 4 in ARC Tr.A & B (S2)	0.041	1.043	SGTR-13, SGTR-21, (PDS-39)
4	NR-AC60HR	OFF-SITE POWER RECOVERY WITHIN 60HR	0.037	1.038	SBOR-44, SBOS-44 (PDS-32)
5	NR-AC15HR	OFF-SITE POWER RECOVERY WITHIN 15HR	0.037	1.038	SBOR-38 (PDS-35)
6	EGDGK3T-1A1B1E	RUNNING CCF 1E DG-01A & 01B & AAC DG-01E FAIL TO RUN	0.037	1.038	SBOR-38 (PDS-35), SBOR-44 (PDS-32)
7	MSOPHSGISOL	OPERATOR FAILS TO CLOSE MSIVs & MFIVs OF AFFECTED S/G	0.036	1.038	SGTR-21, SGTR-9, (PDS-39)
8	MXOPHRWT	OPERATOR FAILS REFILL RWT	0.035	1.036	SGTR-6, SGTR-9, (PDS-39)
9	HCCQMCCPB	Cubicle Cooler for CCW Pump Room B Unavailable due to Maintenance	0.034	1.035	LODCA-16 (PDS-22)
10	HCCQMCCPA	Cubicle Cooler for CCW Pump Room A Unavailable due to Maintenance	0.030	1.031	LODCA-16 (PDS-22), SGTR-13 (PDS-39)

3. Discussion

If the effect of the basic events on Cs-137 release and CDF is exactly the same, the results of this study are meaningless and the CDF-based RIMs for risk management can continue to be used as before. However, from this study, it is obvious that the impacts of the basic events on Cs-137 release and CDF are different. Some basic events affect Cs-137 release more than CDF, while others do the opposite.

These results are better understood by showing the two approaches together, as in Fig. 4, in which the x- and y-axes show CDF-based and Cs-137 risk-based RIMs, respectively. In this graph, based on the y=x straight line, different interpretations for the lower and upper parts are possible. The lower part is composed of basic events for which the RIMs from CDF are larger than those from Cs-137 risk; this means that these basic events contribute relatively little to Cs-137 release, even if they contribute relatively much to core damage. The upper part may be conversely interpreted.

How to utilize these results for risk-management depends on the given safety philosophy. If we only want to thoroughly prevent core damage, we only need to manage the basic events having high values of CDF-based RIMs. On the other hand, to solely focus on the prevention of environmental pollution by Cs-137 regardless of core damage, we only need to manage the basic events having high values of Cs-137 risk-based RIMs. When both core damage and environmental pollution are important, the related RIMs should be carefully assessed in tandem to identify the important basic events.

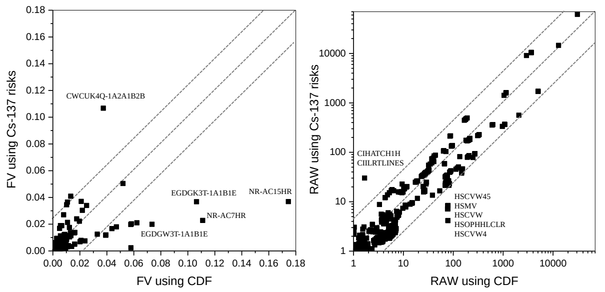

Fig. 4. Comparison of FV importance and RAW using CDF and Cs-137 risk.

As a cost-effective means to manage the Cs-137 rule in the ROK's new NSA (that the total frequency of accidents with a release of more than 100 TBq of radionuclide Cs-137 should be less than 1.0E-6/year), we can focus on the accident scenarios exceeding 100 TBq of Cs-137. Using the approach developed in this study, we can obtain Cs-137 radioactivity information for all accident scenarios, and among them, identify the scenarios that exceed 100 TBq of Cs-137. For this, the radioactivity of Cs-137 can be set to 1.0 for accident scenarios in which Cs-137 radioactivity is higher than 100 TBq, and otherwise set to 0.0. In this way, we can extract only the basic events related with accident scenarios that exceed the 100 TBq limit.

Fig. 5 shows a Cs-137 risk profile with the same structure as the risk profiles used in PSA. The x-axis is the radioactivity of Cs-137 released to the environment instead of fatalities, i.e. Cs-137 radioactivity represents consequence. The y-axis is the exceedance probability, where the y-value for a specific x-value is the probability of which Cs-137 radioactivity exceeds the x-value. The yellow line shows the risk profile of the application results, and the orange line is arbitrarily included to show how the probability of risk can change when risk management of the SSCs is performed. As risk management is actively performed for accident sequences in which Cs-137 release exceeds 100 TBq, related accident scenarios will be greatly reduced.

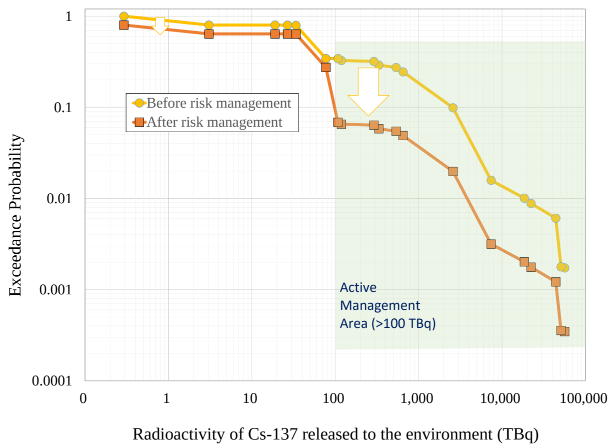

Fig. 5. Conceptual Cs-137 risk profile. The yellow line plots the application results, and the orange line is artificially created to show the concept of active risk management.

4. Conclusions

This paper demonstrated how a new approach consisting of a Level 1 and 2 PSA linked model and the radioactivity of Cs-137 as a consequence index can be used for quantifying risk importance measures. This approach can also be applied to RIMs quantified by other consequence values such as early fatality and latent cancer fatalities. Potential extensions of the current work may include applying RIM uncertainty quantification.

We found three main points in terms of the application of this approach to risk-management. 1) Cs-137 risk-based RIMs should be differently applied to risk-informed management according to safety philosophy. 2) The RAWs of basic events can indicate the risk-significance of the basic events. 3) To satisfy the new Cs-137 rule stated in the recent ROK NSA, Cs-137 risk-based RIMs can be quantified for the accident scenarios that exceed 100 TBq of Cs-137 release.

In view of NPP risk, external events may be more important risk contributor rather than internal events which were analyzed in this study. Moreover, risk results and insights are likely to vary completely depending on the type of events. Therefore, external events such as seismic and flooding should be considered to manage the NPP risk as a further study.

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