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Classification of Radioactive Materials Release Timing for Emergency Preparedness

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1. Introduction

According to the lessons learned from the severe accident of Nuclear Power Plants (NPPs) at Fukushima in Japan in 2011 [1], it is imperative to implement protective actions and related urgent responses to the public in an emergency during severe conditions. It is essential to minimize the risks of fatalities, severe health effects, psychological impacts on individuals, as well as economic and sociological consequences to the public. Therefore, in the event of a severe accident, it is important to develop systematic radiological emergency response plans tailored to specific conditions for each specific NPP for implementing proper emergency response.

In Republic of Korea (ROK), NPPs are regulated to satisfy the following three important probabilities safety criteria in its Nuclear Safey Act (NSA): (1) core damage frequency, (2) large early release frequency, and (3) total frequency of accident sequences releasing Cesium-137 (Cs-137) exceeding 100 TBq, to ensure nuclear safety [2]. According to the third criterion, understanding the characteristics of Cs-137 release during an accident situation is crucial for emergency preparedness.

1.1 *Conventional approach for modeling radiological emergency response*

In level 3 Probabilistic Safety Assessment (PSA), the process includes modeling a radiological emergency response. For this, the information of Source Term Category (STC) from level 2 PSA is utilized as inputs for level 3 PSA. It is necessary to consider much information such as the release timing of radioactive material to the environment for modeling a radiological emergency plan. Although such information can be measured from the results of level 2 PSA, it is difficult to estimate such time-series data from all conditions of level 2 PSA. Finally, certain time points of the accident sequence and the radiological emergency plan need to be assumed.

Fig. 1 is one of the approaches for modeling a radiological emergency plan in Level 3 PSA and shows the important time points of the accident sequence and radiological emergency plan for conservative conditions for general NPPs. As shown in Fig.1 the time point of accident sequences before starting the release into the environment was assumed at 4 hr. after occurring initiating event affecting Large Early Release (LER) for conservative conditions for general NPPs [3]. However, these time points are likely to vary for each specific NPP and initiating event. Therefore, in cases of specific NPPs, the estimation of release starting times should be identified consistently with initiating events of the specific NPPs to efficiently design related radiological emergency plans in each area.

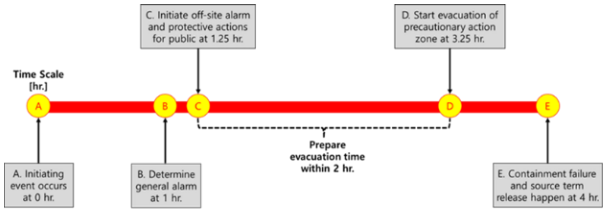


Fig. 1. Important Time Points of the Accident Sequence and Radiological Emergency Plan for Conservative Conditions for NPPs

1.2 *Clustering analysis of release timing*

As shown in Fig.1, the release starting time is an important time point for modeling emergency response**s.** Therefore, accurately understanding the relationship between Cs-137 release and its characteristics of release timing is essential to support accident consequence assessment, management, and response flexibly and realistically in level 3 PSA.

In this study, the clustering analysis of Cs-137 release starting time was conducted. Dirichlet process mixture, that is Bayesian nonparametric models, was used to apply to clustering the release starting time distributions over distribution [4]. Then, proper ranges of release starting times are clustered, and the 95%/95% Cs-137 releases confidential points of each range are identified for proper understanding of that relationship. The analysis of two accidents, Station Black Out (SBO) with the engineering safety feature of containment spray working and Total Loss Of Component Cooling Water (TLOCCW) without containment spray working during early containment failures of OPR-1000 affecting LER, was conducted due to differences in the release characteristics of the two accidents.

2. Methods

This study follows the flow chart in Fig.2. There are four main steps to cluster proper ranges of release starting times and determine the confidential point of Cs-137 release of each range under uncertainty analysis for recognizing an accurate correlation between them. First, the release starting time is investigated from uncertainty analysis of the Cs-137 release. Second, ranges of the release starting time are determined by Dirichlet process mixture clustering. Third, classify the Cs-137 release. Fourth, the confidential Cs-137 release points of each range were estimated.

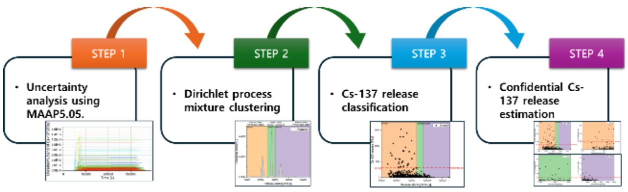


Fig. 2. Flow Chart of classification of Cs-137 release

2.1 Uncertainty Analysis using MAAP5.05

Based on level 2 PSA of OPR-1000 full-power internal events, Uncertainty Analysis has been conducted for SBO and TLOCCW in OPR-1000 [5]. The reference code is MAAP5.05, developed by Fauske & Associates, LLC (FAI) [6]. The Uncertainty parameters, suggested by MAAP5.05 developers, were selected, and input dates were generated by sampling them according to their probability distribution using Monte Carlo sampling. 610 simulation cases were computed and the uncertainty band for Cs-137 over time for SBO and TLOCCW was plotted.

The release starting time of Cs-137 during SBO and TLOCCW was extracted from the uncertainty band. It was then standardized according to Eq. (1) for Dirichlet process mixture clustering.

$$z_{t_{0},i} = \frac{t_{0,i} - \overline{t_0}}{\sigma_{t_0}} \qquad (1)$$

Where $z_{t_{0},i}$ is the standardized data of the i^{th} release starting time, $t_{0,i}$ is the i^{th} release starting time, $\overline{t_0}$ is the mean of release starting time, σ_{t_0} is the standard deviation of release starting time.

2.2. Dirichlet process mixture clustering

In this study, Dirichlet process mixture (DPM) clustering, which is a nonparametric Bayesian model, was used to apply to clustering the release starting time. DPM can infer the number and shape of clusters flexibly from the data. Dirichlet process (DP) is a stochastic process. In theory, the Dirichlet process is a distribution over probability density measures with probability one which is an important process to define discrete distributions. When sampling from a Dirichlet Process (DP) was implemented, the distribution of infinite discrete probabilities would be received. DP was explained in Eq. (2) as follow:

$$G \sim DP(\alpha, H) \qquad (2)$$

DP is the Dirichlet process function. Sampled distribution G is characterized by concentration parameter α and base distribution H. Sampled distribution G is described by following Eq. (3):

$$G = \sum_{k=1}^{\infty} \pi_k \delta(\theta_k) \qquad (3)$$

where π_k is the k^{th} mixing probability proportion. δ is the delta function, and $\boldsymbol{\theta_k}$ is the k^{th} location centered on the cluster parameters.

Mixing probability proportion π_k is the weight summing to one which represents the contribution of each cluster to the overall distribution, thus the probability of selecting each cluster. π_k is defined by the stick-breaking process. The unit length stick break at the random point of Beta distribution β_k to recursively provide a piece of length π_k. This process follows Eq. (4) and Eq. (5) as follow:

$$\pi_k = \beta_k \prod_{l=1}^{k-1} (1 - \beta_l) \qquad (4)$$

$$\pi_k = \beta_k (1 - \sum_{l=1}^{k-1} \pi_l) \qquad (5)$$

In general, the influence of high α on the sampled distributions G of the Dirichlet process will be close to the original distribution H. The randomness of α to generate infinite prior distributions using the stick-breaking process was applied to the observation data to provide posterior distribution for clustering release starting times in this work. Beta distribution of the breaks at random point sticks is influenced by concentration parameter α in which the sum of $\boldsymbol{\beta_k}$ is close to 1 with a negligible difference in Eq. (6) as follows:

$$\beta_k \sim Beta(1, \alpha) \qquad (6)$$

where *Beta* is the beta function.

2.3 Cs-137 release classification

After having the probability density function of posterior distribution from the Dirichlet process mixture, the standardized data of posterior distribution would be converted to identify the ranges of release starting times in each cluster using Eq. (1). Then the ranges of release starting times would be used to classify the Cs-137 releases.

2.4 Confidential Cs-137 release estimation

To estimate 95%/95% confidential estimation of Cs-137 releases, the 95th percentile point in the assumption of normal distribution of each Cs-137 release classification would be identified. The confidential Cs-137 release values and the ranges of release starting times were discussed in this work.

3. Results and Discussion

3.1. Uncertainty Analysis of Cs-137 release

Fig.3 and Fig.4 show the uncertainty band of Cs-137 release over time in the SBO and TLOCCW scenario. As shown in Fig.3, in many cases, the Cs-137 release falls within the range of 100TBq or less. In most cases, the safety goal of not exceeding 100TBq of Cs-137 release is satisfied in the SBO scenario. Nevertheless, there are still many cases where the release of Cs-137 exceeds or significantly surpasses 100TBq and they are distributed within the various release starting times. TLOCCW case in Fig. 4 generally showed a higher Cs-137 radioactive release than the SBO case in the wide ranges with the different release starting times. The results provided that Cs-137 releases in SBO were lower than TLOCCW due to working containment spray. However, whether low or high Cs-137 release cases, they still provided unique release starting times in each Cs-137 release case.

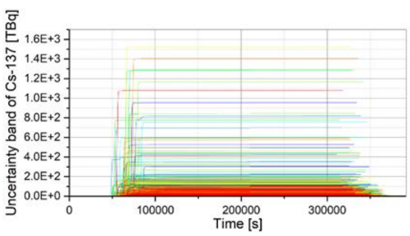


Fig. 3. Uncertainty Band of Cs-137 Releases Timelines of SBO.

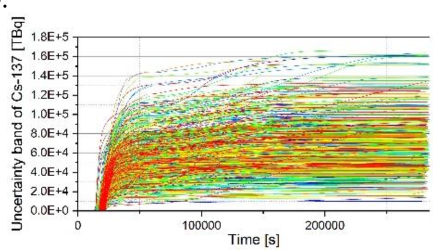
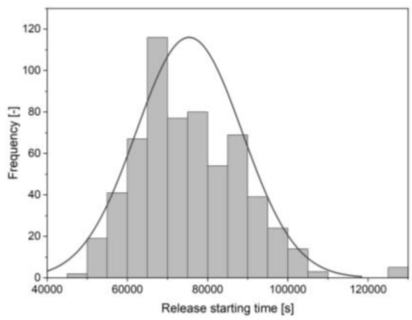


Fig. 4. Uncertainty Band of Cs-137 Releases Timelines of TLOCCW.

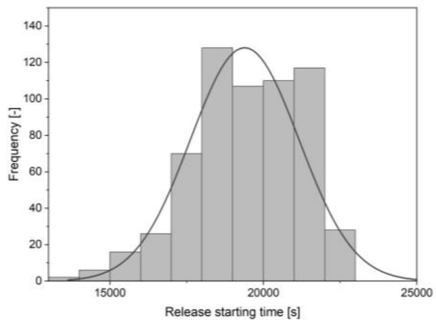
3.2. Clustering Analysis of Release Starting Times

From the uncertainty band in Fig.3 and Fig.4, the release starting time was extracted. The extracted frequencies of release starting time are shown in Fig.5. It is possible to calculate the confidential point of Cs-137 from uncertainty analysis, but this is merely a representative calculation and doesn't consider the relationship between the release of radioactive Cs-137 and their unique release starting time.

Therefore, a clustering analysis of release starting times is conducted in this study. For this, the probability density function of release starting times of SBO and TLOCCW shown in Fig.6 which have several peaks inside their main probability density curves was calculated. To cluster these probability density latent peaks under the normal distribution curves, the Dirichlet process mixture clustering method was applied to group the range of release starting times.

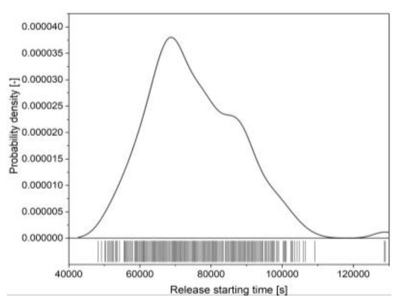


(a) SBO

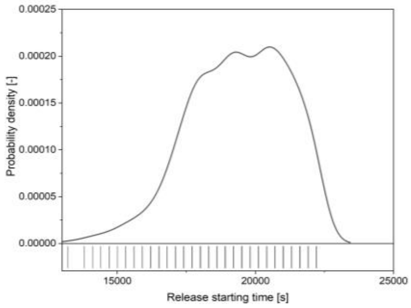


(b) TLOCCW

Fig. 5. Frequency of Release Starting Times of SBO and TLOCCW



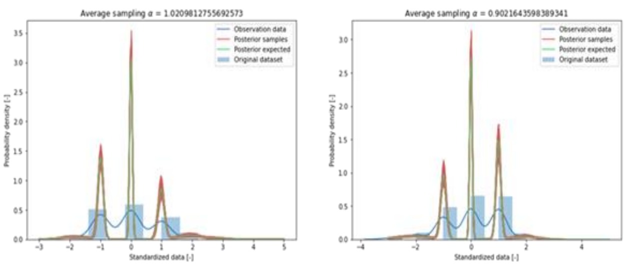
(a) SBO



(b) TLOCCW

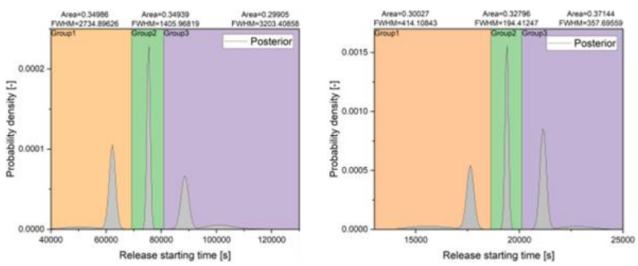
Fig. 6. Probability Density of Release Starting Times of SBO and TLOCCW

Fig. 7 shows the posterior probability density of release starting times of SBO and TLOCCW cases, respectively. The 200 iterations of parameter α in the machine learning process were simulated to provide mixing probability proportions for the two cases. Average sampling parameters α in SBO and TLOCCW cases for clustering were 1.02 and 0.90 respectively. The two parameters α affected the clustering of release starting times of SBO and TLOCCW cases into three groups of the normal distribution with different probabilities. Fig 8 shows the clustering of posterior normal distributions in scales of probability density versus release starting times of SBO and TLOCCW cases, respectively.



(a) SBO (b) TLOCCW

Fig. 7. Posterior Probability Density of Release Starting Times



(a) SBO (b) TLOCCW

Fig. 8. Clustering of Posterior Normal Distributions in Scales of Probability Density versus Release Starting Times

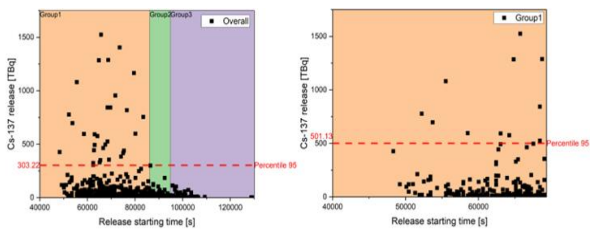
The ranges of release starting times of SBO were divided into 3 groups including Group 1: 40,000 – 69,226 sec (around 11 – 19 hr.) with probability 0.35, Group 2: 69,226 – 80,914 sec (around 19 – 22 hr.) with probability 0.35, and Group 3: 80,914 – 130,000 sec (around 22 – 36 hr.) with probability 0.30. Meanwhile, the ranges of release starting times of TLOCCW were also divided into 3 groups including Group 1: 13,000 – 18,636 sec (around 4 – 5 hr.) with probability 0.30, Group 2: 18,636 – 20,129 sec (around 5 – 6 hr.) with probability 0.33, and Group 3: 20,129 – 25,000 sec (around 6 – 7 hr.) with probability 0.37.

3.3. Classification of Release Starting Times

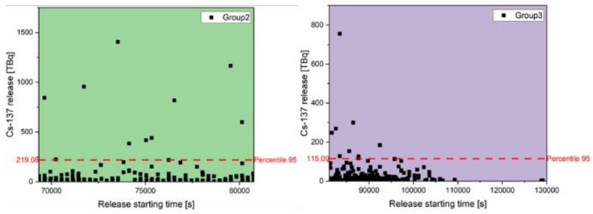
Fig. 8a, Fig. 8b, Fig. 8c, and Fig. 8d show the Cs-137 release classifications using release starting times clustering of posterior distributions of SBO with 95%/95% confidential estimation. In Fig. 14a, within the long-range time at 11 – 36, the overall data provide the confidential point of Cs-137 release 303.22 TBq. However, when considering the clustering of release starting times, it was found that the confidential points of Cs-137 releases changed each clustering. It was found that the confidential points of Cs-137 releases were increased to 501.13 TBq in Group 1 and decreased to 219.08 TBq in Group 2, and 115.09 TBq in Group 3, respectively. The shift of Cs-137 release levels in each group changed significantly.

Fig. 9a, Fig. 9b, Fig. 9c, and Fig. 9d show the Cs-137 release classifications using release starting times clustering of posterior distributions of TLOCCW with 95%/95% confidential estimation. In Fig. 15a, within 4 – 7, the overall data provided the confidential point of Cs-137 release was around 1.24E+05 TBq. However, when considering the clustering of release starting times, it was found that each cluster of Cs-137 releases provided a very short time range within each hour, with close Cs-137 releases including 9.97E+04 TBq in Group 1, 1.10E+05 TBq in Group 2, and 1.37E+05 TBq in Group 3.

According to Fig. 8 and Fig. 9, considering the Cs-137 release and its probability, the timeline of Group 1 around 11-19 hr. in Fig.8 provides the most conservative criteria for emergency preparedness in SBO. However, in the case of TLOCCW, the release starting time is relatively short compared to the SBO case, and the release quantity is also significant, making the conventional conservative estimation of 4 hours for the release starting time reasonable.

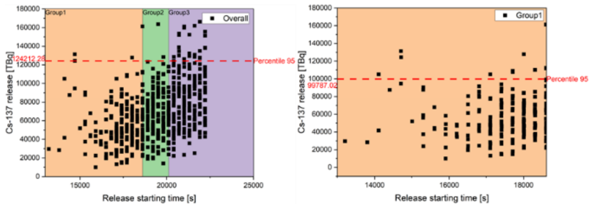


(a) 11-36 hr. (b) 11-19 hr.

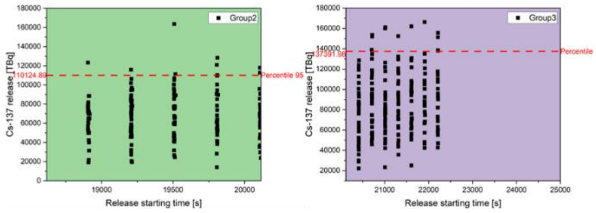


(c) 19-22 hr. (c) 22-36 hr.

Fig. 8. Cs-137 release 95%/95% Confidential Estimation of Each range in SBO



(a) 4-7 hr. (b) 4-5 hr.



(c) 5-6 hr. (d) 6-7 hr.

Fig. 8. Cs-137 release 95%/95% Confidential Estimation of Each range in SBO

4. Conclusion

In this study, the Cs-137 classification using release starting times clustering was conducted. In the SBO case, the first point of the release starting time was around 11 hr. which is higher than the previous conservative estimation of 4 hr. Meanwhile, in the TLOCCW case, the overall short range of release starting time at 4–7 hr. was already agreed with the conservative estimation at 4 hr.

Previously, radiological emergency plan modeling was typically conducted based on conservative estimation. However, the approach for release starting times clustering and classification of Cs-137 release conducted in this study helped provide the framework to support radiological emergency plans for specific initiating events. The application of this method is expected to contribute to other important STCs as a further contribution.

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