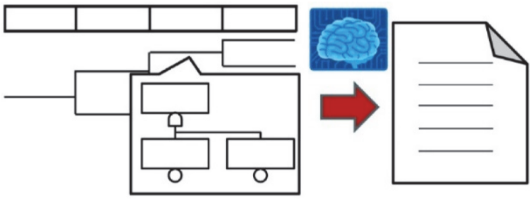
A Validation Method for Results of PRA Using AI Technique



TATSUKI AMITANI[*1] SHUNSUKE HIRAI[*2]
KAZUKI OZAKI[*3] YASUFUMI FUJII[*4]
KATSUAKI MORITA[*5]

The risk of severe accidents occurring in a nuclear power plant is quantitatively evaluated utilizing the probabilistic risk assessment methodology. Given that nuclear power plants consist of complex systems with numerous facilities, equipment, piping and electrical components, the scope of potential accident scenarios requiring assessment is vast. The combinations of failures that could lead to a severe accident, as identified through the probabilistic risk assessment, are validated by verifying the plausibility of the events based on failure modes inferred from the design, operation and experience of the nuclear power plant. While the number of possible failure combinations may be enormous, the numerical outcomes can be deemed credible when the dominant contributors are thoroughly analyzed. The credibility of the assessment may be further enhanced if more of the combinations are subject to the validation. To achieve this, we have employed natural language processing, a branch of artificial intelligence to develop a method that facilitates the efficient and comprehensive validation of the probabilistic risk assessment.

1. Introduction

To enhance the safety of nuclear facilities on a voluntary and continuous basis, nuclear operators conduct assessments for safety improvement. As a part of these initiatives, a probabilistic risk assessment (hereinafter referred to as PRA) is performed to calculate the frequency of events that could result in severe accidents due to equipment failures and other abnormal conditions. In PRA, both event trees and fault trees are utilized to analyze the frequency of abnormal events – referred to as initiating events – that could result in severe accidents, as well as the failure probabilities associated with mitigation functions designed to protect the reactor and the containment vessel from severe accidents. An event tree is a logical diagram resembling a tree structure that represents the event progression following an initiating event depending on the operational conditions of the systems, facilities, and other components of the plant. It is structured with the success or failure of each mitigation function and illustrates the relationship between the initiating event and the mitigation functions. An example of an event tree is shown in **Figure 1**. At the same time, a fault tree defines the failure of the mitigation function as its top event, detailing the underlying factors and logically illustrating the cause-and-effect relationship among those factors, thus enabling an analysis of the causes of mitigation function failures depicted in the event tree. An example of a fault tree is shown in **Figure 2**.

By quantifying event trees and fault trees, cut sets, which are combinations of equipment failures and operational errors (hereafter referred to as “basic events”) that lead to severe accidents, are derived. Summing the frequencies of occurrence of each cut set allows for the calculation of the overall frequency of severe accidents, which is the primary objective of PRA. Examples of cut sets are shown in **Figure 3**. Because each basic event there is assigned a unique ID, the cut set may be treated as a sequence of IDs that represents scenarios leading to a severe accident.

The validity of a cut set is ensured by verifying the plausibility of the events based on failure modes inferred from the design, operation and experience of the nuclear power plant. Given the complexity of nuclear systems, numerous cut sets may be generated. The numerical result can be

*1 Reactor Core & Safety Engineering Department, Nuclear Energy Systems
*2 SRZ Development Project Department, Nuclear Energy Systems
*3 Corporate Management Division, Mitsubishi Heavy Industries Compressor Corporation
*4 Plant Engineering Department, GTCC Business Division, Energy Systems
*5 Engineering Manager, EPI Department, Digital Innovation Headquarters

considered valid if the dominant contributors are examined accordingly. The credibility of the assessment could be further improved by validating a greater number of cut sets.

To facilitate a more efficient validation process, the use of natural language processing (hereinafter referred to as NLP), a technique in the field of artificial intelligence (hereinafter referred to as AI), was explored in this study. One specific NLP method, Word2Vec[(1)], converts individual word in a sentence into a numerical vector based on this contextual relationship with neighboring words and determines similarities in meaning between sentences by computing vector distances. By applying Word2Vec to convert the cut sets (character strings) into vectors, a method that allows for efficient and comprehensive validation of cut sets was developed.

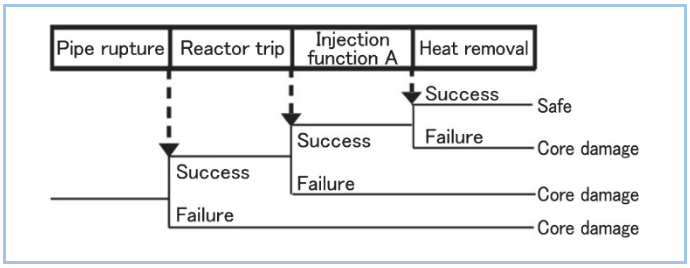


Figure 1　Event tree example

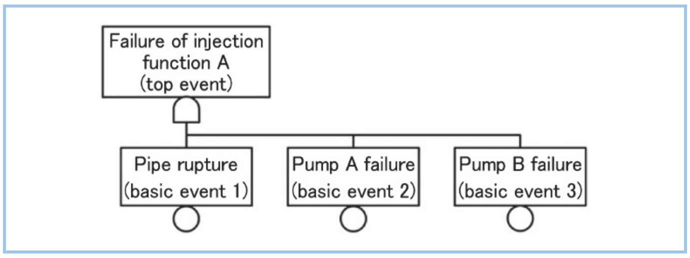


Figure 2　Fault tree example

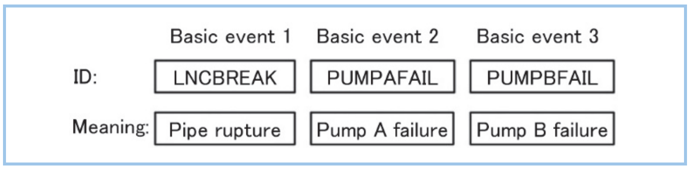


Figure 3　Cut set example

2. Developed methods

2.1 Clustering of cut sets using natural language processing

As mentioned above, cut sets within PRA for nuclear power plants represent scenarios leading to a severe accident in the form of a string of characters. The basic events comprising the cut set denote equipment failures and operational errors. Similar basic events are assigned analogous IDs; similar accident scenarios yield similar cut sets. When cut sets are plotted in vector space using Word2Vec, those representing similar accident scenarios possess similar vector values, as illustrated in the schematic diagram in **Figure 4**. Thus, clustering cut sets with similar vector values produces clusters of cut sets signifying similar accident scenarios.

Impact of the inclusion of Inappropriate inputs into the PRA model may impact cut sets in the following two ways.

(i) An inappropriate cut set that should not appear (hereinafter referred to as “inappropriate cut set”) may be generated.

(ii) A cut set that should be present (hereinafter referred to as “non-appearing cut set”) may not be generated.

This study developed methods to identify these patterns using the characteristics of the cut sets vectors and their clusters.

The PRA model constructed for nuclear power plants are comprised of extensive event trees and fault trees, with tens to hundreds of basic events involved with each system. Consequently, even a single error in the PRA model can affect numerous cut sets relevant to those basic events.

The methods developed in this study are expected to demonstrate a higher error detection rate as clustering is conducted more appropriately. However, it is not essential to identify all affected cut sets to locate inappropriate inputs in the PRA model; identifying at least one affected cut set allows for tracing back to the erroneous inputs through the PRA model. Therefore, the detection rate of the developed methods is expected to surpass the general accuracy of AI-based clustering.

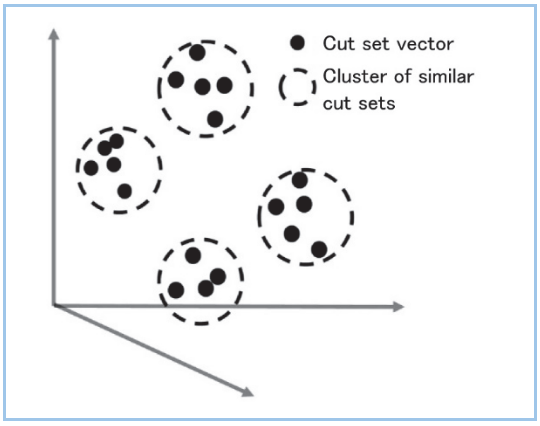


Figure 4 Schematic diagram of vectorized cut sets

2.2 Method to identify inappropriate cut sets

This method narrows the focus on cut sets for validation by the analyst, allowing the identification of inappropriate cut sets that should not be obtained based on the characteristics of the plant being assessed. Examples of inappropriate cut sets include those that involve human error in activating a pump within a system equipped with automatic actuation of the component. The concept of this method is illustrated in **Figure 5**. This procedure vectorizes and clusters a group of previously validated cut sets (hereafter referred to as “correct cut set data”) alongside a group of cut sets in need of validation. Clusters containing the correct cut set data are deemed to require no further validation because they are composed of cut sets similar to the correct cut set data. On the other hand, as clusters lacking the correct cut set data are composed of cut sets that have yet to be validated, the analyst is able to search these clusters for potential inappropriate cut sets by verifying their validity based on the same plant characteristics as previously applied.

As each cluster consists of similar cut sets, it is not necessary to investigate all cut sets individually; validation of the entire cluster can be achieved by examining a limited number of cut sets within each cluster.

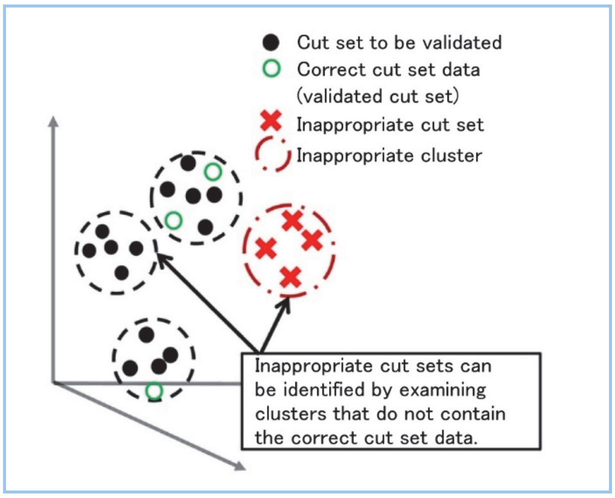


Figure 5 Concept of the method to identify inappropriate cut sets

2.3 Method to identify non-appearing cut sets

This method identifies non-appearing cut sets by comparing them with validated cut sets within the PRA models of a plant. The concept of this method is illustrated in **Figure 6**. This approach involves vectorizing and clustering a group of validated cut sets (preceding model) along with a group of cut sets in the PRA model to be assessed. This process facilitates the extraction of clusters containing cut sets that appeared in the preceding model but are absent in the group yet to be validated. The analyst meticulously examines whether the extracted clusters should exist within the plant being assessed; if cut sets that should appear in the plant are missing, these are labeled as non-appearing cut sets.

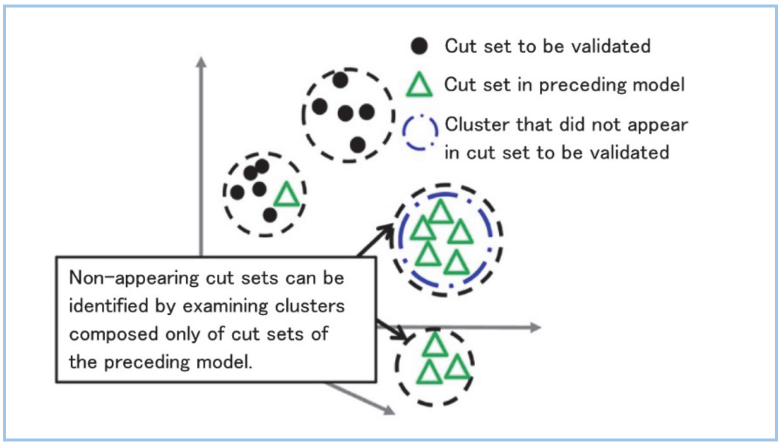


Figure 6 Concept of the method to identify non-appearing cut sets

3. Verification of the developed methods

3.1 Verification of the inappropriate cut set identification method

Approximately 500 inappropriate cut sets were intentionally generated within an internal event PRA model, comprising about 1 % of roughly 50,000 total cut sets, by modifying the structure of one of the fault trees. Using the developed method, we aimed to narrow down clusters suspected of containing inappropriate cut sets. As a result, the method extracted five clusters that required validation, within which inappropriate cut sets were identified. The concept of this verification process is illustrated in **Figure 7**. The method efficiently identified inappropriate cut sets that constituted only about 1% of the total, proving to be effective.

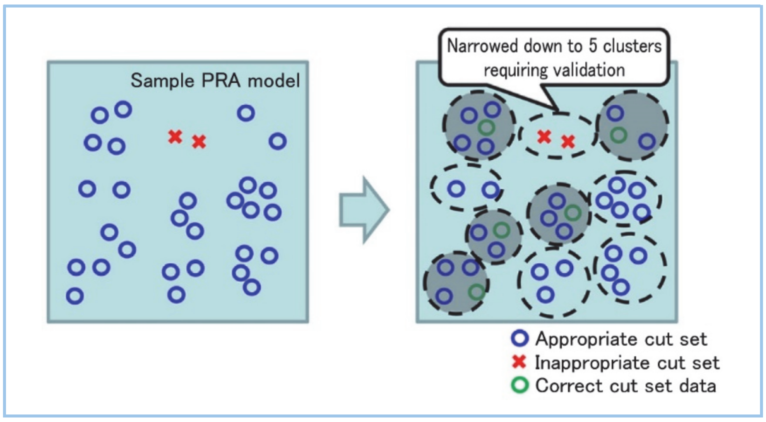


Figure 7 Concept of verification for the inappropriate cut set identification method

3.2 Verification of the non-appearing cut set identification method

A sample PRA model, from which some correct cut sets were removed in various patterns, was created to evaluate the capability of the developed method to detect missing cut sets by comparing all of its cut sets with the cut set generated from four preceding PRA models. The concept of this verification process is illustrated in **Figure 8**. This verification was conducted on four different combinations of events and event progressions (internal and seismic events, level 1 and level 2 PRA), with 30-70 patterns of missing cut sets prepared for each combination. While several combinations yielded a detection rate of 97%, others achieved complete identification of all non-appearing cut sets, resulting in an overall detection rate of 99%. This demonstrates that AI can facilitate the validation of a wider range of cut sets and enhance the detection rate of non-appearing cut sets. Thus, the effectiveness of this method was confirmed.

For this study, separate verifications were performed for the identification methods involving inappropriate cut sets and non-appearing cut sets. However, in general practice of PRA, inappropriate cut sets and non-appearing cut sets are often generated simultaneously due to the interconnectedness of fault trees and event trees and their relations with erroneous inputs in the PRA model. For this reason, if an erroneous input is detected by either method, corrections can be made in a timely manner. Thus, the utilization of both methods is expected to enhance the overall detection rate in practice.

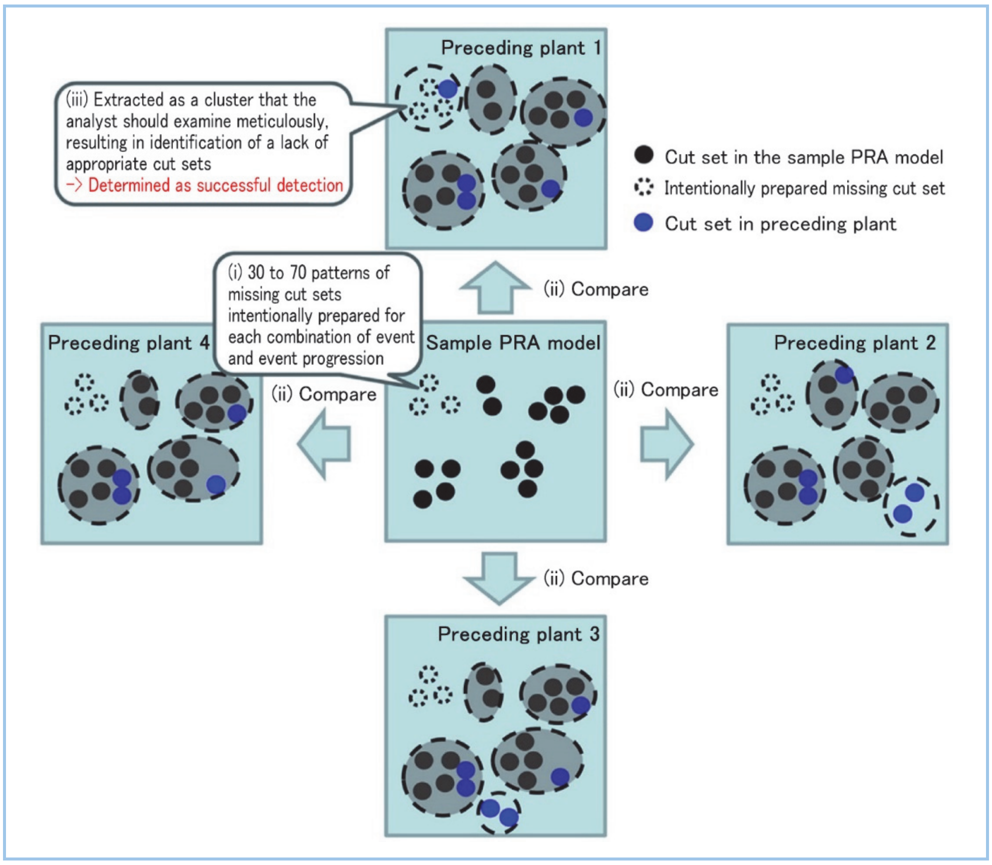


Figure 8 Concept of verification for the non-appearing cut set identification method

4. Conclusion

To further improve the quality of PRA, two validation methods utilizing NLP were developed and their efficacy was substantiated. As mentioned above, given that nuclear power plants are complex systems, the number of cut sets derived from PRA can reach tens to hundreds of thousands. The application of these methods enables comprehensive validation within a realistic timeframe, a feat unattainable with conventional approaches. Adopting this technology to PRA validation is expected to improve the reliability of the assessment in the future.

References

(1) T. Mikolov et al., Efficient estimation of word representations in vector space, (2013), arXiv preprint arXiv:1301.3781