Risk-Informed Performance-Based Licensing Basis Event Selection for the BeSMART Micro Reactor: A Case Study

Kwang Nam Lee [a*], Kye Kwang Jee [a], Kyung Hee Lee [a] , Eungjae Kim [a]
Jangsik Moon [a]
[a] *`Best Engineering in Energy Solutions, #704,18, Daepyeong 3-gil, Sejong-si, Republic of Korea*
[*] *Corresponding author: kane@bees.pro*

***Keywords** : licensing basis event*, risk-informed performance-based, micro reactor, probablistic risk assessment

1. Introduction

The development of advanced reactor technologies has prompted a fundamental shift in nuclear safety philosophy, from reliance on purely deterministic accident analyses toward a risk-informed, performance-based (RIPB) framework [1]. Within this framework, licensing basis events (LBEs) serve as a cornerstone for defining the scope and depth of safety evaluations, enabling a structured integration of probabilistic insights with traditional safety principles. Among advanced reactor concepts, micro reactors introduce both notable opportunities and distinct challenges in safety evaluation. Their compact core configurations, low thermal power levels, and extensive use of inherent and passive safety features indicate the potential for substantially reduced risk compared to conventional large-scale reactors. In this context, BEES is currently developing a micro reactor, BeSMART, for which the systematic application of RIPB based LBE selection has been identified as a key element of the overall safety evaluation strategy. The motivation for this study is to demonstrate how the RIPB framework can be practically and consistently applied to a micro reactor design under development, using a representative probabilistic risk assessment (PRA) model to support LBE identification, classification, and evaluation.

This paper presents a case study of LBE selection for a micro reactor using the RIPB methodology. The study focuses on PRA model development, evaluation of LBEs against Frequency–Consequence (F–C) target, integrated plant risk assessment, and the derivation of risk significance insights that support risk-informed design optimization and licensing decision-making.

2. RIPB Framework for LBE Selection

2.1 LBE Definition

The PRA event sequence families are labeled according to the event classifications that align with the frequency criteria specified in NEI 18-04 [2]. The classifications are defined as follows:

- Anticipated Operational Occurrences (AOOs) have mean frequencies greater than 1.0E-2 per plant-year.
- Design Basis Events (DBEs) have mean frequencies from 1.0E-4 to 1.0E-2 per plant-year.
- Beyond Design Basis Events (BDBEs) have mean frequencies from 5.0E-7 to 1.0E-4 per plant-year.
- Residual Risk (RR) events are excluded from the licensing basis and have mean frequencies less than or equal to 5.0E-7 per plant-year.

2.2 LBE Selection Approach

2.2.1 F-C Evaluation Criteria

Based on insights from the review of existing regulatory criteria, this approach uses a set of F-C criteria; this F-C evaluation correlation, hereafter referred to as the F-C target, is shown in Fig. 1 [2]. The F-C target provides the basis for establishing the risk significance of LBEs.

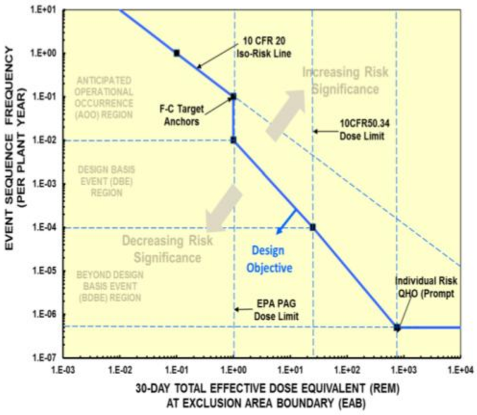

Fig.1. Frequency-Consequence Target

2.2.2 LBE Selection Process

A logic chart illustrating the tasks used to identify and evaluate LBEs in conjunction with the evolution of the design is provided in Fig. 2 as described in NEI 18-04 [2]. This process supports the preparation of appropriate licensing application submittals by clearly describing how the LBEs are derived. Although all of the tasks shown in Fig. 2 contribute to the LBE selection process in various ways, the tasks that are directly related include Tasks 1, 2, 3, 4, 7a, 7b and 7c, and only these tasks are evaluated in this paper.

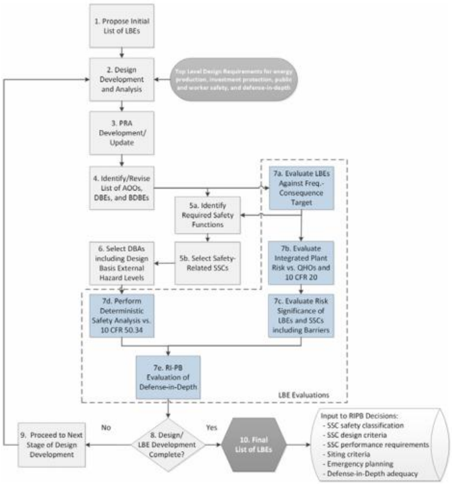

Fig. 2. LBE Selection Process

3. PRA Model Development and Evaluation for the BeSMART Micro Reactor

3.1 PRA Model Development

Development of the PRA model begins with the identification of a comprehensive set of initiating events (IEs) relevant to the reactor. For each identified IE, associated event sequences are developed using integrated event tree and fault tree models. During this process, event sequence families are systematically defined based on the reactor system design and its functional characteristics. The PRA model addresses the full spectrum of internal events and external hazards that challenge plant safety functions. The required level of model detail is commensurate with the reactor's size, complexity, and potential risk profile, ensuring that the PRA adequately supports risk-informed evaluations. The resulting event sequences provide the basis for the identification and selection of LBEs. Quantitative estimates of event sequence frequencies and radiological consequences are used to evaluate their risk significance, which represents a key outcome of the PRA. As the reactor design matures and additional design information becomes available, the PRA is progressively expanded to address a broader range of plant conditions and to provide increasing confidence that established safety objectives are met.

3.2 Design Features of BeSMART Micro Reactor

The BeSMART micro reactor incorporates design features that form the foundation of its licensing basis. The design prioritizes inherent and passive safety mechanisms to control reactivity, remove decay heat, and retain radionuclides under both normal and off-normal conditions. System simplification and the minimization of active components reduce the spectrum of potential initiating events and constrain the complexity of accident sequences. These design attributes are systematically integrated into the risk-informed framework that supports the selection of licensing basis events (LBEs). By explicitly linking design characteristics to safety functions and quantified risk insights, the BeSMART LBE selection methodology ensures that regulatory requirements are addressed in a technically defensible and safety-focused manner, fully aligned with the reactor's overall safety case.

4. Case Study: Application of LBE Selection to BeSMART Micro Reactor

4.1 Event Sequence Quantification and LBE Identification

The results of quantifying each event sequence using the PRA model are shown in Fig. 3 and Fig. 4 and the identified LBEs are as follows:

AOO Event Sequence Family
The first event sequence family is designated as an AOO, as shown in Fig. 3 and Fig. 4 This family includes two sequences—GT1 sequence 1 and GT2 sequence 1—and represents detection of the initiating event followed by an automatic reactor trip actuated by the reactor protection system (RPS). Subsequent to reactor trip, decay heat removal is achieved through successful operation of either the secondary heat removal system or the reactor cavity cooling system (RCCS), depending on system availability.

DBE Event Sequence Family
The second event sequence family is designated as a DBE. This family consists of a single sequence, GT1 sequence 2. GT1 sequence 2 is characterized by the failure or unavailability of the secondary heat removal system following a successful reactor trip, with decay heat removal achieved through reliance on the RCCS.

BDBE-1 Event Sequence Family
The third event sequence family is designated as BDBE-1. This family includes two sequences—GT1 sequence 5 and GT2 sequence 4. In these sequences, a reactor trip is not initiated by the reactor protection system; however, decay heat removal is successfully accomplished through the secondary heat removal system in GT1 sequence 5 and through RCCS in GT2 sequence 4.

BDBE-2 Event Sequence Family
The fourth event sequence family is designated as BDBE-2. This family consists of a single sequence, GT2 sequence 2, and represents detection of the initiating event followed by an automatic reactor trip actuated by the reactor protection system, similar to GT1 sequence 1. Because this sequence involves the failure of decay heat removal via the RCCS, in

combination with the unavailability of the secondary heat removal system, filtered venting of the confinement building is required to mitigate the release of radioactive material to the atmosphere.

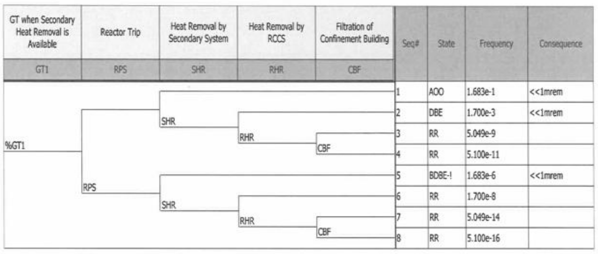

Fig.3 General Transient 1 Event Tree (GT1)

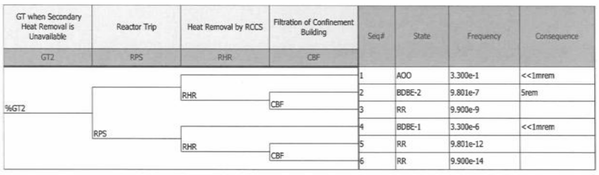

Fig. 4 General Transient 2 Event Tree (GT2)

4.2 LBE Evaluation

4.2.1 Evaluation of LBEs Against F-C Target

The LBEs identified in Task 4 are plotted on the F–C target chart to evaluate their risk acceptability and risk significance. For this illustrative application, conservative engineering estimates of radiological consequences are used to demonstrate the methodology. When plotted on the F–C target chart as shown on Fig. 5, all LBEs identified in Task 4 fall within the F–C target and are located in the non-risk-significant region.

AOO Event

The AOO event is determined to be non-risk-significant based on the F–C target, as shown in Fig. 5. This AOO is evaluated assuming reliable performance of the safety-related reactor protection system, the reactor cavity cooling system (RCCS) for GT2 sequence 1, and the non-safety-related secondary heat removal system for GT1 sequence 1. Under these assumptions, the estimated dose consequence is determined to be substantially less than 1 mrem.

DBE

The DBE is not risk-significant based on the F-C targets, as shown in Fig. 5. This DBE is evaluated with reliability of the RPS and the RCCS. The frequency of the DBE event is estimated to be 1.7E-3/ plant-year and dose consequence is estimated to be substantially less than 1 mrem.

Beyond Design Basis Event (BDBE-1)

The Beyond Design Basis Event (BDBE-1) is determined to be non-risk-significant based on the F–C target, as shown in Fig. 5. The BDBE-1 sequence is evaluated assuming reliable performance of the secondary heat removal system and/or the RCCS. The frequency of the BDBE-1 event is estimated to be 5.0E-6 per plant-year, and the associated dose consequence is calculated to be substantially less than 1 mrem. The system design supporting this BDBE-1 event is assigned performance targets and success criteria such that the two decay heat removal systems—the secondary heat removal system and the RCCS—are capable of maintaining radiological consequences below 1 mrem.

Beyond Design Basis Event (BDBE-2)

The Beyond Design Basis Event (BDBE-2) is determined to be non-risk-significant based on the F–C targets, as shown in Fig. 5. The BDBE-2 sequence is evaluated assuming reliable performance of the RPS and confinement building filtration system. The frequency of the BDBE-2 event is estimated to be 9.8E-7 per plant-year, and the associated dose consequence is estimated to be 5 rem.

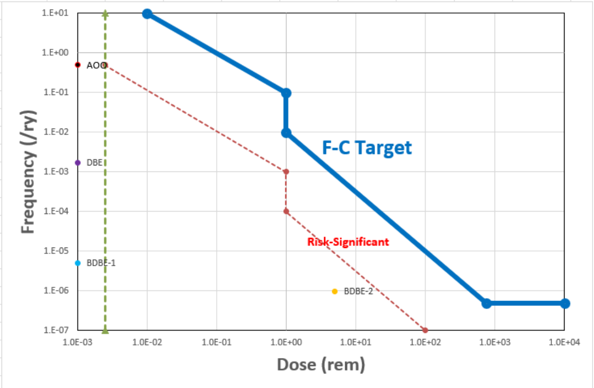

Fig. 5. LBEs Plotted on the F-C Target Chart

4.2.2 Evaluation of Integrated Plant Risk Against QHOs and 10 CFR 20

In this task, the integrated risk of the plant, accounting for all LBEs, is evaluated against the three cumulative risk targets identified in task 7b. To demonstrate the acceptability of cumulative risk, the events identified in Task 4 are evaluated and plotted on a Frequency–Risk curve, as shown in Fig.6. and Fig. 7.

As per the early fatality risk, all LBEs are shown to meet the quantitative health objective targets as illustrated in Fig. 6. As per the latent cancer fatality risk, all LBEs are also shown to meet the quantitative health objective targets as illustrated in Fig. 7. Compliance with the requirements of 10 CFR 20 is evaluated using a PRA that encompasses a complete set of event sequences, operating states, and hazard groups.

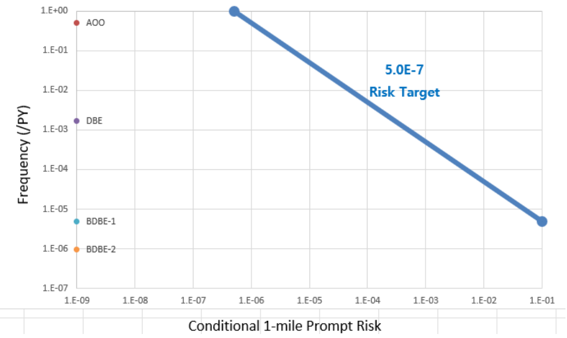

Fig. 6. Early Fatality Risk within 1 Mile of EAB

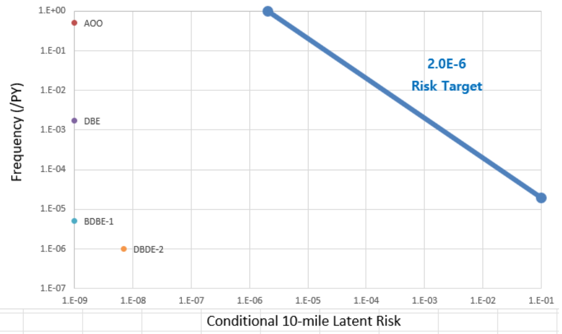

Fig. 7. Latent Cancer Fatality Risk within 10 Miles EAB

4.2.3 Evaluation of LBE Risk Significance

In this task, the detailed definitions and quantifications of the LBEs developed in Task 7a, together with the integrated risk evaluations performed in Task 7b, are used to determine the risk significance of individual LBEs.

Based on Fig. 5, which supports Task 7a, each LBE is evaluated according to its proximity to the F–C target line. Any LBE that lies within 1% of the target line (as indicated by the dotted red line in Fig. 5) is classified as risk-significant. Applying this criterion, none of the LBEs—AOO, DBE, BDBE-1, or BDBE-2—are determined to be risk-significant.

5. Summary and Conclusions

This study presented a case study on the application of a RIPB methodology to the selection of LBEs for the BeSMART micro reactor currently under development. The design characteristics and inherent safety features of BeSMART—including low power density, passive heat removal, strong negative reactivity feedback, and radionuclide retention capabilities—were examined in detail. Based on these characteristics, a plant-specific probabilistic risk assessment (PRA) model was developed. general transient is selected as an IE and event sequences were identified and quantified through integrated event tree analyses, forming the technical basis for LBE classification and evaluation. Each quantified event sequence was classified into the appropriate LBE category (AOO, DBE, or BDBE) based on its mean frequency. For the selected LBEs, frequencies and radiological consequences were estimated and evaluated against the F–C target. In addition, the integrated plant risk was assessed against the quantitative health objectives (QHOs) and the dose criteria of 10 CFR 20. The risk significance of individual LBEs was also evaluated based on proximity to the F–C target and cumulative risk criteria.

The results of this evaluation lead to the following conclusions:

- The applicability of the RIPB methodology to LBE selection for the BeSMART micro reactor has been demonstrated. The process enabled structured and systematic identification, classification, and evaluation of LBEs consistent with the reactor's design characteristics and safety functions.
- Although BeSMART remains at the conceptual design stage, the application of the RIPB approach shows that the overall risk level is to be very low and that all identified LBEs will satisfy the established F–C target and integrated risk criteria with substantial margin.
- The RIPB framework provided valuable insights into the identification of risk-significant LBEs which will support identification of risk significant SSCs, including key radionuclide barriers. These insights support the establishment of performance requirements and guide design optimization to further enhance safety and defense-in-depth.

Overall, this case study demonstrates that the RIPB-based LBE selection process is an effective tool for supporting the safety case and licensing strategy of advanced micro reactors such as BeSMART, while simultaneously informing risk-informed design improvements during early development stages

REFERENCES

[1] Wayne L Moe, Amir Afzali, Idaho National Laboratory, Modernization of Technical Requirements for Licensing of Advanced Non-Light Water Reactors: Final Project Report March 2020.

[2] NEI 18-04, Risk-Informed Performance-Based Technology-Inclusive Guidance for Non-Light Water Reactor Licensing Basis Development, Report Revision 1, August 2019.