Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 9-10, 2024

Analysis on Molten Salt Reactor Component Failure Rate based on Systems and Components Performance of Molten Salt Reactor Experiment

Yeongchan Kim [a], Jeong Ik Lee[a*]
[a]*Dept. Nuclear & Quantum Eng., KAIST, 373-1, Guseong-dong, Yuseong-gu, Daejeon, 305-701, Republic of Korea*
[*]*Corresponding author: jeongiklee@kaist.ac.kr*

1. Introduction

The importance of a component reliability (or failure rate) database is paramount for conducting Probability Risk Assessment (PRA), which is a crucial tool in nuclear safety field used to estimate the frequency of transient, events, and accident. Unlike Pressurized Water Reactors (PWRs), the development of a component reliability database for advanced reactors has been constrained by the limited availability of operational records.

Molten Salt Reactors (MSRs), considered as one of the advanced reactors, offer significant safety advantages with the use of liquid fuel. Such unique safety profile has inspired active development of various MSR designs. Yet, since fuel burnup occurs in a liquid (melt) state, conventional PRA procedures, which primarily address solid-fuel meltdown accidents, may not be directly applicable.

Since Oak Ridge National Laboratory (ORNL) had operated Molten Salt Reactor Experiment (MSRE) for 4 years in 1960's, there has been a collaborative effort between ORNL and Southern Company, the Electric Power Research Institute (EPRI), and Vanderbilt University (VU), to calculate the component reliability of the MSRE [1, 2]. The objective of these calculations is to classify the Licensing Basis Events (LBEs). However, this work has certain limitations: (1) it mainly relied on component reliability data from PWRs, and (2) it focused on specific components such as blowers and the off-gas system.

In this work, a preliminary estimation of MSR component failure rate was carried out based on MSRE system and component performance record [3]. Also, the study described the Frequency-Consequence (F-C) target curve proposed by Nuclear Energy Institute (NEI) for the Licensing Modernization Project (LMP), outlining the intended use of component reliability data for MSR licensing.

2. Methods and Results

2.1 LMP and F-C target curve

The U.S. Department of Energy (DOE) is supporting the LMP to enhance the regulatory framework for advanced reactor designs. Led by Southern Company and backed by DOE, the LMP aims to address regulatory barriers by updating technical licensing requirements and establishing a new pathway for design safety evaluations [4]. As shown in Fig. 1, NEI, a supporting institution, proposes a logic chart identifying and evaluating LBEs alongside design evolution to prepare licensing documents. Also, insights from the review of existing regulatory documents inform the creation of the F-C target curve, positioned on the right-hand side of Fig. 1. LBE categories are decided based on the event sequence frequency of occurrence per plant-year (corresponding to y-axis) and 30-day total effective dose equivalent at exclusion area boundary (corresponding to x-axis). The frequency range of LBE categories are listed in Table 1.

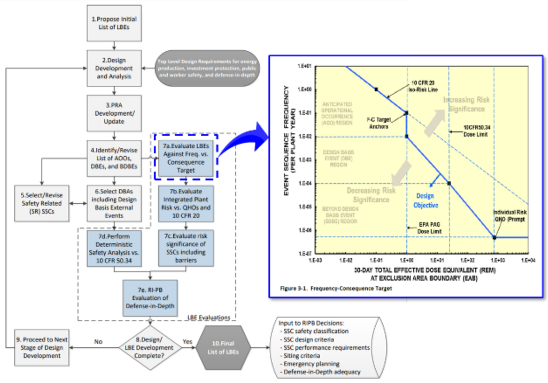

Fig. 1. A flow scheme of evaluating LBEs proposed by NEI and an example of F-C target curve for categorizing LBEs.

Table 1. LBE categories and frequency range [5].

Event category	Event sequence frequency (Plant per year)
AOO (Anticipated Operational Occurrence)	$> 10^{-2}$
DBE (Design Basis Event)	10^{-2} to 10^{-4}
BDBE (Beyond Design Basis Event)	10^{-4} to 5×10^{-7}

In order to estimate event sequence frequency, it is essential to consider component reliability, as illustrated in Fig. 2. Neglecting this aspect would hinder the determination of LBE categories and the development of mitigation strategies to prevent accident, thereby complicating the licensing process.

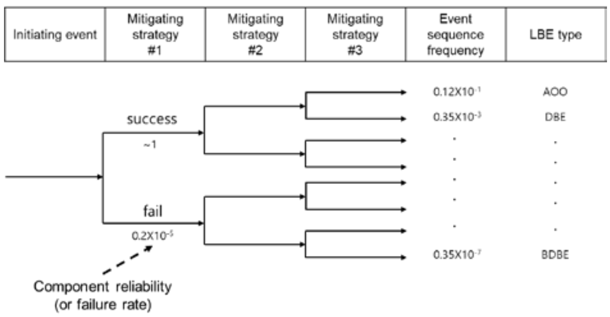

Fig. 2. An example of event tree analysis to classify LBE in accordance with component reliability.

2.2 Molten Salt Reactor Experiment

The MSRE, a 7.4 MW_{th} test reactor, simulated the neutronic kernel of a liquid fluoride thorium reactor. However, the thorium breeding blanket was omitted for engineering testing. It primarily used uranium-235 and later uranium-233 fuel, with heat dissipation facilitated by air-cooled radiators. Beginning with the loading of salt into tanks on October 24, 1964, key events included the circulation of fuel salt through the core on January 12, 1965, and achieving first criticality with U-235 on June 1, 1965 [3]. Upon its shutdown in December 1969, the MSRE had accumulated 13,172 equivalent full-power hours of operation. Throughout this period, the fuel system circulated fuel salt for 21,788 hours, while the coolant system circulated coolant salt for 26,076 hours during both U-235 and U-233 operation, as indicated in Table 2.

Table 2. Accumulated MSRE operating data [3].

	U-235 Operation	U-233 Operation	Total
Time Critical (hrs)	11,515	6,140	17,655
Integrated Power (Mw-hrs)	72,441	33,296	105,737
Equivalent Full-Power Hours	9,005	4,167	13,172
Salt Circulating Time (hrs)			
- Fuel Loop	15,042	6,746	21,788
- Coolant Loop	16,906	9,170	26,026
Helium Circulating Time (hrs)			
- Fuel Loop	4,046	3,384	7,430
- Coolant Loop	3,172	1,535	4,707

ORNL published "MSRE Systems and Components Performance" (TM-3039) [3].in June 1973, providing a high-level overview of MSRE operation, including both intended and unintended interruptions of operations. In the document, the causes of interruptions and related activities to address them are revealed. With these records, MSRE performance-based component failure rate was analyzed.

2.3 MSRE performance-based component failure rate

Leveraging the operational history of ORNL’s Molten-Salt Reactor Experiment (MSRE) could expedite the licensing process for modern salt system designs. Previously Utilizing operational records from EBR-I and EBR-II, the Liquid Metal Engineering Center under the U.S. Atomic Energy Commission (predecessor of the U.S. NRC) published the “Failure Data Handbook for Nuclear Power Facilities”, which provide the failure rate of Liquid Metal Fast Breeder Reactors (LM-FBRs) [6]. Both reactors collectively operated for about 16,000 equivalent full-power hours. Considering this example, it is reasonable to employ MSRE operation records for assessing component reliability.

Table 3 shows the estimation of MSR component failure rate derived from MSRE component performance record. According to TM-3039, a total of 163 interruptions were documented between 1966 and 1969 [3]. In this period, 17,425 hours were operated with the reactor being critical [3]. Planned interruptions, such as those for maintenance and experimental purposes, were excluded from the analysis to ensure a more accurate estimation of component failure rate. Additionally, interruptions associated with fuel processing and electrical connections were not considered in the analysis. Instead, the focus was primarily on evaluating the reliability of the salt circulation system and the off-gas system.

In this study, any issues resulting in equipment malfunction were counted as failure, even if the term "failure" was not explicitly used in ORNL’s TM-3039. Since the design of MSRs was not highly advanced worldwide, a conservative approach to assess component reliability is necessary.

$$\lambda = \frac{k}{T} \quad \text{(Eq.1)}$$

λ = failure rate (hr^{-1})
k = number of failures
T = total operation time (hr)

The failure rate was calculated using Eq.1, which divides the number of failures recorded in TM-3039 by the total operating time of the MSRE between 1966 and 1969.

Table 3. MSRE Performance based MSR component failure rate.

System	Component	Failure rate (hr^{-1})
Fuel System	Fuel pump	1.148×10^{-4}
	Drain tank space cooler	5.739×10^{-5}
	Reactor cell space cooler	1.722×10^{-4}
	Drain tank vent check valve	5.739×10^{-5}
	Overflow tank vent line	1.148×10^{-4}
	Freeze valve	1.722×10^{-4}
Coolant System	Coolant pump	4.017×10^{-4}
	Blower & radiator	7.461×10^{-4}
Off-gas System	Off-gas line	8.608×10^{-4}
	Equalizer line (drain and fuel tank)	1.148×10^{-4}
	Charcoal bed	3.443×10^{-4}
	Coolant off-gas line	2.869×10^{-4}
Fuel and coolant pump lube oil system	Coolant oil flow switch failure	1.722×10^{-5}
	Coolant oil valve leak	1.148×10^{-4}
Instrumentation	Fuel flow indicator	2.296×10^{-4}
Human error	-	6.887×10^{-4}

In Table 3, the off-gas line is noted as having the highest failure rate among components in the MSRE. This is primarily attributed to plugging issues within the off-gas line connecting to the fuel pump. Over time, as experimental knowledge accumulated, ORNL implemented various adjustments and enhancements to the heating system of the off-gas line in attempts to rectify these issues. Additionally, the blower posed challenges within the MSRE system. However, given that the current MSR concept under consideration now incorporates a power conversion system for electricity production, such issues, including those related to the blower encountered in the MSRE, are no longer of significant concern.

3. Conclusions and Further Works

This paper highlights the importance of establishing a component reliability database for advanced reactors. MSRs are focused in this study and the selected component reliability is first estimated by using historical data from the MSRE. The analysis of MSRE's operational records provided a preliminary estimation of failure rates for key components, as detailed in Table 3, revealing critical insights into MSR technology's unique challenges. These findings are crucial step for refining PRA methodologies and supporting the licensing modernization efforts for MSRs. Ultimately this effort will contribute to enhancing the safety and feasibility of advanced nuclear reactor technologies.

Given that MSRs have only one operational experience, determining their failure rates solely based on historical data from the MSRE poses statistical challenges for PRA. Therefore, future investigations will focus on in-depth analyses by coupling component reliability data from PWRs and similar industries to compare with the works of ORNL and Southern Company. Through these future analyses, technical issues specific to MSRs are anticipated to be identified, ensuring that MSR technology satisfies the quality assurance standards expected of PWRs. This approach will be instrumental in addressing MSR's unique challenges and advancing the safety and feasibility of advanced nuclear reactor technologies.

ACKNOWLEDGEMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (RS-2023-00259713).

REFERENCES

[1] Afzali, Amir. (2019). *Molten Salt Reactor Experiment (MSRE) Case Study Using Risk-Informed, Performance-Based Technical Guidance to Inform Future Licensing for Advanced Non-Light Water Reactors*. Southern Company, Sep 2019.

[2] Flanagan, G. F., Chisholm, B., Krahn, S., & Mays, G. T. (2018). *A New Look at Licensing Basis Events for the Molten Salt Reactor Experiment* (No. ORNL/TM-2018/788). Oak Ridge National Lab.(ORNL), Oak Ridge, TN (United States).

[3] Guymon, R. H. (1973). *MSRE systems and components performance* (No. ORNL-TM-3039). ed. and comp.; Oak Ridge National Lab., Tenn.(USA).

[4] Wayne L. Moe, "Licensing Modernization Project for Advanced Reactor Technologies: FY 2018 Project Status Report(INL/EXT-18-46151)", Idaho National Laboratory, Sep 2018.

[5] Moe, W. L. (2019). *Risk-Informed Performance-Based Technology. Inclusive Guidance for Advanced Reactor Licensing Basis Development (NEI 18-04)* (No. INL/EXT-19-55375-Rev000; NEI-18-04). Idaho National Lab.(INL), Idaho Falls, ID (United States); Nuclear Energy Institute, Washington, DC (United States).

[6] Liquid Metal Engineering Center. (1970) Failure Data Handbook for Nuclear Power Facilities: a Guide for the Design, Construction, and Maintenance of Nuclear Power Plants from a Reliability Improvement Standpoint. Volume I. Failure Data and Applications Technology. U.S. Atomic Energy Commission. (United States)