Review of Phenomena Identification and Ranking Table (PIRT) in MSR and HTGR

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1. Introduction

The active development of advanced reactors has been driven by their inherent advantages over conventional Light Water Reactors (LWRs), such as enhanced inherent safety and superior thermal efficiency achieved using diverse coolants. Given the substantial differences in design and operational characteristics, the existing knowledge is not applicable to advanced reactors. Some PIRTs have been established by Oak Ridge National Laboratory (ORNL) for the Molten Salt Reactor (MSR) and by the U.S. Nuclear Regulatory Commission (U.S. NRC) for the High Temperature Gas Reactor (HTGR) [1, 2]. This serves as a critical tool for analyzing the importance and knowledge level of various phenomena.

Given the fundamental differences in design and operating principles between MSRs and HTGRs, such as their coolant and fuel types, the manifestation of phenomena and key safety evaluation outcomes may vary even under identical accident scenarios. Therefore, it is essential to clearly identify these design-specific differences to ensure consistency in the licensing of advanced reactors.

In this study, we conducted a literature review to compare the importance and knowledge levels in major accident scenarios, utilizing PIRT analyses of MSRs and HTGRs. The findings of this review are used to identify reactor-specific development needs. Ultimately, this work is intended to inform licensing readiness and the development of tailored technology strategies for each advanced reactor type.

2. Evaluation Methods and analyses

ORNL and the NRC have developed Fundamental Safety Function (FSF) PIRTs to identify and prioritize phenomena such as radioactive material release, heat removal, and undesired criticality [1, 2]. The PIRT methodology established by ORNL is adopted for the evaluation. The FSFs are structured as follows [1]:

1. Limitation of radioactive material release
2. Removal of heat (from the reactor and from spent fuel/waste storage)
3. Control of reactivity

Following four stages of the PIRT process, the knowledge level and importance are ultimately evaluated.

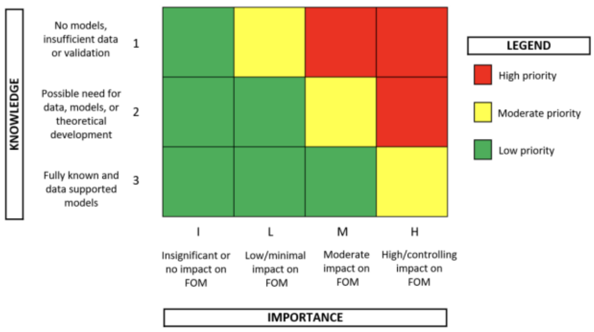

Fig.1 Results matrix for research prioritization [1].

Reactor types have different criteria for importance, which vary based on how each accident scenario affects the Figure of Merit (FOM). In addition, the knowledge level is determined by the availability of experimental data, models, and validated analytical tools for specific phenomena [1].

2.1. MSR PIRT

For the MSR, the excessive number of Licensing Basis Event (LBE) scenarios were condensed into six generic scenarios.

Table 1. Evaluation scenarios (MSR) [1]

I	Salt spill accident
II	Dynamic system thermal / hydraulic / power response
III	Water-molten salt interactions
IV	Accidental criticality external to the core region
V	Emergency response system failures
VI	Radwaste management system failures

Through the six scenarios, a total of 25 phenomena were identified, among which 20 were related to salt release accidents [1]. This indicates that salt release accidents can encompass major phenomena from other scenarios during the accident progression. A salt release may result in the formation of a pool of high-temperature liquid fuel salt outside the primary system, which constitutes a risk factor associated with the FSFs. Accordingly, this work focuses on accidents characterized by the formation of high-temperature liquid fuel salt pools in salt release events.

2.2. Salt release accident: Molten salt pool

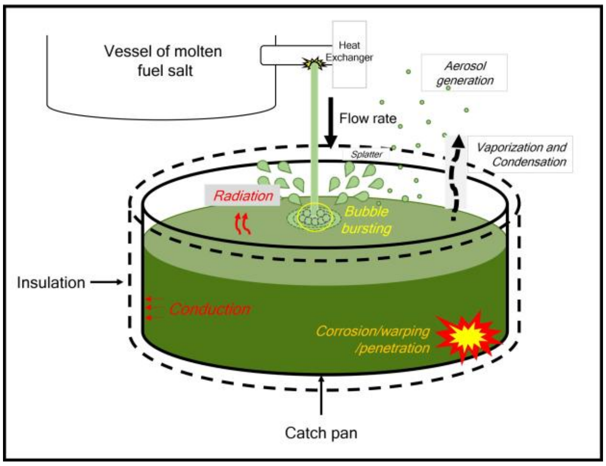

Fig.2 Conceptual design of engineering-scale molten salt spill test apparatus.

In this scenario, we discuss phenomena occurring during the formation of a molten salt pool inside the external cell due to fuel salt leakage. Fig.2 shows a model of molten salt pool formation, focusing on salt diffusion, vaporization, and condensation. These processes are the main causes of radioactive material leakage to the outside [3]. There are also cases proposed to support safety assessments for MSR licensing [3]. Furthermore, items evaluated as FOM were evaluated in the same manner as FSF [1].

2.2.1 I09: Solubility of constituents within the salt pool

The scenario mentioned here, I09, belongs to category I, which is defined in Table 1. In this I09 scenario, after the formation of the salt pool, the resulting physics-chemical states are examined, and the evaluation is performed using the FOM [1].

Table 3. Phenomena ranking table 1 [1].

	Importance	Knowledge	Priority
FOM-1	H	2	
FOM-2	M	1	
FOM-3	M	1	

The behavior of fission products (FPs) in a MSR system is a key risk factor. For example, uncertainty about how the inert gas xenon (Xe) behaves when bubbles form could significantly increase external radiation exposure, as it relates to the release of radioactive material.

Chen and Brooks analyzed Simulink simulations and actual experimental data to accurately understand the behavior of Xe [4]. In startup scenarios, experimental data and simulation results showed strong consistency, with Fig.3(a) accurately describing the transient phenomenon. However, shutdown scenarios were less precise [3]. As shown in Fig.3(b), the simulation failed to capture the expected "iodine pit" phenomenon, showing a significant discrepancy compared to the experimental data [3].

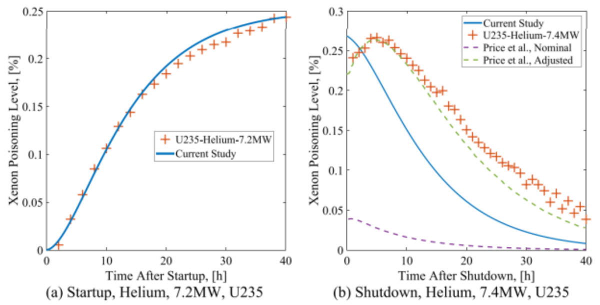

Fig.3 Comparison between simulation and experimental xenon transients in Molten Salt Reactor Experiment (MSRE) [4]

The Simulink model effectively predicted the steady-state and transient xenon behavior of the MSRE. However, its failure to predict phenomena like iodine pits suggests a gap in our understanding of either the xenon-graphite interaction or the xenon removal system in the pump bowl. These findings highlight the need for more research into the underlying transport mechanisms [4].

An additional phenomenon that was observed was the accumulation of insoluble solid particles (e.g., precious metals) in the pump-bowl [1]. These phenomena underscore the imperative for a comprehensive understanding of the solubility of nuclides in molten salt [1]. Additionally, the accumulation and precipitation of FPs can result in localized heat generation and control of reactivity [1]. However, experimental data concerning the deposition location, chemical form, solubility, and specific heat generation rate of FPs, excluding inert gases, are extremely limited.

2.3 HTGR PIRT

In the case of HTGRs as well, major scenarios were identified through LBEs [2].

Table 4. Evaluation scenario (HTGR) [2].

I	Normal operation
II	General Loss of Forced Circulation (LOFC)
III	Pressurization - LOFC
IV	Depressurization - LOFC
V	Air ingress (After D-LOFC)
VI	Reactivity transients-including anticipated transients without scram (ATWS),
VII	Processes coupled via IHX (IHX failure with molten salt), and
VIII	Steam/Water ingress.

There are eight major scenarios, and through the evaluation of a total of 11 panel members, 75 phenomena were identified and compiled into a comprehensive evaluation table [2]. This section will focus on Loss of Forced Circulation (LOFC), which considers the behavior of coolants to be of importance [2]. LOFC accidents progress in the order of Pressurization and Depressurization, with the level of importance increasing toward the latter stages. This work focuses on P-LOFC, which occurs immediately after the trip of the coolant circulator.

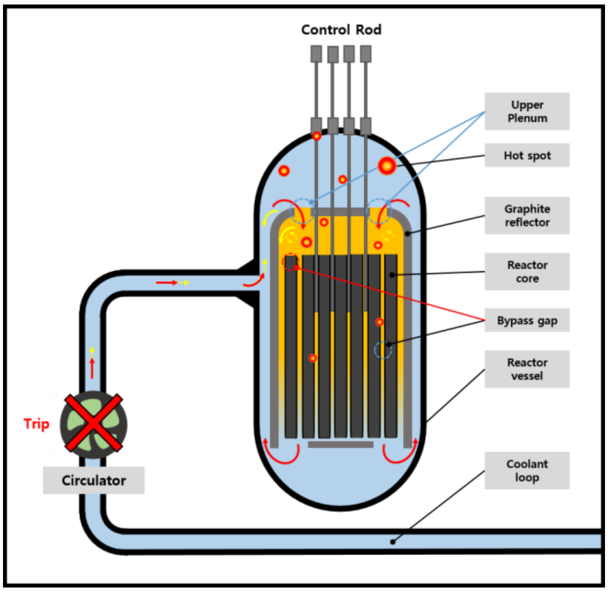

Fig.4 Conceptual design of engineering-scale P-LOFC.

In addition, evaluation criteria were applied in place of FOMs, and they are defined as follows.

Table 5. Figure of Merit (HTGR) [2].

1	Dose at the site boundary or radioactive release from the confinement structure;
2	Worker dose
3	Fuel failure fraction during events (accidents)

However, the evaluation criteria were not clearly specified in the PIRT, FOM-specific analyses are not addressed in this work.

2.3.1 III04: Reactor core coolant flow distribution

The scenario mentioned here, III04, belongs to category III, which is defined in Table 4. For this scenario, evaluations were conducted by only 8 panel members, and the results can be summarized as follows [2]. The asterisk (*) in 'Total analyses' indicates a point of contention.

Table 6. Phenomena ranking table 2 [1, 2].

Panels	Importance	Knowledge	Priority
Total analyses	H	2*	■ (red)
ORNL 1	H	1	■ (red)
CEA, France	H	2	■ (red)
SNL	H	2	■ (red)
INL	H	1	■ (red)
ORNL 2	M	2	■ (yellow)
ORNL 3	M	2	■ (yellow)
ANL	H	1	■ (red)
Texas A&M	H	2	■ (red)

In HTGRs, the Coolant flow distribution represents the most significant thermal-hydraulic phenomenon, determining the temperature distribution of fuel and structural components. Its importance is thus rated as "High" [2]. In the context of this accident scenario, a series of phenomena, including coolant flow redistribution, backflow, stagnation, and natural circulation, transpire, leading to the concentration of the heat load on the upper plenum and upper reactor vessel head. [2]. Specifically, the downward bypass flow exerts a dominant influence, impeding heat dissipation and giving rise to localized hot spots. These hot spots exert a direct effect on the maximum fuel temperature and the thermal environment of the structures surrounding the control rod drive assembly (CRD) [2]. However, the extent of knowledge concerning these phenomena is evaluated as "level 2*" or below [2]. While the progression and flow of the LOFC scenario are accurately understood, there was contention regarding the difficulty in precisely identifying and tracking key physical properties [2]. This is due to the fact that the influence of bypass flow, which bypasses the core, on heat removal has only been experimentally verified to a limited extent [2]. Furthermore, the phenomenon of laminar flow in the heat transfer layer near the wall is challenging to predict, and minute geometric changes within the core have a significant impact on flow and heat transfer distribution [2]. Recently, a 1D fluid-3D solid heat conduction model was employed to reflect detailed modeling [5]. In addition, P-LOFC accident simulations demonstrated that the temperatures of the primary structures of the HTGR were maintained within safe limits [5].

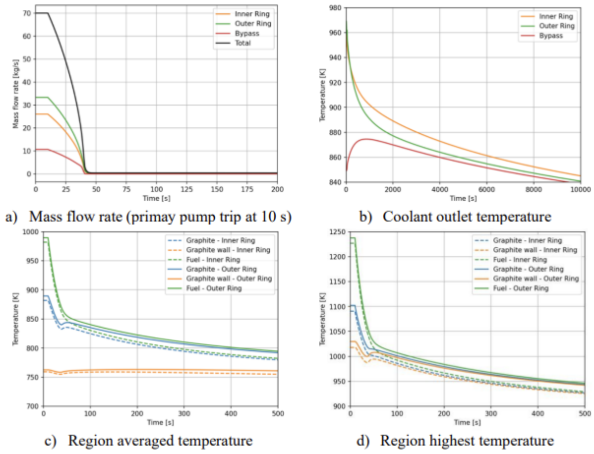

Fig.5 P-LOFC simulation results – short term [5]

The results in Fig. 5 demonstrate our ability to predict complex thermal-hydraulic behaviors, such as bypass flow during the initial P-LOFC transient. This was made possible by new, computationally efficient simulation methods, as shown by the mass flow and coolant temperature data. This is a major step forward, filling critical gaps in reactor safety analysis and leading to more reliable designs and licensing processes.

3. Conclusion

The present study sought to make a comparison and evaluation of the importance and knowledge level of key safety phenomena in major accident scenarios. This was achieved by means of PIRT analysis of MSR and HTGR. This approach enabled the interpretation of how key safety phenomena manifest in relation to the distinctive design characteristics inherent in each reactor.

- In the context of MSR, the behavior and solubility of FPs during a fuel salt spill accident have been identified as a key safety phenomenon. Consequently, further research is necessary to obtain experimental data on the physico-chemical behavior of FPs and to advance the development of models for its precise prediction.
- The distribution of coolant flow within the core has been identified as the most significant thermal-hydraulic phenomenon during a P-LOFC event in HTGRs. Consequently, conducting meticulous experimental studies is imperative to substantiate intricate, multifaceted thermal-fluid phenomena.

Acknowledgenmet

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