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Linking Design Basis Event (DBE) Analysis with Phenomena Identification Ranking Table (PIRT) of Molten Salt Reactors

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1. Introduction

The employment of liquid fuel sets Molten Salt Reactor (MSR) designs apart from other next generation nuclear reactors. This results in the notable distinction of safety characteristics from the solid-fuel nuclear power plants. Leveraging these unique safety attributes, numerous MSR designs are currently under active development.

Oak Ridge National Laboratory (ORNL) has established the MSR Phenomena Identification and Ranking Table (PIRT), which is designed to have broad applicability across various MSR designs [1]. This achievement is built upon the proven track record of the successful and safe operation of the Molten Salt Reactor Experiment (MSRE), while also incorporating design elements from eight distinct MSR concepts currently in the developmental phase [1].

The US Department of Energy (DOE) leads the Technology Inclusive Content of Application Project (TICAP) to streamline the regulatory pathway for advanced nuclear technologies [2]. Collaborating with industry and the US Nuclear Regulatory Commission (NRC), TICAP develops the guidance for specific sections of license applications, simplifying the approval process while maintaining safety and promoting innovation [2]. Under the TICAP initiative, the design and safety features of the Molten Chloride Reactor Experiment (MCRE) are being reviewed and evaluated. Through the MCRE TICAP tabletop exercise in 2021, a preliminary set of Licensing Basis Events (LBEs) was selected and reviewed by the MCRE design team [2].

In this study, a preliminary examination of the development of a chloride salt-based MSR PIRT was carried out through a literature review. In this study, a connection between ORNL MSR PIRT and the initiating events of MCRE chosen during the MCRE TICAP tabletop exercise is established to ultimately develop MCRE PIRT with more detail. Given the substantial number of initiating events, this work specifically focuses on the investigation of Design Basis Events (DBE) from all licensing basis events.

2. Methods and Results

2.1 Ranked phenomenon in ORNL MSR PIRT

ORNL developed MSR fundamental safety function PIRT to identify and rank the phenomena that could lead to a release of radioactive material, inhibit heat removal, or create an unwanted criticality accident. The framework aims to achieve three fundamental safety functions: i) limiting the release of radioactive material, ii) removing heat from the reactor and waste storages, and iii) controlling reactivity [1].

The ORNL PIRT team identified 140 potential LBEs for different MSR types in a 2019 workshop [3]. Due to time constraints, these were grouped into general scenario categories. To streamline analysis for various designs, common generic scenarios were developed. The ORNL PIRT aims to be broader, and more performance based than the previous PIRT efforts, ensuring applicability to the diverse range of MSR designs under development. The ORNL PIRT created six generic scenario categories, combining expert judgment, postulated initiating events, and accident progression models, as shown in Table 1 [1].

Table 1. six generic scenario categories in ORNL fundamental safety function PIRT [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

Within the context of the six generic scenario categories, the process of elicitation was undertaken to identify associated phenomena. This effort yielded a total of 25 elicited phenomena, with 20 of them impacting the assessment of salt spill accidents as listed in Table 2. The majority of these phenomena pertain to salt spill accidents specifically. Notably, scenario categories III and V did not yield any identified phenomena through this elicitation process since these two categories are largely depending on the system designs [1].

Table 2. Ranked phenomenon in ORNL MSR PIRT. [1]

ID #	Phenomenon name
I01	Base/floor material thermochemical interactions with molten salt (e.g., concrete, steel)
I02	Radionuclide inventory (mass) or activity, speciation, and distribution)
I03	Mass/volume and energy of molten salt (fueled salt) pool
I04	Initial temperature of molten salt pool and structures within the volume
I05	Molten salt spreading
I06	Salt fragmentation
I07	Generation of dross/crust layer on surface of salt pool
I08	Vaporization and release of salt components and radioactive material from the surface of a molten salt pool
I09	Solubility of constituents within the salt pool

I10	Reactions with fuel salt and atmosphere
I11	Bubble rupture and splash at the surface of a molten salt pool
I12	Beta-recoil droplet release
I13	Mixing and fluid dynamics within the molten salt pool
I14	Mass transport and diffusion of radionuclides within the molten salt pool and to the surface of the pool
I15	Heat transfer within the molten salt pool
I16	Heat transport from pool to cell atmosphere and structures
I17	Mixing and convection of air/gas flow with the atmosphere
I18	Radionuclide transport and interactions within the cell atmosphere
I19	Radiolysis of salt, moisture in cell atmosphere, and concrete decomposition or water incursion into cell
I20	Water–salt interactions, including hydrolysis in salt
II01	Over-temperature, over-pressure conditions
II02	Leak/rupture of primary heat exchanger tube and radionuclide release to secondary systems
IV01	Unrecognized accumulation of fissile material
IV02	Overcooling leading to precipitation and accumulation
VI01	Radwaste and other non-fuel radioactive gas/fluid system failures

2.2 MCRE and LBEs in TICAP MCRE

2.2.1. MCRE overview

The MCRE project is a 200 kW_{th} nuclear experiment. The primary objective of the MCRE project is to reduce the technical, regulatory, and operational/human factors risks of the MCFR technology, and ultimately support the MCFR Commercial design. The experimental system will not have power conversion equipment and will not rely on traditional solid fissile material for fuel. The intention of the project is to demonstrate the operation of molten fuel salts at temperatures sufficient to drive traditional subcritical and super-critical Rankine cycles, CO_2 power cycles, or other less conventional power cycles [4]. Once operating, MCRE will be the first critical fast-spectrum circulating fuel system using chloride salt [4].

2.2.2. LBEs in TICAP MCRE tabletop exercise

A total of 47 initiating events were designated as Licensing Basis Events (LBEs) during the MCRE TICAP tabletop exercise. These events have been categorized into groups, which include high power generation, loss of heat removal, mechanical failures, excessive heat removal, chemical events, drain and load failures, and fuel storage failure. These events were chosen based on the reactor's knowledge at the time and past design experience [2]. The MCRE LBEs were systematically identified and the LBE category and frequency range are shown in Table 3.

Table 3. Event category and frequency range. [2]

Event category	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}

2.3 Categorizing ranked phenomenon

Once the scenario categories associated with each initiating event are identified, the corresponding phenomenon IDs for each initiating event can be also systematically classified. To simply link initiating events and phenomenon IDs, parameters affecting reactor safety are selected: fuel temperature, reactivity insertion, over pressure, mechanical failure of non-fuel system, radioactive material leakage, fuel salt leakage, and impurity of fuel salt.

The parameters and their corresponding phenomenon ID numbers are listed in Table 4. The detailed descriptions for each phenomenon are in Appendix B of the ORNL MSR PIRT report [1]. It is noteworthy that the leakage of fuel salt is relevant to all phenomena in salt spill accident (Scenario category I).

Table 4. Categorization of ranked phenomenon with proposed parameters.

Parameter		Phenomenon ID number
Fuel temperature		I09, I13, I14, I15
	High	I08, I11, II01
	Low	I07, IV02
Reactivity insertion		IV01
Over pressure		II01
Mechanical failure of non-fuel system		VI01
Radioactive material leakage		I02, I14, I17, I18, I19
Fuel salt leakage		I01~I20 (all applicable in scenario category I)
Impurity of fuel salt		I07

2.4 Results and discussion

Table 5 presents the classification of DBE initiating events along with the corresponding scenario category and phenomenon ID shown in Table 4. While scenario categories have been classified, there are initiating events for which phenomenon IDs have not been categorized. This is because a variety of initiating events are concerned with thermal-hydraulics, yet there are only two phenomena under the scenario category II (Dynamic system thermal / hydraulic / power response). For example, once cold fuel enters the core, not only does the temperature decrease, but the properties of the fuel salt may also alter, potentially influencing the fuel circulation. Thus, the additional clarification of phenomena might be necessary to address the inconsistency.

Table 5. Classification of DBE initiating events and the corresponding scenario category and phenomenon ID.

Initiating events (group in bold)	LBE Category	Scenario Category	Phenomenon ID
High Power Generation			
Fuel Precipitate Enters the Core	DBE	I, IV	I07, IV01
Cold Fuel Enters the Core	DBE	I, II	I07, I09, I13, I14, I15
Loss of Heat Removal			
PCS Gas Break outside	DBE	I, II, VI	I07, I09,

bunker			I11, I13, I14, I15, II01, VI01
PCS Gas Break Inside Bunker	DBE	I, II, VI	
Loss of All PCS Cooling Coils	DBE	I, II	I07, I09, I11, I13, I14, I15, II01
Mechanical Failures			
Pump Seal Failure	DBE	VI	VI01
Cover Gas Supply Line Break or Dewar Leak	DBE	VI	VI01
Cover Gas Purge Line Break	DBE	VI	VI01
Vessel Leak to PCS Leg	DBE	I	I01 ~ I20
Overflow Line Break	DBE	I	I01 ~ I20
Chemical Events			
Fuel Salt Thermo-Physical Degradation	DBE	I	I04, I06, I07, I09, I13, I19
Fuel Precipitates on the Vessel Wall	DBE	IV	IV01
Drain and Load Failures			
Fuel Tank Leak	DBE	I	I01 ~ I20

3. Conclusions and Further Works

The preliminary study to develop chloride salt based MSR PIRT has been conducted. Due to the limited information available regarding chloride salt-based MSR, the reference was made to both the MCRE TICAP tabletop exercise and the ORNL MSR PIRT. By using the Design Basis Events (DBE) selected in the MCRE TICAP tabletop exercise, scenario categories and ranked phenomena from the ORNL MSR PIRT were re-evaluated. This dataset not only aids in PIRT development of molten salt chloride salt reactor but also classifies the phenomenon list based on DBEs, making it potentially useful for the chloride salt-based MSR design. Furthermore, this study revealed the need for detailed phenomenon clarification, particularly in relation to thermal-hydraulic aspects.

In the future, there are plans to comprehensively align MCRE's LBEs, such as AOO and BDBE, with the ORNL MSR PIRT. Additionally, specific efforts will be made to identify thermal-hydraulic phenomena requiring detailed clarification for the development of MSR PIRT.

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