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

Phenomena Identification for Accident Condition of Molten Salt Reactor

Byeonghee Lee*, Sung-Il Kim
Korea Atomic Energy Research Institute, Daedeokdaero 989-111, Yuseong, Daejeon, Korea 34057
*Corresponding author: leebh@kaeri.re.kr

1. Introduction

Molten salt reactor (MSR) is a promising candidate of next generation nuclear reactors because of its intrinsic safety. The reactor is operated in low-pressure condition and the large negative feedback coefficients of the core enables self-regulation of reactor power by a reactivity insertion event. In addition, the reactor has relatively less fissile material in the fuel salt comparing to a PWR, because the off-gas system continuously remove the fission products from the fuel during normal operation.

The conventional term of severe accident does not exist in a MSR system because the fuel is already molten during normal operation. Even if the fuel salt escape the boundary of reactor system, it rapidly solidifies by the low temperature of atmosphere, thereby minimizing the release of fission products. Nevertheless, there's still a change that the fission product escape from the fuel salt and be released out of the containment until the spilled salt is cooled down and is solidified. Therefore, salt spill accidents are considered as the most significant event in the MSR system in terms of the public safety.

Korea atomic energy research institute (KAERI) and several industrial companies are currently developing a 100MWth MSR using chloride salt fuel. To develop models to analyze the accident consequence by salt spill accidents and to setup a safety strategy for the reactor system, major phenomena followed by the accident need to be identified clearly.

In this article, the major phenomena expected to occur during salt spill accident in the MSR system are suggested and grouped by hierarchal level,

2. Phenomena Categories

Oak ridge national laboratory (ORNL) developed the phenomena identification and ranking table (PIRT) for general MSR design referencing previous PIRT reports [1-4]. The report summarize the important phenomena during accidents generally applicable for various MSR design, and suggested their importance and their knowledge level based on the available information of MSR research, mainly from the MSRE operated in 1960's in ORNL[5]. The phenomena are categorized based on the different accident scenario groups, and many of them are in the category of salt spill accident.

For the MSR currently under development by KAERI consortium, two different PIRTs are being developed, one for the system design and the other for the model development for accident conditions. The PIRT considered in this article is latter, for the accident condition of the MSR, which cause the fission product release out of the reactor system.

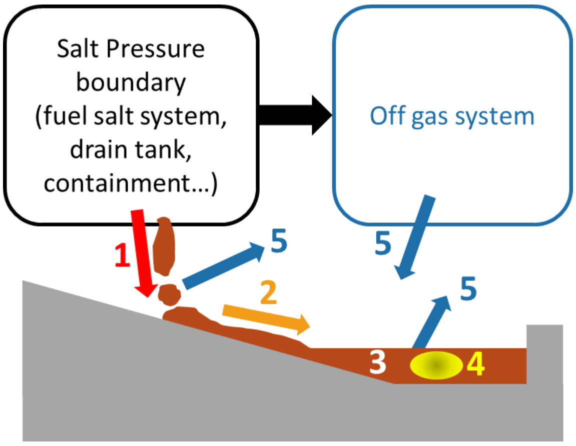

Fig. 1 Schematic categorization phenomena by salt spill accident

The phenomena identified for the accident condition starts from the salt spill accident, or similar accident which induces the fission product release out of the reactor system. The other possible scenario other than salt spill accident is the rupture of off-gas system, which causes a fissile gas release out of the reactor pressure boundary.

Figure 1 shows the semi-sequential categorization of phenomena during the events. First, the fuel salt is ejected from the reactor system by rupture of the pressure boundary (1). Then, the spilled fuel salt flows and exchange heat and mass with surroundings (2). The spilled salt can form a salt pool at a certain location (3), and then the recriticality can be a concern in the salt pool (4). The fission products (FPs) can be released either from the salt, or from the off-gas system (5).

Table 1 Hierarchy of phenomena identification during accident in MSR

Level 1	Level 2
Salt behavior in system	Not interested in accident condition
A. Salt behavior out of system	A1. Rupture of salt containing system
	A2. Salt discharge
	A3. Salt spreading
	A4. Thermodynamics in Salt pool
	A5. Salt chemistry
	A6. Recriticality in salt pool
B. Fission product (FP) behavior	B1. FP inventory
	B2. FP release
	B3. FP Transport
	B4. FP Chemistry

Table 1 shows the categorization of phenomena group with the sequential behaviors of salts and FPs. Since we only consider the phenomena after the salt spill accident or the off-gas system rupture, the in-system behavior of salt is not interested and is the scope of the other PIRT, the one for the system design.

3. Phenomena Identification

Table 2 shows the specific phenomena categorized in "A. salt behavior out of system". The phenomena mostly deals with the heat and mass transfer of spilled salt, including the chemical reaction of the salt with the other material such as structures, moistures, and gases. The chance of criticality in the salt pool by fissile material accumulation or moderation/reflection of neutron are also included in the salt behavior.

Table 2 Phenomena related salt behavior out of system

Level 2	Level 3
A1. Rupture of salt containing system	Initial temperature and pressure
	Initial decay heat level
	Rupture mechanism (fatigue, mechanical rupture)
	Rupture position and size
A2. Salt discharge	Mass flow rate of discharged salt
	Splash and fragmentation
	Erosion by salt jet impingement
A3. Salt spreading	Fluid dynamics of liquid fuel salt (spreading)
	Convection heat transfer by salt flow
	Solidification/melting at the structure-salt interface
	Crust formation/remelting
	Radiation between molten salt and the environment
A4. Thermodynamics in Salt pool	Mixing and fluid dynamics within the molten salt pool
	Heat transfer within the molten salt pool
	Thermal stratification or layer seperation
A5. Salt chemistry	Water-salt interaction including hydrolysis
	Reaction of salt with structural material (metal)
	Reaction of salt with structural material (non-metal)
	Reaction of salt with atmosphere
A6. Recriticality in salt pool	Overcooling leading to precipitation and accumulation
	Unintended fissile material accumulation
	Unintended moderation and reflection of neutron

Table 3 Phenomena related fission product behavior

Level 2	Level 3
B1. FP inventory	Initial radionuclide inventory, redioactivity, distribution in salt
	Radionuclide inventory in the off-gas system
B2. FP release	FP release from gas volume (including off-gas system)
	FP release by splashing salt droplets
	Vaporization and release from bulk fuel salt
	Bubble rupture & spash from the salt pool surface
	Solubility of FPs in the salt pool
	Beta-recoil droplet release
B3. FP Transport	Transport of solid FP (noble metal)
	Mass transfer and diffusion of FPs in the salt pool
	Aerosol dynamics (agglomeration, deposition, etc)
	FPs transport in the air
B4. FP Chemistry	FP chemistry in the salt pool (chemical speciation)
	FP chemistry outside the salt pool
	Radiolysis of salt, water and the others

Table 3 shows the phenomena categorized in "B. FP behavior". The phenomena covers the initial inventory of FPs in the salt or in the off-gas system, and their release and the transport. The chemistries of FPs in the salt or in the surrounding air are also important phenomena determining the final FPs release to the environment.

All the phenomena identified in Table 2 and 3 are then planned to be ranked in terms of their importance and of their current available knowledge level, to determine the priority of research to develop the MSR system.

4. Summary

The important phenomena related to the salt spill accident or the similar severe event of MSR system were identified and grouped based on the hierarchal level. The top level of the hierarchy were the salt behaviors out of the system and the corresponding fission product behaviors.

Under the top-level categories, the relevant phenomena were identified and listed. The salt behaviors covers from the initial salt ejection from the system pressure boundary to the salt flow and the pool formation. The phenomena related to the recriticality are included in the category. The FPs behaviors covers from the intial inventory in the fuel salt or in the off-gas system, to the transport of them until they are released out of the final containment barrier.

The phenomena identified are then ranked by their importance and the current knowledge level, for the model development required for the MSR research.

Acknowledgement

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (RS-2023-00261295).

REFERENCES

[1] David E. Holcomb et. al. "Molten Salt Reactor Fundamental Safety Function PIRT" (ORNL/TM-2021/2176), Oak Ridge National Laboratory, 2021

[2] X. Sun, G.L. Yoder, R.N. Christensen, S. Shi, H-C. Lin, and S. Zhang, "Thermal Hydraulics Phenomena Identification and Ranking Table (PIRT) for Advanced High Temperature Reactor (AHTR)", IRP-14-7829, 2016

[3] David J. Diamond, Nicholas R. Brown, Richard Denning, and Stephen Bajorek, "Phenomena Important in Modeling and Simulation of Molten Salt Reactors", BNL-114869-2018-IR, April 23, 2018

[4] Hummel, E.W., Y.S. Chin, M. Yetisir, G.A. Glowa, "Phenomena Identification and Ranking Table (PIRT) for a Severe Accident in a Molten Salt Small Modular Reactor", Canadian Nuclear Laboratories, 153-120200-REPTf-033, February 2020

[5] Beall, S., P. Haubenreich, R. Lindauer, J. Tallackson, "MSRE Design and Operations Report, Part V, Reactor Safety Analysis Report", ORNL-TM-732, 1964