Design Concepts and Requirements of Passive Molten Salt Fast Reactor (PMFR)

Jae Hyung Park [a], Wonjun Choi [a], Jihun Lim[a], Taeseok Kim [a], Yonghee Kim[b], Youngsoo Yoon[c], Sangtae Kim[a], Sung Joong Kim[a,d]*
[a] *Department of Nuclear Engineering, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul 04763, Republic of Korea*
[b] *Department of Nuclear and Quantum Engineering, Korea Advanced Insitute of Science and Technology., 291 Daehak-ro, Yuseong-gu, Daejeon 34141, Republic of Korea*
[c] *Department of Materials Science and Engineering, Gachon University, 1342 Seongnam-daero, Sujeong-gu, Seongnam-si, Gyeonggi-do 13120, Republic of Korea*
[d] *Institute of Nano Science and Technology, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul 04763, Republic of Korea*
**Corresponding author: sungjkim@hanyang.ac.kr*

1. Introduction

In order to resolve the global climate crisis, the policies aiming carbon-neutrality have been established. CO_2 emission, the representative parameter measuring the environmental impact, has increased with the consumption of the fossil fuel such as coal, petrol, and natural gas [1]. In particular, the electricity production and transportation by fossil fuel contributed more than half of the total CO_2 emission in 2016. Accordingly, the energy sources for electricity production and transportation, which can substitute fossil fuel and reduce the CO_2 emission, have been highlighted.

Among the alternative candidates for electricity production, renewable energies such as solar, wind, and hydro energies release much less CO_2 than fossil fuel. However, their power densities are low and their efficiency can be affected greatly by climate and weather. In other words, the disadvantages such as inflexible site selection and large site area are expected. Thus, the hybrid energy system of renewable and nuclear power generation was proposed to cope with the electricity consumption [2].

In terms of the transportation, hydrogen, an alternative fuel, has been proposed to replace the fossil fuel because hydrogen exhibits high energy density and extremely low CO_2 emission. However, still many technical and economical concerns need to be resolved for the practical deployment of the hydrogen. Although several methods such as natural gas conversion and by-product hydrogen to produce hydrogen have been proposed, the limitations such as CO_2 emission and low output are the barrier for successful deployment. Accordingly, high temperature electrolysis by nuclear energy is proposed due to low CO_2 emission and high productivity.

As shown in Fig. 1, the efficiencies of electricity generation through supercritical CO_2 (SCO_2) Brayton cycle and hydrogen production by using high temperature electrolysis increase with the operating temperature [3]. To achieve the high efficiency of approximately 40%, the temperatures of higher than ~600°C is required. Among the nuclear reactor types, very high temperature reactor (VHTR) and molten salt reactor (MSR) can supply the intensive heat source, whose temperature exceeds 600°C. VHTR can ensure the high efficiency with the temperature of ~1000°C. However, the thermal density in the core is low due to low heat removal capability of He gas, the working fluid of the VHTR. Accordingly, the VHTR system is expected to be larger.

On the other hand, the operating temperature of the MSR ranges 600 to 700°C. Accordingly, the MSRs can secure sufficiently high efficiency over 40% despite the lower temperature than VHTR as shown in Fig. 1. In terms of the downsizing, the MSR is more advantageous than VHTR as the MSR does not require high pressurization. In addition, outstanding safety characteristics can be secured as MSR operates with the molten salt mixture of nuclear fuel and reactor coolant, which practically eliminates the possibility of severe accident.

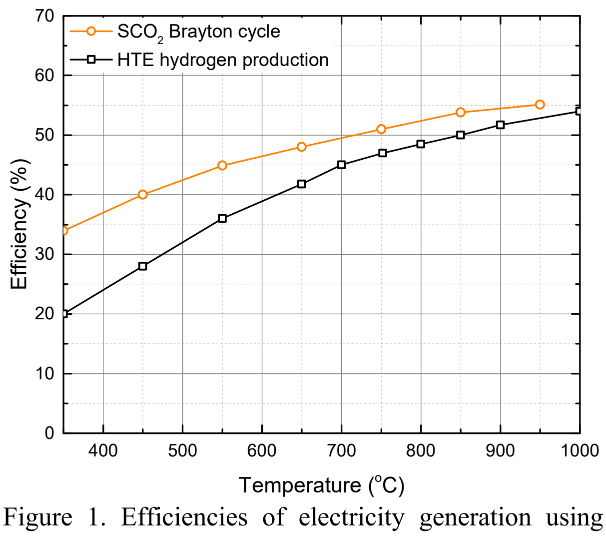

Figure 1. Efficiencies of electricity generation using SCO_2 Brayton cycle and HTE hydrogen production over wide operating temperature.

In this paper, the review of MSR was carried out to analyze and determine the requirements for an advanced design of MSR. The design concepts of the passive molten salt fast reactor (PMFR), an advanced design of MSR under development in Republic of Korea, are described. In addition, the required studies for the practical employment of the molten salt mixture of nuclear fuel and reactor coolant were investigated.

2. Review of molten salt reactors

The major characteristics of MSR were discussed compared to the most common reactor type, pressurized water reactor (PWR). In addition, the MSRs categorized according to the neutron energy spectrum and outstanding characteristics were presented. Finally, the requirements for an advanced design of the MSR selected as one of the next generation nuclear energy systems by the Generation VI International Forum (GIF) were determined through the review.

2.1 Major characteristics of MSR in comparison with PWR

Figure 2 shows the general system diagrams of MSRs and PWRs. Eutectic fuel mixtures such as UF_4 and UCl_3 dissolved in the coolant salts such as FLiBe ($LiF\text{-}BeF_2$) and NaCl are adopted as the working fluid in the primary system of the MSRs. Accordingly, many unique features compared to the PWR systems are derived from the difference between the liquid mixture of salt fuel and salt coolant and light water. Thus, the major components of the two reactor types differ greatly.

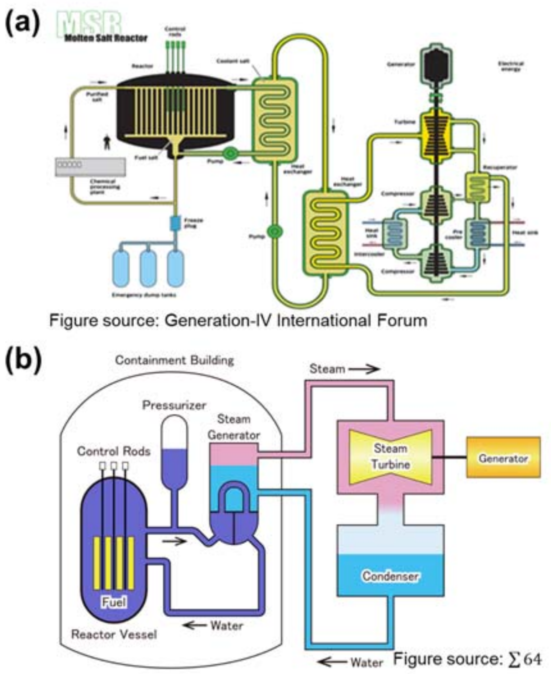

Figure 2. Schematic diagrams of (a) MSR, (b) PWR.

The major characteristics of the PWRs are summarized as follows. UO_2 with 2~5% enriched U-235 is manufactured as the form of pellet for PWRs. The fuel pellets with zircaloy cladding forming a fuel rod and assembly are installed in the reactor core. The moderator is required because the nuclear fission of U-235 is induced by low-energy neutron (thermal neutron) in the PWRs. Light water serves as both the moderator and the coolant simultaneously in the primary system of PWRs owing to the sufficient moderating ratio and the good heat transfer performance. To prevent coolant boiling in the primary system, the system is pressurized up to 15.5 MPa during normal operation. The PWRs operate at the temperature considering the thermal safety margin below the saturation temperature of ~342°C at 15.5 MPa. The cycle efficiency is as high as 33% by using steam Rankin cycle with the turbine inlet temperature of 290°C. On a 3-batch scheme, the refueling cycle is 18 months. The nuclear fuel after 3 times of the refueling cycle is treated as the spent fuel. The spent fuel is cooled in the pool that can maintain the temperature of 30~40°C and in the dry storage after the decay heat is decreased sufficiently. Otherwise, to reuse the spent fuel, the pyroprocessing has been developed.

On the contrary, for thermal spectrum MSRs (TS-MSRs), a separate moderator such as graphite is needed because moderating ratio of the salt mixture is low [4]. Otherwise, for fast spectrum MSRs (FS-MSRs), the moderator is not required as the fast neutron spectrum is adopted. The online reprocessing is possible for both TS-MSRs and FS-MSRs. The MSRs controls the reactivity by online reprocessing, flow rate in the primary system, temperature and composition of the coolant salt. Because liquid fuel is burned in the primary system, the fission products need to be removed from the primary system by dedicated devices. The removal process during operation is required to achieve high burnup as the liquid fuel maintains the homogeneity.

Depending on the type of fuel salt, the boiling point of the salt mixtures is as high as 1400°C under atmospheric pressure and the possible operating temperature ranges 600 to 700°C. Thus, the high pressurization is not required as the high cycle efficiency can be achieved even under the atmospheric pressure. As the system pressure is much lower than the PWRs, the reactor and the pressurizer can be downsized even for the same power level. This advantage shows that the MSRs can be a candidate for transportation propulsion. However, the intermediate system is required to minimize the problem related to radioactive material by capturing tritium. The intermediate system also functions as a thermal storage filled with high temperature molten salt.

The SCO_2 Brayton cycle is promising owing to its high efficiency as shown in Fig. 1. The efficiency is expected to be larger than steam Rankin cycle at the high operating temperature of the MSRs. Otherwise, the thermal energy can be used to produce the hydrogen by HTE.

Liquid salt mixtures in the MSRs exhibit the larger thermal expansion compared to the solid fuel in the PWRs. Accordingly, the reactivity decreases when the temperature increases unintentionally. In addition, even during the representative design basis accident such as loss of coolant accident (LOCA) of the light water reactors (LWRs), the coolant salt is solidified in a short time due to high operating temperature and low melting point.

In addition to the TS-MSR, the FS-MSRs can be developed in three designs [5]. They are an LWR-derived TRU burner, a U-Pu breeder, a natural U-fueled minimal-separation converter. In case of insufficient solubility of spent fuel, methods to transform the chemical forms and materials that have high solubility of TRU were investigated [6]. Thus, there exist many unique and attractive characteristics of the MSRs, which contribute to improving the safety, economic feasibility, high-efficiency electricity and hydrogen production, and solution to the spent fuel from the PWRs.

2.2 Major characteristics of MSRs by neutron energy spectrum

The major differences of the MSRs are addressed by the neutron energy spectrum. The major characteristics of TS-MSRs and FS-MSRs are described as follows.

Figure 3 shows the number of neutrons available for breeding in U-Pu (U-238 to Pu-239) and Th-U (Th-232 to U-233) cycles with thermal and fast neutron spectra [7]. U-Pu fuel cycle has a positive value of the available neutron only with the fast energy spectrum. However, the Th-U fuel cycle can breed with both thermal and fast neutron energy spectra. Accordingly, TS-MSRs adopts the concept of thermal breeder, which irradiates neutrons to the fertile material Th-232 and converts them into fissile material U-233.

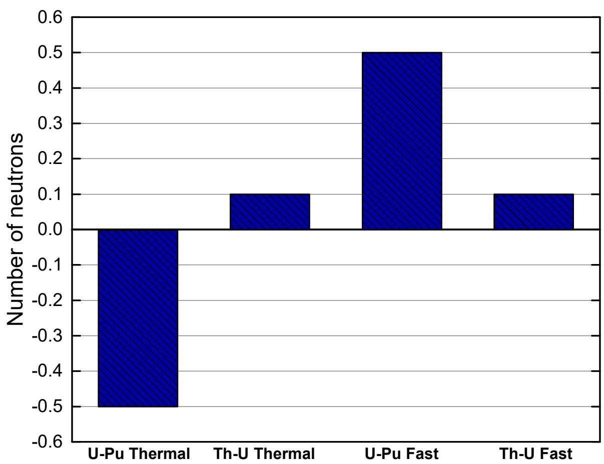

Figure 3. Number of neutrons available for breeding in U-Pu and Th-U cycles with thermal and fast neutron spectra [7].

Th is known to be reserved in earth more than U. In addition, the Th-U cycle can achieve a higher burnup compared to the U-Pu cycle. In terms of spent fuel, the long-life radioactive material is expected to be reduced with the Th-U fuel cycle with thermal spectrum. As shown in Fig. 4, the radiotoxicity of the Th-U cycle was evaluated much lower than others [7].

In the TS-MSRs, the fluoride salts are mainly adopted. They are more effective to moderate neutrons than other halides. Moreover, the fluoride salts are thermally and radioactively stable and their reactivity with water, air, and structural material is sufficiently low. However, the candidates for the working fluid in the TS-MSRs cannot moderate fast neutrons sufficiently. Thus, the graphite is adopted as the moderator. The graphite is expected to be replaced every 3~4 years, which is a high-level nuclear waste, disturbing the longer operation cycle.

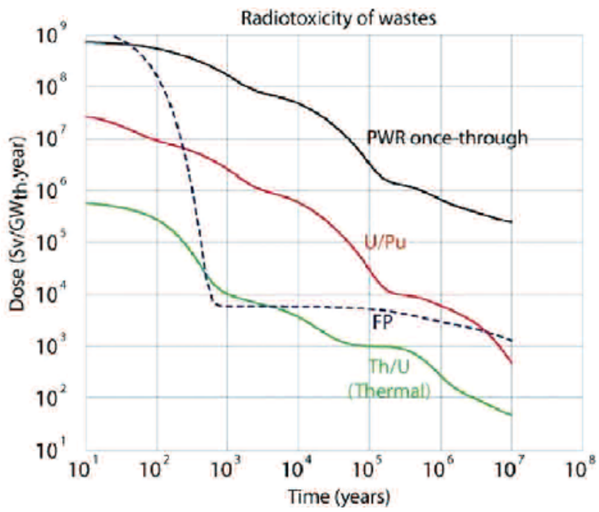

Figure 4. Radiotoxicity of high activity radioactive wastes over time [7].

To utilize the TS-MSRs, there exist a critical point despite the remarkable advantages. Pa-233 can be produced during nuclear reaction of Th-U cycle. Pa -233 becomes U-233 through radioactive decay. It takes a long time as the half-life of the Pa-233 is 27 days. In addition, Pa-233 can be converted to U-234 when Pa-233 absorbs more neutron before the decay. Thus, to prevent the undesirable operation, the Pa-233 has to be separated and decay alone [8]. However, it cannot be adopted in countries where reprocessing is not allowed because the process violates the Nuclear Non-Proliferation Treaty (NPT).

To eliminate the problem caused by Pa-233, the U-Pu cycle with fast spectrum can replace it instead. The neutron economy can be enhanced much greater than Th-U cycle as shown in Fig. 3. In addition, the nuclear wastes are reduced as the moderator is not required for the FS-MSRs. In addition, the nuclear wastes can be reduced because the FS-MSR does not require the moderator while the graphite moderator needs to be periodically replaced for TS-MSRs. Accordingly, the FS-MSRs are expected to be more advantageous in achieving long-term operation than the TS-MSRs.

In terms of the coolant salts in the FS-MSRs, the chloride salts such as NaCl and KCl are preferred due to lower neutron moderation. In addition, TRU such as Pu is more soluble in chloride salts. However, because Cl exhibits various oxidation forms, corrosion mechanisms are more complicated. So more extensive researches on the materials in the FS-MSRs need to be carried out because previous studies on the corrosion by chloride salts are insufficient. Moreover, when Cl-35 absorbs a neutron, it becomes a chlorine isotope, Cl-36, whose beta decay has the long period of half-life [5]. Accordingly, to reduce the production of Cl-36 during operation, another chlorine isotope, Cl-37, has to be enriched.

3. Passive Molten salt Fast Reactor (PMFR)

Due to the attractive characteristics as described above, many countries and institutions have been developing the MSRs technologies. However, some areas which do not have clear solutions or sufficient studies still remain as imminent work for commercialization of the MSRs. To develop the innovative and essential technologies for the MSRs, the Research Center for Development of Innovative Original Technology of a Severe Accident Free Multi-purpose Long-lifetime Small Modular Molten Salt Reactor (I-SAFE-MSR research center) was launched in Republic of Korea. To embrace the research on thermal-hydraulics and safety, reactor physics, and material all together, the research center was organized with Hanyang University, KAIST, and Gachon University. The final goal of the I-SAFE-MSR research center is to develop the Passive Molten salt Fast Reactor (PMFR) adopting the key technologies proposed. The key concepts and requirements of the PMFR are summarized as follows:

- ✓ Natural circulation operation of the primary system
- ✓ Non-soluble fission products separation
- ✓ Severe-accident-free and passive safety system
- ✓ Long-lifetime core design of the PMFR
- ✓ Corrosion-resistant base material and coating in molten salts
- ✓ Original multi-physics numerical analysis platform

Deployment of a reactor coolant pump (RCP) is one of the concerns in the MSRs. The corrosion by the high temperature molten salts can damage the RCP. Thus, to prevent the undesirable situation due to the malfunction of the RCP, the PMFR adopts natural circulation operation. The preliminary analysis on the PMFR showed that it is possible to simplify the core structure as U-Pu fuel cycle with fast spectrum and the reactivity controller [9]. Accordingly, the pressure drop in core region can be reduced. This expectation is positive for the employment of the natural circulation as a driving force. However, more complicated phenomena need to be solved.

To remove the non-soluble fission products such as noble metals and gases from the core region, helium (He) bubbling method is adopted. Although it is effective to separate the fission products, the detailed assessments through numerical and experimental studies are insufficient. Thus, the moving particle semi-implicit (MPS) code and He bubbling experiment using simulant of the working fluid candidates for the PMFR will be carried out. In addition, due to the He bubbling, the two-phase flow through the core and riser is expected. Accordingly, the circulation was investigated and its results showed that the He bubbling method can improve the circulation [10]. The detailed numerical analysis and experimental analysis on natural circulation with He bubbling in molten salt will be conducted.

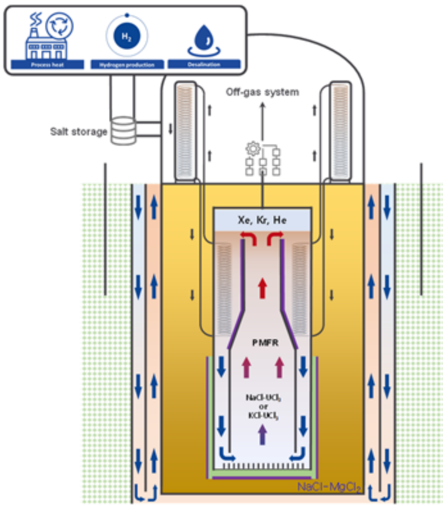

Figure 5. Schematic diagram of the PMFR.

The reactor vessel of the PMFR is installed in a molten salt pool as shown in Fig. 5. The core melting event considered as the severe accident of reactor types of solid fuel cannot occur because the fuel material is already liquified. Nonetheless, the radioactive materials can be released into the environment upon boiling. To ensure the passive safety during hypothesized accidents, an air-cooling system similar to the reactor vessel auxiliary cooling system (RVACS) was investigated with the PMFR. As shown in Fig. 6, the result from the lumped analysis show that the core temperature can be controlled below the boiling point by air-cooling. However, detailed modelling is needed for more accurate results. In addition, it is envisioned to analyze major accidents which may occur in MSRs including the PMFR and to investigate the accident consequences through numerical analysis.

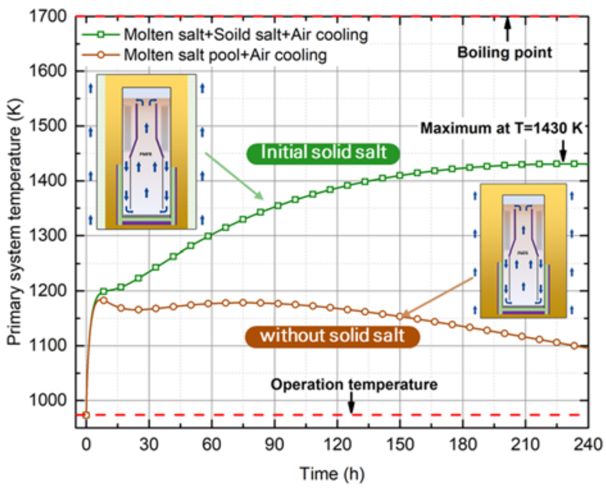

Figure 6. Temperature in the primary system using passive air-cooling.

The preliminary analysis on the PMFR in terms of reactor physics was carried out [9]. Chloride salts such as NaCl-UCl_3 and KCl-UCl_3 and reactivity control drum are adopted. The thermal power and the computed period were set as 400 MWt and 21 years, respectively. The results showed the PMFR with fast spectrum can ensure sufficiently long lifetime.

The candidates of the base material of the structure were selected as stainless steel 316L, Hastelloy C-276, and Hastelloy N1000003, which are well-known corrosion-resistant materials. The experiment results showed that the base material characteristics changes noticeably after reaction with molten salts. Thus, the coating method to enhance the corrosion resistance against the molten salts is under development.

The multi-physics numerical analysis platform has been constructed with OpenFOAM code to analyze thermal-hydraulics, In-house code to analyze reactor physics, and material database and corrosion characteristics in molten salts. The volumetric heat source will be updated as the computed heat generation through the In-house code. Likewise, to assess the reactor physics accurately, the thermal-hydraulic behavior will be updated during calculation. To provide the insufficient data of the physical properties of molten salts, molecular dynamics (MD) simulation has been carried out.

4. Conclusion

In this study, the MSR was reviewed and design concepts and requirements for the PMFR, which is the advanced MSR, were described. The major characteristics of the MSRs were summarized in Tables 1 and 2.

Through the thorough review of the limitations from the previous MSR design, the PMFR, an advanced design of the FS-MSRs, was proposed. The final goals of the I-SAFE-MSR research center and the concepts and requirements of the PMFR were summarized. In addition, the recent progress of the I-SAFE-MSR research center was briefly presented.

As the studies on the PMFR are carried out, the key technologies which is essential and innovative to the MSRs will be developed.

Table 1. Summary of the major characteristics of MSRs

Characteristics	Details
High melting and boiling points	Enhancement of safety due to fast solidification
	Downsizing pressurizer and system structure
	Large thermal safety margin
High operating temperature	High efficiency to produce electricity and hydrogen
	SCO_2 Brayton cycle
	High quality heat source
Eutectic mixture of coolant and fuel salts	Intermediate system to capture tritium
	Online-reprocessing and separation of non-soluble fission products
	Inherent safety due to large thermal expansion

Table 2. Summary of comparison between PWR and MSR

Parameters	PWR	MSR
Nuclear fuel	Low enrichment, UO_2 pellet (solid)	Th salts or U salts (Liquid)
Moderator	Light water	Graphite (Thermal), No (Fast)
Coolant	Light water	Molten salts
Fission products	Pyroprocessing or disposal	Online reprocessing
Operating temperature [°C]	~330	600~700
Operating pressure [MPa]	15.5	0.1~1
Power generation	Steam Rankin cycle	SCO_2 Brayton cycle

Acknowledgments

This research was supported by the National Research Foundation of Korea (NRF), grant funded by the Korea government (MIST) (No. NRF-2021M2D2A2076382 and No. NRF-2016R1A5A1013919).

REFERENCES

[1] G.P. Peters et al., Carbon dioxide emissions continue to grow amidst slowly emerging climate policies, *Nature Climate Change*, **10**, 3-6, (2020).

[2] A.M. Bayomy et al., Nuclear renewable hybrid energy system assessment through the thermal storage system, *International Journal of Energy Research*, **45(8)**, 11689-11711, (2021).

[3] V. Dostal et al., The supercritical carbon dioxide power cycle: comparison to other advanced power cycles, *Nuclear Technology*, **154(3)**, 283-301, (2006).

[4] Y. Zhu, Analysis of neutron thermalization in liquid FLiBe, Ph.D Thesis, North Carolina State University, (2018).

[5] D.E. Holcomb et al., Fast spectrum molten salt reactor options, Oak Ridge National Laboratory, ORNL/TM-2011/105, (2011).

[6] V. Ignatiev et al., MOSART fuels and container materials study: Case for Na, Li, Be/F solvent system, *Proc. 2003 ANS/ENS International Winter Meeting (GLOBAL 2003)*, New Orleans, (2003).

[7] S. David et al., Revisiting the Thorium-Uranium nuclear fuel cycle, *Europhysics news*, **38(2)**, 24-27, (2007).

[8] M. Lung et al., Perspectives of the thorium fuel cycle, *Nuclear Engineering and Design*, **180(2)**, 133-146, (1998).

[9] S. Hong et al., Preliminary study on the candidate fuel salt of molten chloride salt fast reactor, *Transactions of the Korean Nuclear Society Virtual Spring Meeting*, May 13-14, (2021).

[10] J. Lim et al., Preliminary analysis of the effect of the gas injection on natural circulation for molten salt reactor type small modular reactor system operated without a pump, *Transactions of the Korean Nuclear Society Virtual Autumn Meeting*, October 21-22, (2021).