DOI: 10.15669/pnst.8.82

Progress in Nuclear Science and Technology
Volume 8 (2025) pp. 82-85

ARTICLE

Risk Assessment Methodology for Heat Transfer Tube Failure in a Sodium-Molten Salt Heat Exchanger for Sodium-Cooled Fast Reactor Coupled to Molten Salt Thermal Energy Storage System

Kazuya TAKANO*, Kenichi KURISAKA and Hidemasa YAMANO

Japan Atomic Energy Agency, 4002 Narita-cho, Oarai-machi, Higashi Ibaraki-gun, Ibaraki-ken, 311-1393, Japan

As part of the development of safety assessment technologies for sodium-cooled fast reactor coupled to thermal energy storage (TES) system with sodium–molten salt heat exchanger (HX), the database on the number of heat transfer tube failure in molten salt HX and the exposure time of concentrated solar power (CSP) system to molten salt was surveyed on the basis of reported practices of accidents in the existing CSP systems with the molten salt TES system. Using the database, a risk assessment methodology of the heat transfer tube failure frequency was also studied with a Bayesian estimation method to obtain a risk insight for improving the HX.

KEYWORDS: sodium-cooled fast reactor, molten salt, sodium-molten salt heat exchanger, heat transfer tube failure

I. Introduction

Next-generation innovative reactors have a new value of their flexibility with variable renewable energy, in addition to safety and economic competitiveness.[1] A sodium-cooled fast reactor (SFR) can make flexibility by coupling a thermal energy storage (TES) system with molten salt. The TES technology is advantageous to achieve a large-capacity energy storage, in terms of flexibility and cost.[2] In the United States, TerraPower has been developing an SFR with TES, named Natrium™, which enables to increase power generation output from 345 MWe to 500 MWe for 5.5h in order to flexibly adapt to electricity demand change due to the expansion of renewable energy introduction.[3] In France, Hexana has also been developing an SFR concept composed of two small reactor units (150 MWe each) and TES to flexibly adapt to electricity demand and to supply heat for industrial needs.[4] In Japan, an SFR with TES concept is studied as one of promising technologies for synergy of nuclear and renewable energy by Japan Atomic Energy Agency (JAEA).[5]

The schematic diagram of SFR with TES system is shown in **Fig. 1**. A development issue specific to the SFR with TES is a heat exchanger (HX) between sodium and molten salt. There is no information regarding its HX as far as the authors know. In addition, there is no guideline for safety design and evaluation for SFRs with TES although a safety standard of TES using molten salt is published by ASME.[6] Furthermore, the safety design needs to consider the risk of sodium-molten salt contact that might occur in a heat transfer tube failure in the HX. Therefore, JAEA has been investigating chemical reaction characteristics between sodium and molten salt.[7] A probabilistic risk assessment is required by regulatory body for nuclear power plants for licensing. For the SFR with the molten-salt TES system, there is no data used in the risk assessment as far as the authors surveyed. Therefore, failure data related to the TES system are necessary for safety design based on the risk assessment.

The purpose of the present study is to develop a risk assessment methodology for the SFR coupled to the TES system with sodium–molten salt HX in order to obtain a risk insight for improving the HX. First, this study surveyed the database on the number of heat transfer tube failure in the molten salt HX and the exposure time of concentrated solar power (CSP) system to molten salt on the basis of reported practices of accidents in the existing CSP systems with the molten salt TES system. Next, using the database, a risk assessment methodology of the heat transfer tube failure frequency was studied with a Bayesian estimation method. This paper also describes estimation of the heat transfer tube failure frequency for small modular reactors (SMRs) of the SFR with the TES system.

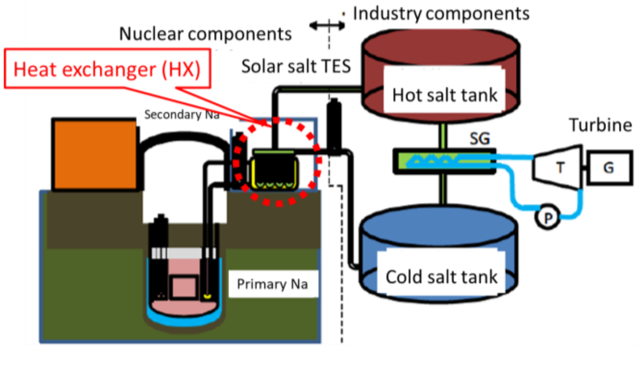


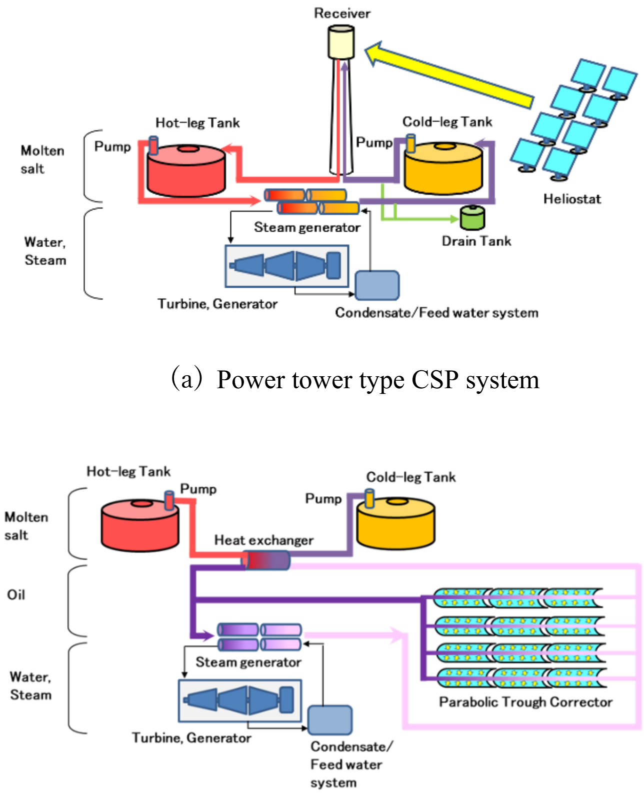
Fig. 1 Schematic diagram of SFR with TES system[8]

*Corresponding author, E-mail: takano.kazuya@jaea.go.jp

II. Heat Transfer Tube Failures and Molten Salt Exposure Time

The existing CSP systems are generally categorized as power tower type or parabolic trough type as shown in **Fig. 2**. Power tower CSP systems have steam generators heated by molten salt. Parabolic trough CSP systems have the steam generators heated by heat transfer oil and the HXs between molten salt and heat transfer oil. Heat transfer tube failures at the steam generators have mainly been reported from the power tower CSP systems. Thus, the database on the number of heat transfer tube failures at the steam generators and at the HXs between molten salt and heat transfer oil was surveyed on the basis of reported practices of accidents in the existing power tower CSP systems and the parabolic trough CSP systems, respectively.[9,10] The target CSP systems for the database consist of 1 demonstration plant and 9 commercial plants of power tower type and 29 commercial plants of parabolic trough type. The obtained database is summarized in **Table 1**. In the case of there is no given quantitative number in the reports, the estimated number considering its description is shown in Table 1. For example, when the reports indicated there were plural failures or numerous failures, two failures or 10 failures were respectively considered at least in the present study.

Molten salt exposure time in the CSP systems was estimated based on their in-service period and utilization factor tentatively considered as 0.5. Although the heat transfer tube failure frequency can be affected by in-service inspection, it is not assumed in the present study tentatively. The molten salt exposure time for each CSP system is shown in **Fig. 3** with their power output of TES system as the horizontal axis. In order to grasp the tendency among the CSP types, the averaged molten salt exposure time for each CSP type is shown in **Fig. 4**. It is more significant accumulating operation experiences and increasing in facility size in the parabolic trough CSP system with the HXs between molten salt and heat transfer oil than that in the power tower CSP system. It is estimated the number of failures would increase in larger TES systems as the number and each length of heat transfer tubes in the HXs increase. Thus, the molten salt exposure time was considered as that multiplied by the thermal output of TES system, year·MWt to take into account the capacity of TES system in the following evaluation.



(a) Power tower type CSP system

(b) Parabolic trough type CSP system

Fig. 2 Schematic diagram of General CSP systems

Table 1 Database on the number of heat transfer tube failure[9,10]

Type	Target	Occurrence point		Number of failures*
Power tower	1 demonstration plant	Steam generator heated by molten salt	Partition plate	1
			Heat transfer tube	2
	9 commercial plants		Connections between tubes and tube sheets	10
			Heat transfer tube	2
Parabolic trough	29 commercial plants	HXs between molten salt and heat transfer oil	Heat transfer tube	2
			Connections between tubes and tube sheets	2

* In the case of there is no given quantitative number in the reports, the estimated number considering its description is shown.

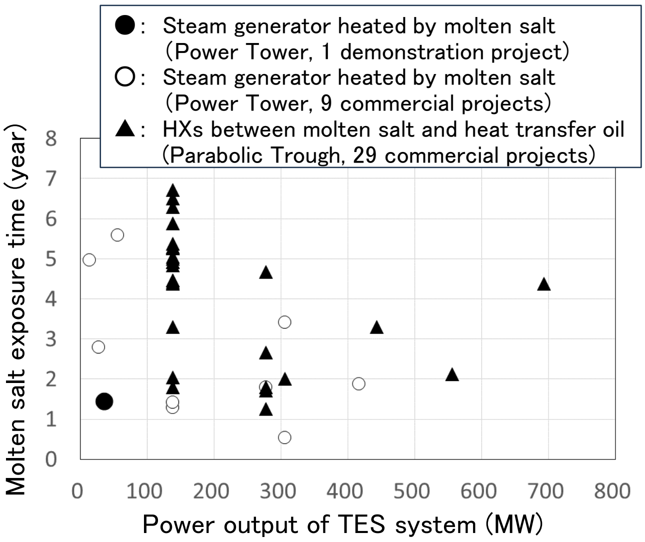


Fig. 3 Molten salt exposure time of CSP systems

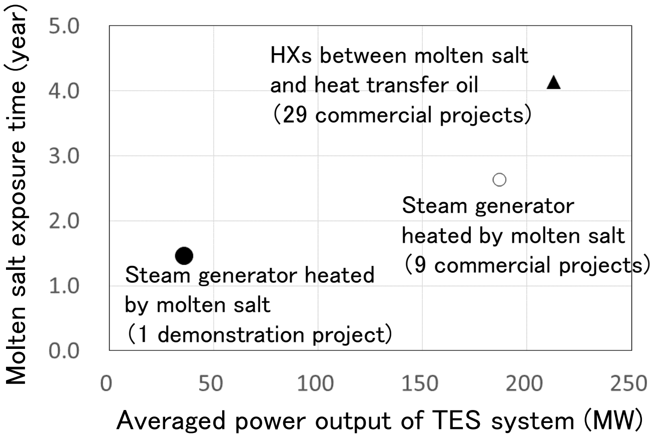


Fig. 4 Averaged molten salt exposure time of CSP systems

III. Heat Transfer Tube Failure Frequency Evaluation

The heat transfer tube failure frequency was evaluated with the molten salt exposure time, number of heat transfer tube failures, and a Bayesian estimation method.[11] Generally, when troubles occur at random, the probability that troubles occur at a fixed occurrence rate λ and that the number of troubles is x at the observation time t is considered to follow a Poisson distribution. In that case, the conjugate prior distribution of the trouble occurrence rate λ in the Bayesian estimation method becomes a gamma distribution, and the posterior distribution becomes the same gamma distribution as the prior distribution. The gamma distribution is described with the gamma parameters, α and β as follows.

$$f(\lambda) = \frac{\beta^{\alpha}}{\Gamma(\alpha)} \lambda^{\alpha-1} e^{-\lambda\beta} \tag{1}$$

In the Bayesian estimation method, the mean value of the posterior distribution is obtained for the trouble occurrence rate λ which is given by α/β.

Using Jeffreys' uninformative prior distribution as the uninformative prior distribution to be applied when information for determining the prior distribution is not obtained, α_{prior} and β_{prior} of the gamma distribution representing the prior distribution are 1/2 and 0, respectively. Then, the posterior distribution parameters α and β of the trouble occurrence rate λ are expressed as follows.

$$\lambda = \frac{\alpha}{\beta} = \frac{x + \alpha_{prior}}{t + \beta_{prior}} = \left(x + \frac{1}{2}\right) / t \tag{2}$$

Here, λ is the heat transfer tube failure frequency (= averaged occurrence frequency), x is the number of heat transfer tube failures (= events in time t), t is the molten salt exposure time. Evaluated heat transfer tube failure frequency is shown in **Fig. 5**.

Although the evaluated heat transfer tube failure frequency is higher in the early development phase, the failure frequency decreases as its development phase progresses. The evaluated heat transfer tube failure frequency for HXs between molten salt and heat transfer oil is one order of magnitude lower than that of the steam generator heated by molten salt.

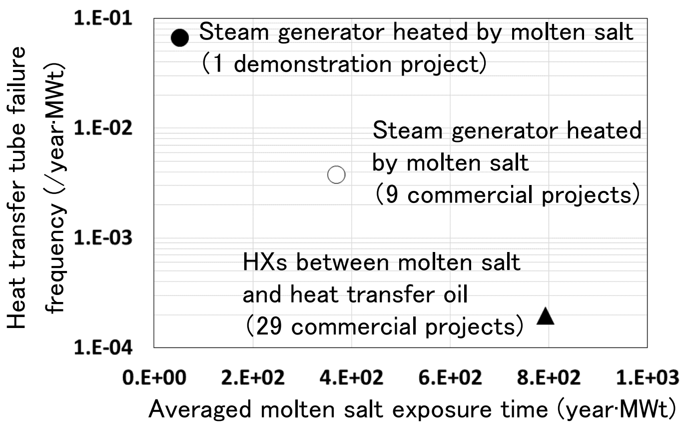


Fig. 5 Evaluated heat transfer tube failure frequency (/year·MWt)

IV. Estimation of Heat Transfer Tube Failure Frequency in SMR-SFR with TES system

A small sized SFR with TES system, 200MWe (560MWt) and a medium sized SFR with TES system, 650MWe (1800MWt) were considered to estimate the heat transfer tube failure frequency (/year) in an actual plant. Heat transfer tube failure frequency in the SMR-SFR with TES system (/year) were evaluated multiplying as the evaluated heat transfer tube failure frequency (/year·MWt) by thermal output of the systems (MWt). The evaluated results are shown in **Fig. 6**.

Although there is no available information on the failures in HXs between sodium and molten salt, it is more similar to the HXs between molten salt and heat transfer oil that steam generator heated by molten salt as they are common in terms of heat exchange between molten salt and heat transfer fluid.

Thus, it is assumed that the heat transfer tube failure frequency in HXs between molten salt and heat transfer oil is applicable to that in HXs between sodium and molten salt, in the present study. Then, assuming a small size SFR coupled to TES system of 500 MWt, the heat transfer tube failure may occur once every 10 years based on the present evaluation. It should be noted that the influence of in-service inspection is not assumed in the present evaluation.

It is important to improve the reliability of HXs between sodium and molten salt to be designed as one of the nuclear power plant facilities.

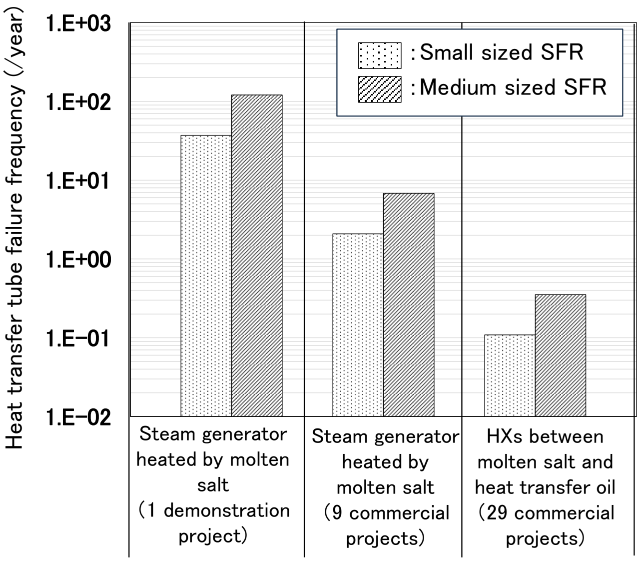


Fig. 6 Heat transfer tube failure frequency in SMR-SFR with TES system (/year)

V. Conclusion

The present study has developed the risk assessment methodology for SFR coupled to TES system with sodium–molten salt HX. the database on the number of heat transfer tube failure in molten salt HX and the exposure time of CSP system to molten salt was surveyed on the basis of reported practices of accidents in the existing CSP systems with molten salt TES system. Using the database, the risk assessment methodology of the heat transfer tube failure frequency was also studied with a Bayesian estimation method. This assessment gives us a risk insight that the reliability of HXs between sodium and molten salt should be improved.

Acknowledgment

This work was supported by MEXT Innovative Nuclear Research and Development Program Grant Number JPMXD0222682675.

References

1) METI, Agency for natural resources and energy, Ongoing nuclear innovation. https://www.enecho.meti.go.jp/about/special/johoteikyo/smr_01.html
2) C. Forsberg, P. Sabharwall, H. D. Gougar, Heat Storage Coupled to Generation IV Reactors for Variable Electricity from Base-load Reactors: Workshop Proceedings: Changing Markets, Technology, Nuclear- Renewables Integration and Synergisms with Solar Thermal Power Systems, INL/EXT-19-54909 Revision 0 (2019).
3) Natrium™ Reactor and Integrated Energy Storage. https://www.terrapower.com/our-work/natriumpower/
4) CEA, The CEA presents two nuclear startups, Hexana and Stellaria. https://www.cea.fr/english/Pages/News/cea-presents-two-nuclear-startups-hexana-and-stellaria.aspx
5) JAEA, "SMR Development by JAEA", https://www.jaea.go.jp/04/sefard/faq/files/material0601.pdf [in Japanese]
6) ASME TES-1 Safety Standard for Thermal Energy Storage Systems: Molten Salt, (2020).
7) H. Yamano, et al., "Development of safety design technologies for sodium-cooled fast reactor coupled to thermal energy storage system with sodium-molten salt heat exchanger," *New Energy and Future Energy Systems, Advances in Transdisciplinary Engineering*, **45**, 27-34. DOI:10.3233/ATDE231072.
8) JAEA, Advanced reactor development. https://www.jaea.go.jp/04/sefard/ordinary/2022/2022090901.html
9) R. Moore, M. Vernon, C. K. Ho, N. P. Siegel, G. J. Kolb, "Design Considerations for Concentrating Solar Power Tower Systems Employing Molten Salt," Sandia National Laboratories, SAND2010-6978 (2010).
10) M. Mehos, H. Price, R. Cable, D. Kearney, B. Kelly, G. Kolb, F. Morse, "Concentrating Solar Power Best Practices Study," National Renewable Energy Laboratory, NREL/TP-5500-75763 (2020).
11) NUREG/CR-6823, SAND2003-3348P, "Handbook of Parameter Estimation for Probabilistic Risk Assessment," Sandia National Laboratories (2003).