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Core Reactivity Analysis during Fuel Draining Process in the Molten Salt Fast Reactor

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ABSTRACT

A study of the core criticality during the draining process of liquid fuel salt on Molten Salt Fast Reactor (MSFR) was done. Two accident scenario that causes the draining process were loss of freeze valve coolant and loss of secondary coolant. This study used basic design of the MSFR with the salt fuel compositions of LiF (77.5%) – ThF4 (19.985%) – 233UF4 (2.515%). The criticality calculation has been analyzed from the value of the effective multiplication factor obtained from Open MC (Monte Carlo base) calculation. The effective multiplication factor was calculated with a variation on the number of freeze valves open; 1, 8, and 16 valves. The calculation has resulted in the value of effective multiplication factor decreasing exponentially during the draining process. Results from this study could be used as basic for the future study of the accident condition in MSFR, since there are still many MSRs accident scenarios that still haven't been taken into account.

1. INTRODUCTION

Molten salt fast reactor (MSFR) is a concept of the molten salt reactor (MSR) which utilizes fast neutron spectrum instead of thermal neutron spectrum. It is one of six nuclear reactors included in the Generation IV nuclear reactor. Research and development of an MSFR focus on sustainability, non-proliferation, safety, and waste management, to build better quality reactor for the future (Merle-Lucotte et al., 2015).

MSFR consists of a three fluids loops respectively: a primary loop, an intermediate loop, and a power conversion loop (Figure 1). The primary loop contains a core cavity connected to the inlet and outlet pipes, a gas injection system, salt-bubble separators, a primary pump, and an intermediate heat exchanger (Merle-Lucotte et al., 2014). MSFR has no solid moderator in the core, where it is filled up by half volume of fuel salt from the total volume in the primary loop of 18 m^3. While the rest of the fuel salt is located on the outside of the core. The initial fuel salt is made by LiF (77.5 mol %) – ThF4 (19.985 mol %) – 233UF4 (2.515 mol %) where it has maximum operating temperature of 750° C (Allibert et al., 2016). Core in this reactor shield by fertile blanket made from the same salt of the fuel without fissile material-with the propose to improve the breeding ratio of the reactor (Brovchenko et al., 2013).

Heat exchangers are installed surrounding the core to extract the power from the heat of fuel salt. The criteria of heat exchanger should have compact size, resistance to high temperature (up to 750 – 800°C), low salt inventory, and low pressure drop. The maximum volume of fuel salt in the intermediate heat exchanger is 0.56 m^3 smaller than the fuel salt inside the core. The heat transfer process existed in the intermediate heat exchanger from the fuel salt into cooling salt in the intermediate loop (Di Ronco, et al., 2020). The heat from the coolant salt is transferred to liquid in the power conversion loop in the secondary heat exchanger.

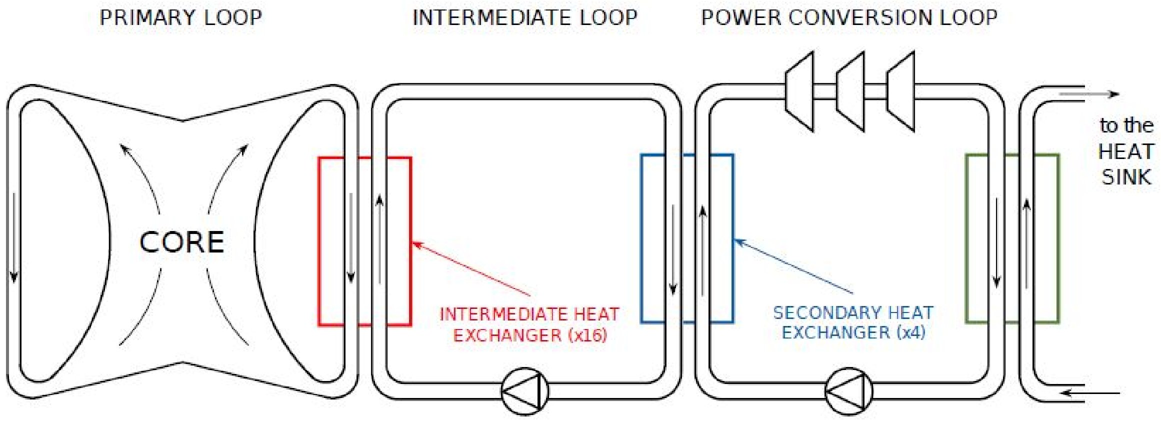

Figure 1. Three circuit in molten salt fast reactor (Di Ronco et al, 2020)

MSFR has passive draining system that allows the fuel salt drains from the core to the emergency draining tank (Figure 2). Frozen salt as key component of the passive safety system in this reactor, where it is located between reactor core and drain tank. The passive safety system works automatically in the case of accident. The temperature of fuel salt increases due to an accident and generates melting process of the frozen salt. The draining process starts when the frozen salt open. This safety is also utilized for a planned reactor shutdown (Tano et al, 2018).

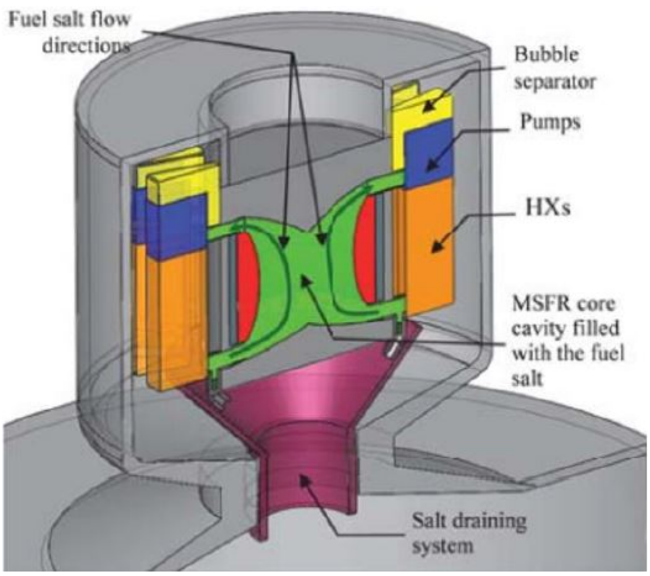

Figure 2. Fuel circuit of molten salt fast reactor

Study of the MSFR draining system is strongly related to the neutronic condition and fuel temperature in the reactor core. Tano et al. (2018) had calculated the fuel salt temperature in the core before and during the draining process without considering the subcritical condition must be done by neutronic calculation. Therefore, the neutronic calculation to understand the reactor criticality has been done in this study, so that the evacuation process of the fuel will safely occur.

Open MC is a neutronic calculation code for nuclear reactors based on Monte Carlo method has been developed by The Computational Reactor Physics Group at Massachusetts Institute of Technology (MIT) (Romano et al., 2015). This code has an ability to calculate the core criticality and also allows depletion calculation for nuclear fuel using several options of depletion chain (Romano et al., 2021). This article presents the criticality calculation of MSFR using Monte Carlo method in Open MC during the fuel draining process.

2. METHOD

2.1 Reactor design

The MSFR design was adopted from Brovchenko et al. (2019), utilized U^{233} for fissile material. The detailed specification shown on Table 1. Ni-based alloy was used and placed surrounding the core (Figure 3) as reflector to minimized neutron leak. It also was used as a barrier between fertile blanket and fuel salts to avoid mixing the two materials as those are in a liquid state during reactor operation. The composition of the Ni-based alloy is shown in Table 2.

Table 1 Specification of the MSFR

Thermal power (MWth)	3000
Electric power (MWe)	1500
Fuel composition (mol%)	LiF (77.5)-$^{232}ThF_4$(19.985)-$^{233}UF_4$(2.515)
Fuel density (g/cm^3)	4,1249
Fuel salt volume (m^3)	18
Fertile blanket composition (mol%)	LiF (77.5)-$^{232}ThF_4$(22.5)
Blanket salt volume (m^3)	7,3
Neutron absorber composition	B_4C with 19.8% of ^{10}B and 80.2% of ^{11}B
Neutron absorber density (g/cm^3)	2.52
Reflector	Ni-based alloy
Reflector density	10
Core dimension (mm)	Radius: 1127.5 Height: 2255

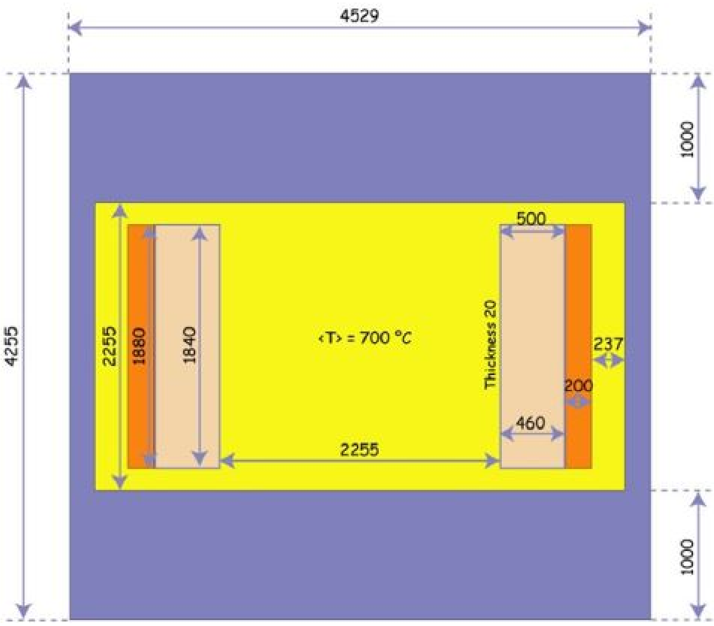

Figure 3. MSFR core geometry (in mm) with fuel salt (yellow), the fertile blanket (pink), the neutron absorber (orange), and the reflectors (blue).

Table 2 The composition (in mol%) of Ni-based alloy

Ni	W	Cr	Mo	Fe	Ti	C
79.432	9.976	8.014	0.736	0.632	0.295	0.294
Mn	**Si**	**Al**	**B**	**P**	**S**	
0.257	0.252	0.052	0.033	0.023	0.004	

The reactor core is cylindrical with a diameter of 4529 mm equal to the reactor height (Figure 3). It consists of a fertile blanket with 500 mm thick and 1880 mm height, neuron absorber with 200 mm thickness and 188 cm height, 20 mm reflector surrounding the fertile blanket, and fuel salt area (yellow color in figure 3). In the vertical position, this reactor is covered by a reflector with a thickness of 1000 mm, and in the horizontal position is covered by a reflector with a thickness of 200 mm.

2.2 Draining time and fuel height level calculation

Liquid fuel salt levels in the reactor core respectively decreased during the draining process. This condition gave an impact on the reactivity in the core was determined by number of effective multiplication. The draining time was calculated for three conditions; one freeze valve open, half of the total freeze valve open (8 freeze valves), and all freeze valves open (16 freeze valves). The components of the safety draining system are simplified in Figure 4.

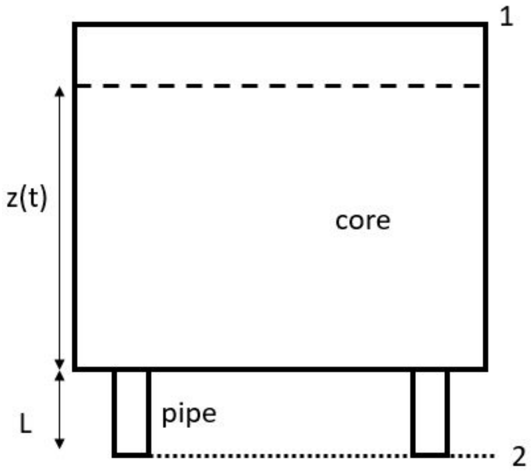

Figure 4. Simplified schematic of the MSFR core and draining pipe

The fuel salt was moved from the reactor core to the draining tank through the pipe since the valve was opened. The flow was defined by the Bernoulli equation, by also considering the conservation of mass and the dissipation energy due to the viscosity of the fluid. The final formula to calculate the draining time is shown in Eq.1. Moreover, the fuel height level was calculated from velocity equation (Eq.2).

$$t = \frac{R_{core}^2}{nr_{pipe}^2}\sqrt{\frac{2\left(1+4f\frac{L}{D}+K_L\right)}{g}}(\sqrt{H+L}-\sqrt{L} \quad (1)$$

$$V_2 = -\frac{R_{core}^2}{nr_{pipe}^2}\frac{dz(t)}{dt} \quad (2)$$

R_{core} : core radius
r_{pipe} : pipe radius
f : Fanning friction factor
L : pipe length

D : pipe diameter
K_L : resistance coefficient
H : core height
g : gravity acceleration
V_2 : fuel decreasing velocity
$z(t)$: fuel height level
n : number of pipes

2.3 Simulation Process

The basic principle of Monte Carlo method in particle transport problems are simulating a life of a single particle from birth to death. In the nuclear neutronics calculation, the life of a single neutron is represented as a single particle born from the emission until the eventual death by absorption or escape outside the system boundaries. The frequencies and outcomes of the various interactions that may occur during the life of the particle are drawn at random. Where these are simulated according to the law of interaction derived from particle physics (Leppänen, 2007).

Open MC uses successive generation method to converge on the fission source distribution in an eigenvalue method. In this method, a finite number of neutron histories are tracked through their lifetime iteratively. A set of XML (eXtensible Markup Language) files is required in the Open MC to describes the model. The basic input files are materials, geometry, and settings (Romano et al., 2013).

In this study, the materials file is adjusted to the material specification in Table 1 and Table 2. Furthermore, the geometry file is also based on Figure 3. In settings file, the number of particles, number of active, and inactive batch are inserted (Romano & Forget, 2013).

In this preliminary study, two steps were used to validate the Open MC code. The first step in the Open MC simulation is determining the optimum number of particles. The value of effective multiplication number for the different numbers of particles was calculated where it was started from 500 to 20000 particles with interval 500 particles. The second step was comparing the results from the Open MC to the other simulation code with the same data library ENDF/B-7.

The second simulation is the criticality calculation defined by effective multiplication factor during fuel draining process. There is two different accident scenario in this study which caused the freeze valve melt and lead to the fuel draining process. It is loss of freeze valve coolant and loss of secondary coolant. In the loss of freeze valve coolant scenario, there is no increasing temperature in the core, so the fuel temperature will be adjusted to 750ºC. Meanwhile the loss of secondary coolant, the fuel temperature increases about ~200 K in 2 minutes after the failure of the pump happened (Koks, 2016). This simulation uses ENDF/B-8 data library, the newest version of ENDF/B data library provided by OpenMC. ENDF/B-8 library in OpenMC have nuclear data limited for several temperature; 237 K, 600 K, 900 K, 1200 K, and 2500 K (n.n, 2021). According to the fuel temperature in two accident scenarios above, the OpenMC simulation will use the nearest temperature to the original scenario, which is 900 K and 1200 K.

3. RESULTS AND DISCUSSION

3.1 Code Validation

Open MC is a neutronic code base on the random number of the particles. Therefore, the validation code by considering variation of the particles number had been done preliminary. The effective multiplication factor of the MSFR was calculated by combining number of particles, where the results are shown on Figure 5. The red circle in Figure 5 shows the convergence condition, where it was obtained since the number of particles was used higher than 6000. The multiplication effectives are similar for the number of particles used between 6000 and 20000 particles.

Furthermore, second validation was done to ensure that Open MC is reliable to be used in this study. In the previous study, calculation of the multiplication effective was done by utilizing SERPENT code with data library ENDF/B7 (Brovchenko et al., 2019). By using the same reactor design and data library, the calculation of multiplication effective was also carried out by Open MC code with 1000 particles. Table 3 shows the results of the two calculations, where it has a difference value of only 0.00023. It was caused by different calculation method was used in Open MC and SERPENT, especially in the definition of the energy level in the macroscopic cross section. SERPENT uses a unionized energy grid while Open MC uses an indexing technique to give some algorithmic benefit and requiring much less memory. Our result indicates that Open MC has an excellent performance for the neutronic calculations.

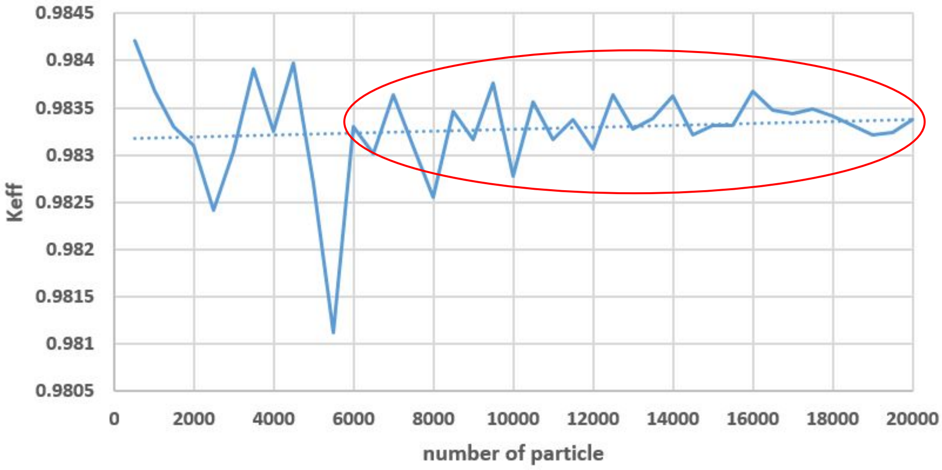

Figure 5 The value of effective multiplication factor of the MSFR for different number of particle

Table 3 The value of effective multiplication factor calculation result by different code

OpenMC ENDF/B-7	SERPENT ENDF/B-7 (Brovchenko et al., 2019)	*Δ*k
0.98278	0.98301	0.00023

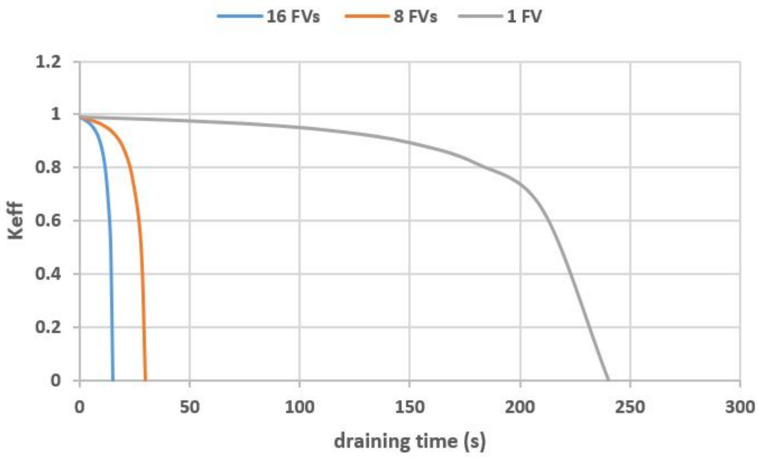

Figure 6 The effective multiplication factor for three scenarios of the valve opening in the case of loss of coolant accident.

3.2 Core Criticality in the Case of Loss of Coolant Accident

From the calculation, the draining time for three cases; 1, 8, and 16 freeze valves open was 247, 31, and 15 seconds respectively. It was assumed the draining process was started since the freeze valve was fully open. The draining process was also utilized to determine the liquid salt level in the reactor core. The liquid salt level was utilized to determine the geometry in the case of neutronic calculation to obtain the effective multiplication factor during draining process. Figure 6 shows the value of effective multiplication factor during draining process for three cases. Loss of coolant accident (freeze valve open due to loss of coolant) was used for accident scenario in this study. The effective multiplication factor decreases exponentially along with the fuel draining process (which means the reduction of the fuel height level) in the core. There is no significant difference in the number of effective multiplications for the three opening freeze valve scenarios. The subcritical condition is satisfied during the draining process, especially when the fuel height level reached half of the maximum height.

In this study, the concentration of the fission product such as minor actinide, and xenon had been calculated during the draining process in order to see those material's impact on the effective multiplication factor. Concentration of the minor actinides and xenon for 16 freeze valve open is shown in Figure 7 and 8, respectively. The concentration of minor actinides went down, where it did not give an impact on the reactor criticality (Figure 7). Moreover, the concentration of xenon (Figure 8) increased then remain stable during the draining process. Xenon has high neutron capture microscopic cross-section, where it gave impact to the reduction of the value of effective multiplication factor.

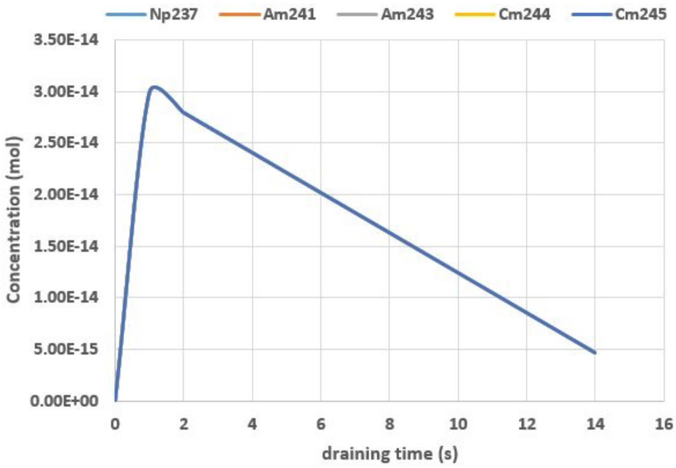

Figure 7 Concentration of minor actinides during fuel draining process for 16 freeze valve open

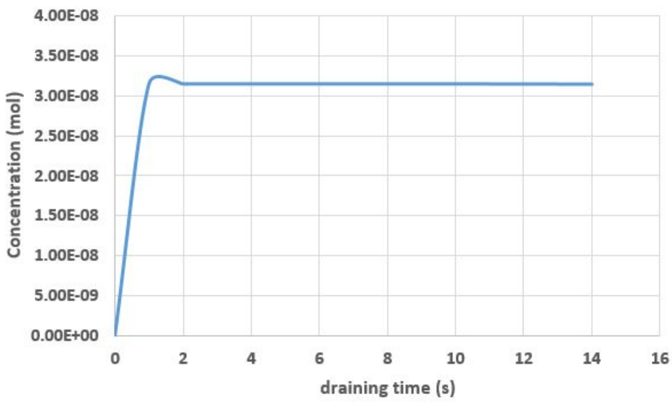

Figure 8 Concentration of xenon during fuel draining process for 16 freeze valves open

3.3 Core Criticality Analysis for Two Accident Scenario

Figure 9 shows the effective multiplication factor for two accident scenarios; loss of freeze valve coolant and loss of secondary coolant. These simulation used 16 freeze valve open scenario to see the effect of different initial temperature to the neutronic behavior during draining process. The value of effective multiplication factor for the loss of secondary coolant scenario is lower than the loss of freeze valve coolant. This is opposite to the hypothesis that higher temperature in a case of an accident will cause the worse condition in the core. This phenomenon is caused by Doppler broadening effect that occurs in the absorption cross-section. In the high temperature, the resonance area becomes shorter. It causes more neutrons absorbed and decreases the number of fission neutrons.

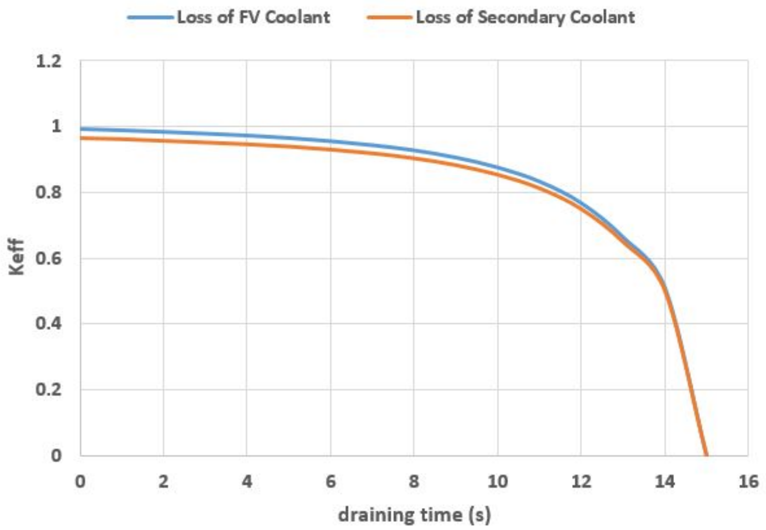

Figure 9 The effective multiplication factor of MSFR for different accident scenario

Figure 10 shows the absorption macroscopic cross section between temperature 900 K (loss of freeze valve coolant scenario) and 1200 K (loss of secondary coolant scenario). By considering red circles and red rectangles in Figure 10, resulted that the resonance area is getting shorter in higher temperature condition.

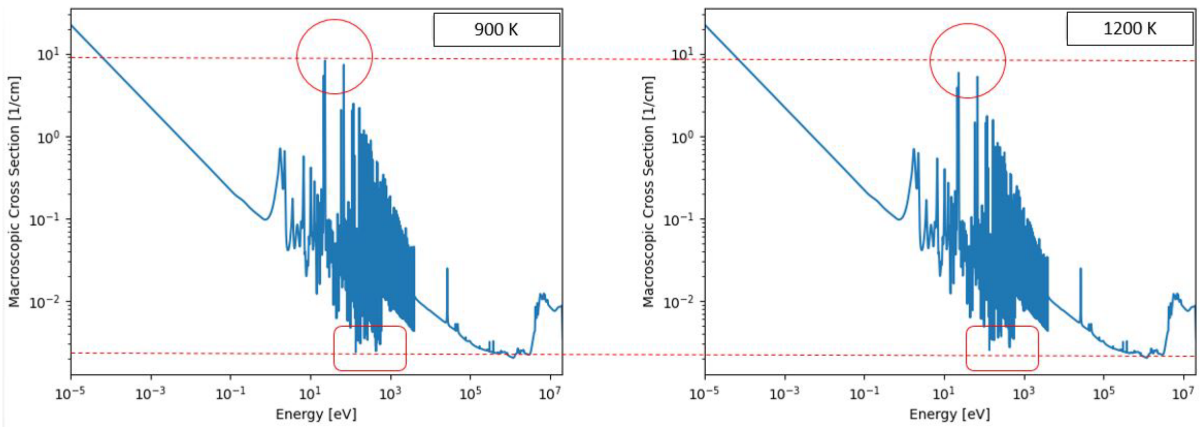

Figure 10 Temperature effect on the fuel absorption macroscopic cross section, for 900 K (left) and 1200 K (right).

4. CONCLUSION

The MSFR has a safety draining system that allows the fuel to flow automatically to the draining tank in the case of accident. To ensure the system works safely and meets the desired neutronic condition during the fuel draining process, the criticality calculation defined by the effective multiplication factor was done. The simulation using Open MC shows the subcritical condition during the draining process for the different numbers of freeze valve open and different accident scenarios. Two accident scenarios with different temperatures affect the absorption macroscopic cross-section of fuel which makes the difference in the criticality calculation. Results from this study could be used as basic for the future study of the accident condition in MSFR, since there are still many MSRs accident scenarios that still haven't been taken into account.

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