Preliminary Analysis of Fission Product Plateout on Primary Loop of a Micro-Molten Salt Reactor

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1. Introduction

The Molten Salt Reactor (MSR) is among the Generation IV nuclear energy options for advanced nuclear power reactors [1]. It employs a liquid salt mixture containing fissile materials such as uranium, which serves both as nuclear fuel and coolant. The MSR system is top-ranked in sustainability among the Generation IV reactors due to its closed fuel cycle and efficient nuclear waste reduction capabilities. It could be rated very good in passive safety. Possibility of core-meltdown accidents could be basically excluded since fuel is already in liquid form. Upon release from the reactor system, the liquid fuel quickly solidifies, trapping most of fission products within the solidified fuel.

One of the crucial design issues in an MSR system is fission product plateout around primary circuit. Experience from the Molten Salt Reactor Experiment (MSRE) indicated that many fission product elements (such as Rb, Cs, Sr, Ba, Y, Zr, and lanthanides) formed stable fluorides and remained soluble in fuel salt. In contrast, noble metal elements (such as Nb, Mo, Tc, Ru, Ag, Sb and Te) tended to deposit on various system surfaces and accumulate during reactor operation [2]. Fission product plateout could result in positive and negative effects on an MSR system. In terms of safety, it reduces amount of source terms to environment. However, the present work focuses on great concern about local blockage of cooling channels, particularly in compact heat exchangers with small channel sizes.

Despite its significance, there have been very few in-depth studies on fission product plateout in MSR systems to date. The main objective of this paper is to underscore the importance of predicting plateout in an MSR. This study presents preliminary results of fission product plateout on primary loop of a micro-MSR. A computer code, named POSCA [3], was utilized to obtain the plateout distribution around the primary loop based on perfect sink assumption for sorption.

2. Fission Product Plateout

The POSCA code was originally developed for the fission product plateout across the primary coolant loop of a High Temperature Gas-Cooled Reactor (HTGR). It was verified and validated against analytic solutions and plateout experiment data available [4]. Although design characteristics of MSR and HTGR are significantly different, it is considered that POSCA can be used as preliminary works since plateout phenomenon itself is the same. The biggest difference would be concentrations of fission products in coolant and formations of chemical compounds. Formations of chemical compounds are not considered in this work, which is the major limitation of the present study.

As depicted in Fig. 1, the POSCA code employs a three-layer model to simulate the fission product plateout. One-dimensional (1-D) model is used in POSCA to obtain the plateout distribution. The governing equations are described by Eqs. (1) and (2).

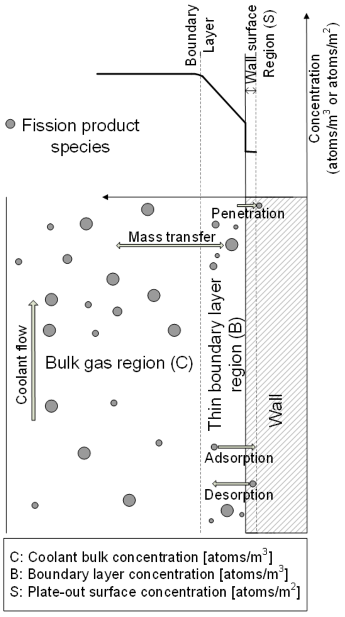

Fig. 1. Three layer model adopted in POSCA [4].

$$\frac{\partial C_i}{\partial t} = \dot{q}_{c,i} + \sum_{j=1}^{N_T} a^*_{i,j} C_j - \frac{P_W}{A_F} h_i (C_i - B_i) - \frac{1}{A_F}\frac{\partial}{\partial x}(A_F v C_i) \tag{1}$$

Where C_i = fluid concentration of nuclide i, B_i = boundary layer concentration of nuclide i, $\dot{q}_{c,i}$ = generation source in coolant, N_T = total number of considered nuclides, $a^*_{i,j}$ = decay chain and removal matrix, P_w= wetted perimeter, A_F= flow area, h_i= mass transfer coefficient, v = coolant velocity.

$$\frac{\partial S_{R,i}}{\partial t} = \dot{q}_{R,i} + \sum_{j=1}^{N_T} b^*_{i,j} S_{R,j} + h_i (C_i - B_i) \tag{2}$$

Where $S_{R,i}$ = wall surface concentration of nuclide i, $\dot{q}_{R,i}$ = reversible nuclide generation source, $b^*_{i,j}$= decay chain and removal matrix.

3. Numerical Analysis and Results

A micro-MSR using KCl-UCl$_3$ and a Printed Circuit Heat Exchanger (PCHE) are considered in this work. Among various design candidates for the micro-MSR, the PCHE-equipped configuration design was chosen in this study to investigate the worst-case scenario for channel blockage due to its smallest channel size. The off-gas system is not included in this analysis.

3.1 Inventory of fission products

Fig. 2 displays the total inventory of fission products which are candidates of the plateout elements. It was obtained by a nuclear physics calculation [5]. Among the calculated inventory, K, Cl, U, Pu, and noble gases were excluded in Fig. 2 due to their low probability of plateout. Although it is expected that some noble metal elements are plated out on wetted surfaces, all the elements shown in Fig. 2 (total mass = 10.2 kg) are included in the subsequent plateout thickness calculation for a conservative estimate.

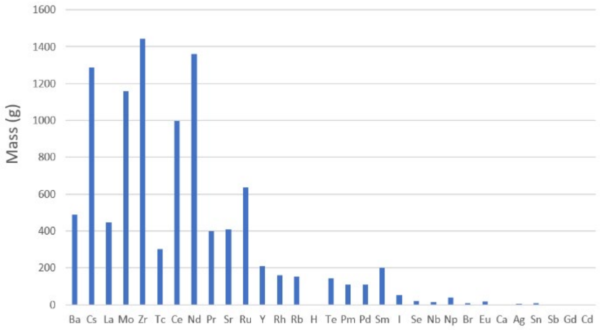

Fig. 2. Total inventory of fission products [5].

3.2 Variables affecting plateout

A perfect sink sorption $(\mathrm{i.e.}, B_i = 0)$ is assumed in this study based on the existing results for HTGRs. Such an assumption for noble metal elements is known to be reasonable. Surface temperature, wetted area, and mass transfer coefficient are critical variables influencing plateout. However, the temperature variation around the primary loop of the micro-MSR is ~30 ºC. Therefore, the plateout area and the mass transfer coefficient are the key variables affecting the plateout across the loop. Fig. 3 shows the plateout area of the micro-MSR. It is obvious that most of plateout occurs at the heat exchanger surface. The mass transfer coefficient around the loop is shown in Fig. 4. The largest value is observed at the pump. It is mainly due to rapid salt velocity at the impeller.

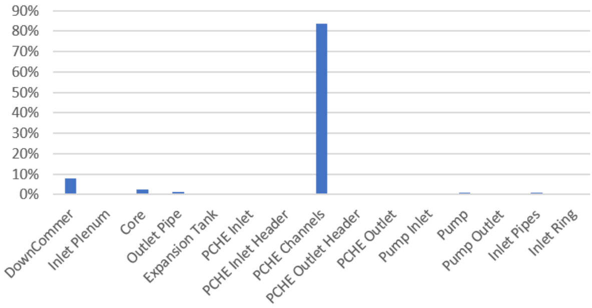

Fig. 3. Plateout area fraction.

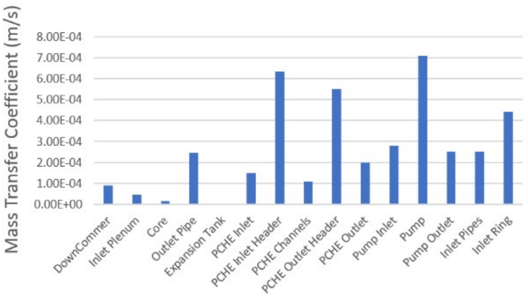

Fig. 4. Mass transfer coefficient

3.3 Plateout distribution

In order to investigate the plateout distribution around the loop, the POSCA calculation was performed assuming 20 years of operation. A stable nuclide (i.e., Zr-94) was selected for the calculation. All the design data for the present calculation are adopted from the references [5,6].

Table I summarizes the calculated mass balance after 20 years. It shows that circulating Zr-94 is negligibly small and most of Zr-94 (> 99.9999%) is plated out on the structure wall surfaces. This highlights the likelihood of noble metal elements being plated out if they do not decay.

Table I: Zr-94 Mass Balance and Distribution after 20 Years of Reactor Operation

	No. of Atoms	Fraction
Total release inventory into primary circuit	1.92e+24	
Circulating	2.29e+17	1.19e-05%
Plateout	1.92e+24	>99.9999%
Removal by decay	0	0%

Fig. 5 displays the fluid concentration of Zr-94 around the loop after 20 years. It is shown that the fluid concentration is more or less uniform around the loop except the expansion tank. The low concentration at the expansion tank is due to stagnant modeling and ignorance of the diffusion. Fig. 6 shows the plateout density of Zr-94. Higher plateout densities are shown at the PCHE inlet header and the pump where the mass transfer coefficient is higher (See Fig. 4.). The calculated plateout fraction of Zr-94 is shown in Fig. 5. As expected, significant fraction of Zr-94 is plated out on the PCHE channels. Based on the assumption that the plateout distribution is the same for the all elements (shown in Fig. 2), the thickness of the plateout is roughly estimated using the mass proportion. The result is shown in Fig. 5. The plateout thickness at the PCHE channels is estimated less than 0.02mm. Despite extremely conservative assumption, the plateout thickness is calculated to be much smaller than the PCHE channel size (=2mm).

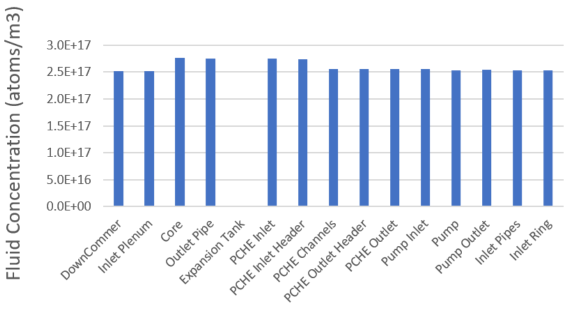

Fig. 5. Calculated fluid concentration of Zr-94.

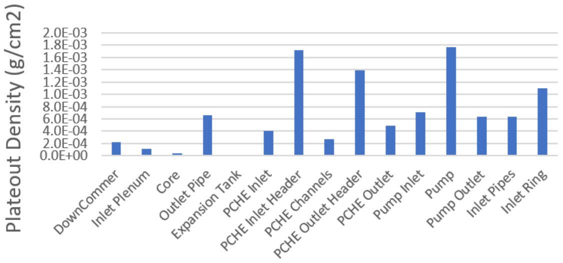

Fig. 6. Calculated plateout density of Zr-94.

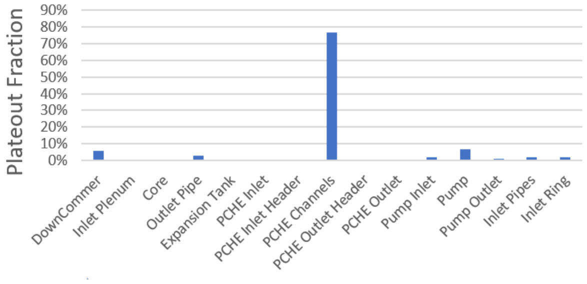

Fig. 7. Calculated plateout fraction of Zr-94.

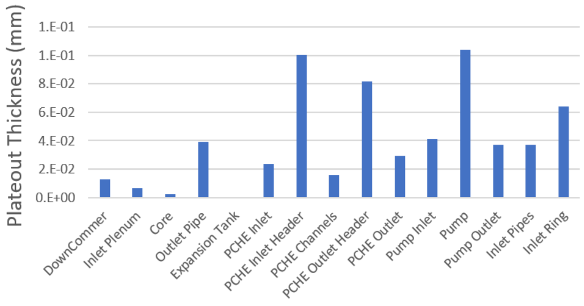

Fig. 8. Calculated plateout thickness considering all possible plateout elements.

4. Conclusions

In this work, preliminary analysis of fission product plateout on the primary loop of the micro-MSR was performed. Particular attention was paid to the potential for local blockage of PCHE channels induced by plateout. Although extremely conservative assumptions were applied, the calculated plateout thickness was much smaller than the PCHE channel size. Therefore, fission product plateout is unlikely to cause local blockage in PCHE channels. If the other type of a heat exchanger such as helical coils is adopted for the micro-MSR, the local blockage by fission product plateout seems to be impossible.

It should be noted that the formation of chemical compound (e.g., $ZrCl_4$) was not considered in this work. Therefore, future work should incorporate various chemical compounds in salt for improved predictions.

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