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Evaluation of Delayed Neutron Fraction in TRU-loaded Molten Salt Reactor

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1. Introduction

A molten salt reactor (MSR) is a reactor that uses molten salt as both fuel and coolant where the liquid phase of the fuel allows such type of reactor to attain strong negative feedback that stems from relatively high thermal expansion [1]. Such an attribute not only provides means of inherent safety feature but also signifies flexible power operation including passive load follow operation. Whereupon, the molten salt reactor is regarded as one of the most desirable Generation IV reactors.

However, the flow of the fuel insinuates a loss of delayed neutron fraction, which must be correctly appraised for the development of MSR. The delayed neutron fraction (β) is defined as the ratio of delayed neutron number to the total fission neutron number:

$$\beta_g = \frac{\iiint\limits_{\text{In core}} \nu_{d,g}\Sigma_f(\vec{r},E)\phi(\vec{r},E,\vec{\Omega})dVdEd\vec{\Omega}}{\iiint\limits_{\text{In core}} \nu\Sigma_f(\vec{r},E)\phi(\vec{r},E,\vec{\Omega})dVdEd\vec{\Omega}} . \quad (1)$$

If the external reactivity exceeds the delayed neutron fraction of the system, the reactor becomes prompt critical that could entail serious damage or catastrophic accidents [2]. Likewise, the delayed neutron fraction dictates the permissible range of reactivity, which must be properly assessed while incorporating the design feature of the reactor system, especially for the MSR.

2. Description of the Simplified MSR Core

The molten salt reactor is composed of an active core and ex-core regions, where the molten salt fuel circulates between them. Unlike the static fuel-based reactors, the precursors generated in the active core region circulate through the whole core for MSRs, where a considerable number of delayed neutrons are emitted at the ex-core region. Because delayed neutrons emitted in the ex-core region cannot induce fission, such a feature dwindles the delayed neutron fraction. Note that loss of delayed neutron fraction becomes noteworthier for the TRU (transuranic)-loaded molten salt reactor due to the presence of Pu-239.

In a narrow sense, TRU signifies plutonium and minor actinides. However, because it is technically hard to exploit pure TRU from the spent fuel of LWR, the TRU considered in this manuscript further includes non-negligible contributions of uranium and rare earth elements, e.g., 20.18 wt.% uranium, 70.95 wt.% pure TRU (plutonium and minor actinides), and 8.87 wt.% rare earths. A detailed description of the actual TRU for this work is enumerated in Table 1. For the pure TRU, where uranium and rare earth elements are removed, its composition is given in Table 2.

Table 1: Actual TRU composition in wt.%

U	20.177	Bk	3.04E-11	Nd	4.562
Ac	7.27E-10	Cf	1.36E-07	Pm	0.01
Th	5.25E-05	Yb	7.00E-07	Gd	0.184
Pa	4.20E-06	Lu	2.29E-20	Tb	0.003
Np	4.35	Y	0.011	Dy	0.002
Pu	60.583	La	0.588	Ho	1.06E-04
Am	5.513	Ce	2.309	Er	4.08E-05
Cm	0.508	Pr	1.2	Tm	3.32E-07

Table 2: Pure TRU composition in wt.%

Ac	1.02E-09	Np	6.131	Cm	0.716
Th	7.40E-05	Pu	85.383	Bk	4.28E-11
Pa	5.92E-06	Am	7.770	Cf	1.92E-07

Three different TRU based salts were considered as the fuel candidates: NaCl-$TRUCl_3$, KCl-$TRUCl_3$, and NaCl-$MgCl_2$-$TRUCl_3$. The mole fraction of each constituent was set to be that of the eutectic point. It is worthwhile to articulate that a phase diagram based on the $PuCl_3$ has been utilized in lieu of $TRUCl_3$ as shown in Fig. 1, since plutonium is the major element for TRU of interest.

As depicted in Fig. 1, the eutectic point of NaCl-$TRUCl_3$ can be found with mole fraction of NaCl and $TRUCl_3$ as 62:38, eutectic point of KCl-$TRUCl_3$ can be found with mole fraction of KCl and $TRUCl_3$ as 43:57, eutectic point of NaCl-$MgCl_2$-$TRUCl_3$ can be found with mole fraction of NaCl-$MgCl_2$-$TRUCl_3$ as 62:18:20.

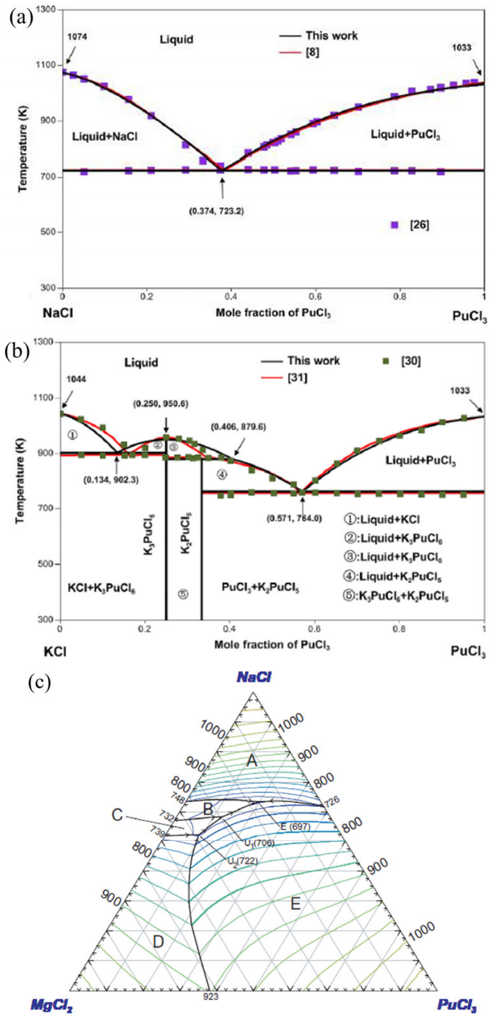

Fig 1. Phase diagrams of (a) NaCl-PuCl$_3$, (b) KCl-PuCl$_3$, and (c) NaCl-MgCl$_2$-PuCl$_3$ [3, 4]

A simplified cylindrical MSR core was envisioned as illustrated in Fig. 2, where its active core diameter (D) was set to be identical with its height (H). Note that such a condition moderately minimizes the reactor volume. The active core consists of molten salt fuel being encapsulated by 10 cm thickness of Hastelloy-N container. A stainless-steel based reflector further encircles the core with 40 cm thickness.

The ex-core region is omitted for simplicity, where one assumes the importance of such region as zero, i.e., neutrons born in the ex-core region do not contribute to fission.

The evaluation of both multiplication factor and delayed neutron fraction was performed via KAIST iMC code (Monte Carlo based neutron transport and reactor analysis code [5]) for the aforementioned

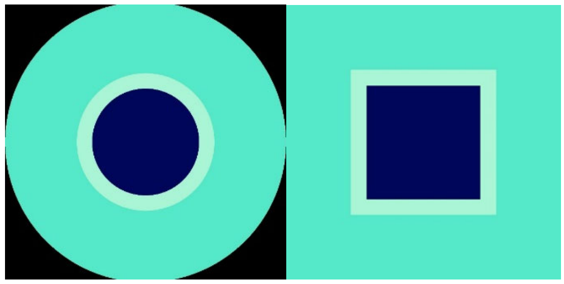

Fig 2. Top view (left) and side view (right) of the simplified MSR model

simplified cylindrical MSR model. The analyses result is further described in the following section.

3. Numerical Results

To assess the size of the active core region, the critical height of the reactor was estimated for each fuel candidate. Tables 3 and 4 enumerates the active core size and its associated multiplication factor while postulating stagnant fuel condition, where one can notice that TRU rich fuel requires a relatively small active core dimension.

Table 3: Sizes and multiplication factors of the MSR using actual TRU-loaded fuels

Fuel	D [cm]	k_{eff} (± SD [pcm])
62NaCl-38TRUCl$_3$	70	1.07804 (± 20)
43KCl-57TRUCl$_3$	62	1.09866 (± 23)
62NaCl-18MgCl$_2$-20TRUCl$_3$	110	1.04445 (± 21)

Table 4: Sizes and multiplication factors of the MSR using pure TRU-loaded fuels

Fuel	D [cm]	k_{eff} (± SD [pcm])
62NaCl-38TRUCl$_3$	50	1.07006 (± 21)
43KCl-57TRUCl$_3$	42	1.04250 (± 23)
62NaCl-18MgCl$_2$-20TRUCl$_3$	80	1.06828 (± 20)

The fuel flows from the bottom of the active core to the top with a constant speed (V_{fuel}). After the fuel egresses from the active core, it requires noticeable time for it to re-enter the bottom of the active core. Such time is referred to as recirculation time (T_{c}), which is adjusted accordingly to the prescribed fuel speed as illustrated in Table 5. Note that history number of 50,000, inactive cycle number of 50, and active cycle number of 200 were universally employed for the calculation.

Table 5: Recirculation time according to fuel speed

V_{fuel} [cm/s]	0	5	7.5	10	15
T_{c} [sec]	-	30	20	15	10

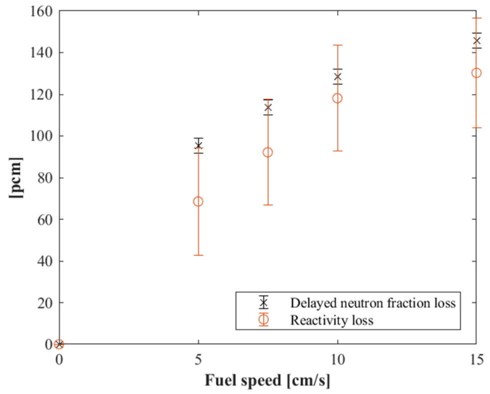

Fig 3. Delayed neutron fraction loss and reactivity loss of 62NaCl-38TRUCl3 MSR with flowing fuel

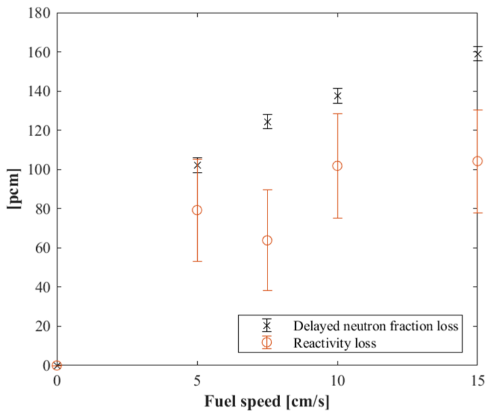

Fig 4. Delayed neutron fraction loss and reactivity loss of 43KCl-57TRUCl3 MSR with flowing fuel

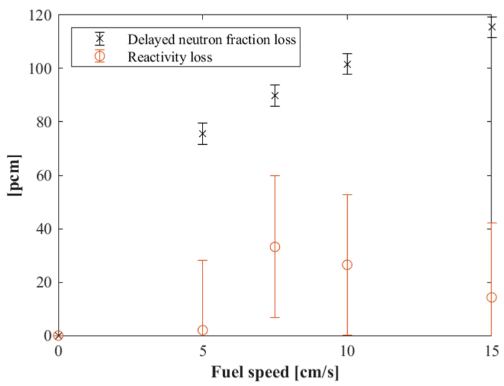

Fig 5. Delayed neutron fraction loss and reactivity loss of 62NaCl-18MgCl2-20TRUCl3 MSR with flowing fuel

Table 6: Delayed neutron fraction and reactivity loss of 62NaCl-38TRUCl3 MSR

V_{fuel} [cm/s]	0	5	7.5	10	15
β [pcm]	296	200	182	167	150
β loss [pcm]	0	95	114	128	146
ρ loss [pcm]	0	69	92	118	130

Table 7: Delayed neutron fraction and reactivity loss of 43KCl-57TRUCl3 MSR

V_{fuel} [cm/s]	0	5	7.5	10	15
β [pcm]	298	195	173	160	138
β loss [pcm]	0	102	124	138	159
ρ loss [pcm]	0	79	64	102	104

Table 8: Delayed neutron fraction and reactivity loss of 62NaCl-18MgCl2-20TRUCl3 MSR

V_{fuel} [cm/s]	0	5	7.5	10	15
β [pcm]	300	224	210	198	184
β loss [pcm]	0	76	90	102	115
ρ loss [pcm]	0	2	33	26	14

Figures 3, 4, and 5 illustrate the loss of delayed neutron fraction and reactivity concerning the fuel speed for actual TRU based reactor configurations, i.e., TRU that includes uranium and rare earth elements. Tables 6, 7, and 8 further summarizes such results, where the loss of delayed neutron fraction tends to intensify with the enhanced fuel speed. It is noteworthy to articulate that uncertainty of the reactivity loss is significant, where authors speculate its cause as an insufficient sample size. However, the tendency of reactivity loss at various fuel speeds could be recognized, which is similar to that of the delayed neutron fraction loss.

Comparing delayed neutron fraction loss for three different fuel salt candidates, the largest loss was observed for 43KCl-57TRUCl3, and the smallest deficit occurred with 62NaCl-18MgCl2-20TRUCl3. Such tendency originates from the higher TRU composition, which manifests as a smaller active core size. Because the absolute residence time of the precursor within the active core is proportional to the height of the system, a decrease in the dimension signifies less residence time. Hence the TRU rich core becomes more susceptible to loss of delayed neutron fraction due to the flow.

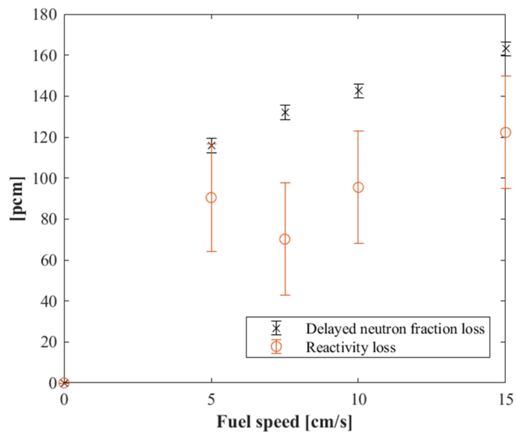

Fig 6. Delayed neutron fraction loss and reactivity loss of 62NaCl-38TRUCl3 (pure TRU) MSR with flowing fuel

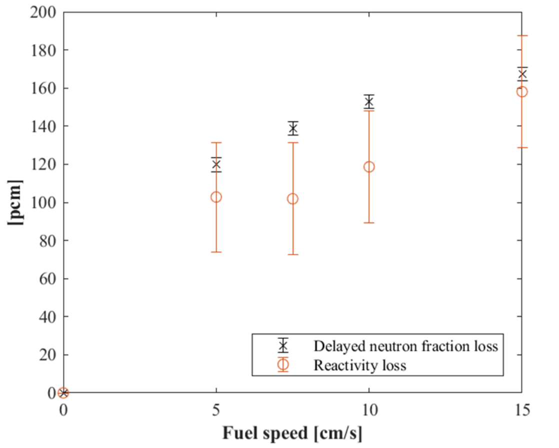

Fig 7. Delayed neutron fraction loss and reactivity loss of 43KCl-57TRUCl3 (pure TRU) MSR with flowing fuel

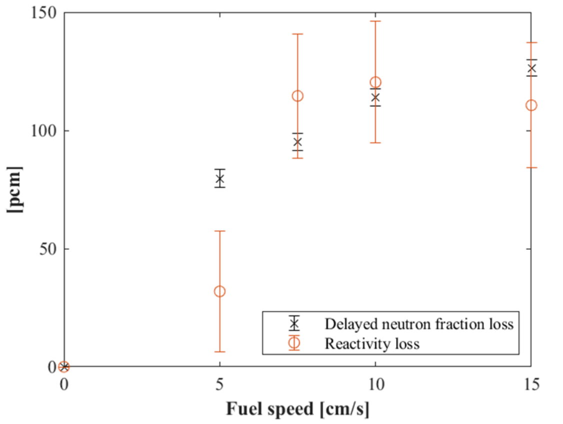

Fig 8. Delayed neutron fraction loss and reactivity loss of 62NaCl-18MgCl2-20TRUCl3 (pure TRU) MSR with flowing fuel

Table 9: Delayed neutron fraction and reactivity loss of 62NaCl-38TRUCl3 (pure TRU) MSR

V_{fuel} [cm/s]	0	5	7.5	10	15
β [pcm]	274	158	142	132	111
β loss [pcm]	0	116	132	143	163
ρ loss [pcm]	0	90	70	95	122

Table 10: Delayed neutron fraction and reactivity loss of 43KCl-57TRUCl3 (pure TRU) MSR

V_{fuel} [cm/s]	0	5	7.5	10	15
β [pcm]	270	150	131	117	102
β loss [pcm]	0	120	139	153	167
ρ loss [pcm]	0	103	102	119	158

Table 11: Delayed neutron fraction and reactivity loss of 62NaCl-18MgCl2-20TRUCl3 (pure TRU) MSR

V_{fuel} [cm/s]	0	5	7.5	10	15
β [pcm]	272	192	177	158	145
β loss [pcm]	0	80	95	114	126
ρ loss [pcm]	0	32	115	120	111

An analogous analysis has been made with the hypothesis of having pure TRU, i.e., no uranium and rare-earth contribution. As described in Tables 9, 10, and 11, and Figs 6, 7, and 8, tendencies of delayed neutron fraction loss and reactivity loss are similar to that of the actual TRU fuel. However, the extent of delayed neutron fraction loss intensifies for having pure TRU composition, which stems from the smaller core size which accords with the dominant plutonium fraction in the fuel. From such observation, the authors cautiously conjecture that exploitation of pure TRU, i.e., lower uranium and rare-earth portion in the fuel salt, does not always guarantee the integrity of the reactor.

4. Summary and Conclusions

This manuscript investigates the effect of flowing fuel in terms of delayed neutron fraction and reactivity loss for TRU based molten salt reactors. Both actual and ideal TRU compositions were considered, where the extent of loss aggravates with enhanced fuel speed for both cases. In addition, it was found that higher plutonium concentration results in a smaller active core size, which entails a more salient loss of delayed neutron contribution.

Comprehensively, this manuscript highlights the dependency of delayed neutron attributes with respect to both flow of the fuel salt and its composition. Since procurement of higher delayed neutron fraction is favourable in terms of safety, the findings imply meticulous measures must be taken for selecting the fuel salt and its circulation speed while designing the MSR.

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