LEU-based Molten Salt and Metal Reactor for Ultramicro Miniaturization

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1. Introduction

The utilization of nuclear power for substituting fossil fuels for energy generation is being rekindled these days, however, there exists a clear limit for the extent of its deployment. Such a situation includes a military base, mining industry, small villages in a remote area, space, etc. To render nuclear power to be suitable for such conditions, the concept of a miniaturized and transportable reactor, where its small size expedites loading and transportation, is widely being recognized. In this work, the feasibility of designing such a reactor based on the Molten Salt Reactor (MSR) concept is investigated.

The active core for MSR consists of fuel salt which contains fissile materials, which also serves as a coolant that circulates between the core and the primary heat exchangers. Such a unique feature entails the following advantages: no meltdown, no hydrogen formation from zirconium, convenient residual heat removal during an emergency, and strong negative feedback due to heat expansion of the fuel [1]. However, conventional thermal MSR design poses inherent adversities including proliferation concerns stemming from online reprocessing, and radioactive waste generation from the usage of graphite moderator and tritium from fluoride salt. Recently, attention was drawn upon the concept of MSFR (Molten Salt Fast Reactor) which utilizes a fast spectrum to overcome such aforementioned issues, and a novel endeavor for miniaturizing such a reactor is made in this study.

It is worthwhile to articulate that conventional MSFR requires considerable size for achieving criticality, e.g., the reactor diameter should be at least 215 cm for a square cylindrical MSFR using NaCl-UCl_3 with 19.75 wt.% enrichment. Considering the fact that a typical container is about 235 cm in its width and height in about 239 or 270 cm, such a reactor cannot be loaded within it, insinuating MSFR using HALEU (high-assay low-enriched uranium) to be an inappropriate candidate. Furthermore, the initial fuel mass is estimated to be about 20-30 tons, resulting in a considerable economical problem from considerable material cost.

To overcome such technical difficulties, a concept of Molten Salt and Metal Reactor (MSMR) is proposed in this paper. A preliminary analysis for appraising the possibility for miniaturizing the reactor and neutronic optimization of the ultra-long-life operation without refueling is addressed.

2. Conceptual design of MSMR

MSMR consists of metal-fuel and molten salt coolant in layers of two liquids, the former resides in the lower layer, and the latter occupies the upper layer. The fission reaction occurs in the lower segment of the reactor and the generated heat is transferred to the upper molten salt region. Metal fuel that comprises the lower layer is composed of an alloy such as U-Fe, U-Mn, or U-Cr, etc. Because the fuel is relatively dense compared to conventional MSRs and uranium concentration is high, the size of the reactor core can be downsized whilst retaining a high fuel conversion ratio. And the reduced fuel mass can help curtail material costs, and that can ease the commercialization.

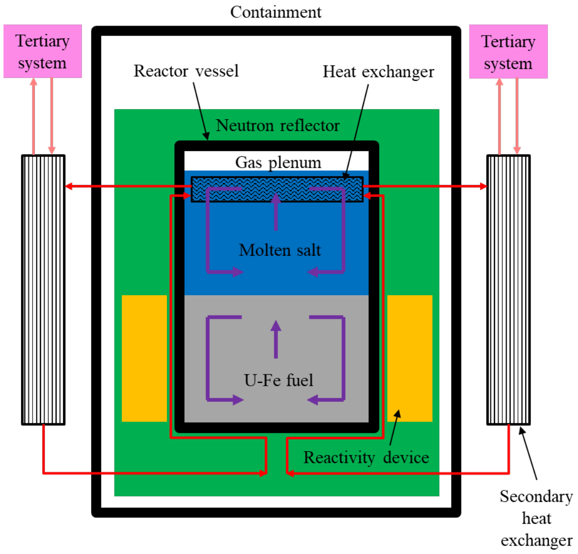

Fig 1. Conceptual description of MSMR

The following several candidates are considered for the molten salt region: NaCl-$MgCl_2$, NaCl-KCl-$ZnCl_2$, or NaOH, which removes the heat generated from the lower layer and transfers it into a primary heat exchanger. Note that heat removal can be performed by natural circulation or pump operation, where the latter means of heat removal could significantly enhance the heat removal rate leading to extension of power range during operation. In addition to heat removal, the presence of molten salt could serve as a trap for non-gaseous fission products, which could prevent the escape of noxious elements during an accident, i.e., noble metal remains in the metal fuel, and non-noble metal dissolves in the upper salt region.

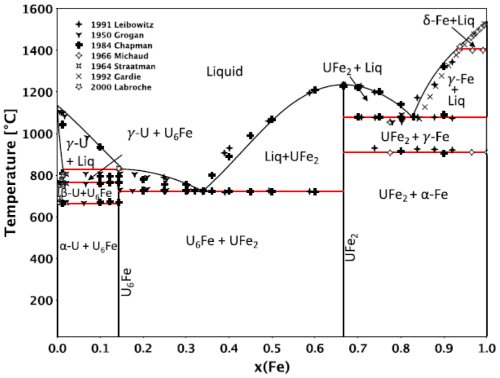

Fig 2. Binary phase diagram of U-Fe system [2]

To withstand both corrosive and high-temperature environments, the reactor vessel is mainly composed of Hastelloy-N where its inner surface is coated with Tantalum. At the top of the reactor vessel, a free surface so-called gas plenum exists, which accommodates both the heat expansion of liquid metal and molten salt and gaseous fission products produced during operation. The secondary system transfers heat from the primary heat exchanger to the tertiary system, which directly cools the outer surface of the reactor vessel. The overall description of the MSMR is illustrated in Fig. 1.

The eutectic U-Fe alloy has been selected for metallic fuel in this study where its phase diagram is given in Fig. 2. The molar composition of eutectic U-Fe is 66-34 and the associated eutectic melting point is about 723°C [2]. The temperature dependency concerning the density of U and Fe are given below [3, 4]:

$$\rho_{\mathrm{U}} = 19.520 - 1.601 \times 10^{-3} T[K], \tag{1}$$

$$\rho_{\mathrm{Fe}} = 8.618 - 8.83 \times 10^{-4} T[K], \tag{2}$$

which are exploited to estimate the density for U-Fe alloy based on the well-known Ideal Liquid Model as described in Eq. (3).

$$\frac{1}{\rho} = \sum_i \frac{w_i}{\rho_i} \tag{3}$$

For the upper layer of the proposed MSMR, eutectic NaCl-MgCl$_2$ mixture has been utilized where its phase diagram is shown in Fig. 3. The molar composition of eutectic NaCl-MgCl$_2$ is 58-42 where its eutectic melting temperature is about 445°C. The density for such salt can be estimated as below [5]:

$$\rho_{\text{58NaCl-42MgCl}_2} = 2.2971 - 5.07 \times 10^{-4} T[℃] \tag{4}$$

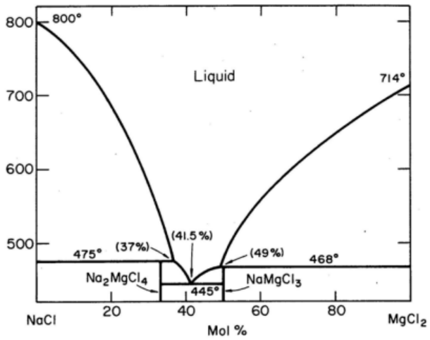

Fig 3. Binary phase diagram of NaCl-MgCl$_2$ system [5]

3. Numerical Results

To examine the feasibility of long-life operation, computational analysis has been performed with Monte Carlo based reactor analysis tool Serpent 2, utilizing ENDF/B-VII.1 library. 200 inactive cycles, 300 active cycles, and 50,000 histories per cycle are sampled.

In order to appraise the effect of uranium enrichment on the reactor size for criticality, the proposed MSMR was simplified as a square cylinder without any molten salt components as depicted in Fig. 4. It is assumed that the reactor vessel and reflector is composed of Hastelloy-N with 10 cm thickness and stainless steel with 40 cm thickness respectively, and the operation temperature is set to be 1,000°C. Table 1 enumerates the size of the critical reactor for various uranium enrichments. It could be recognized that the metallic fuel-based reactor can be small enough to be loaded in a container although LEU has been used as a fuel. And the smaller uranium mass from the miniaturized volume can provide a lower economic burden for equipping the required fuel.

Table 1. Reactor diameter for criticality

Enrichment [wt.%]	Diameter [cm]	Multiplication factor	U mass [kg]
19.75	36	1.02348 ± 32 pcm	530
15	48	1.02743 ± 32 pcm	1,213
13	54	1.01088 ± 32 pcm	1,727
12	59	1.00832 ± 32 pcm	2,253
11	66	1.00565 ± 32 pcm	3,153
10	76	1.00345 ± 32 pcm	4,815

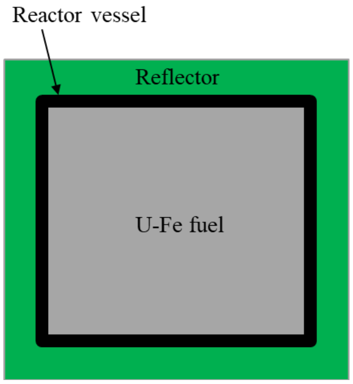

Fig 4. Structure of simplified reactor for preliminary test

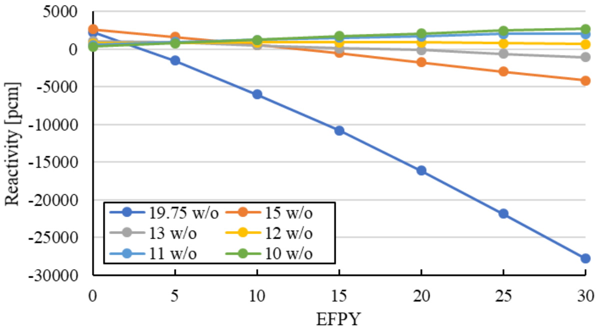

Fig 5. Reactivity change for the simplified reactors

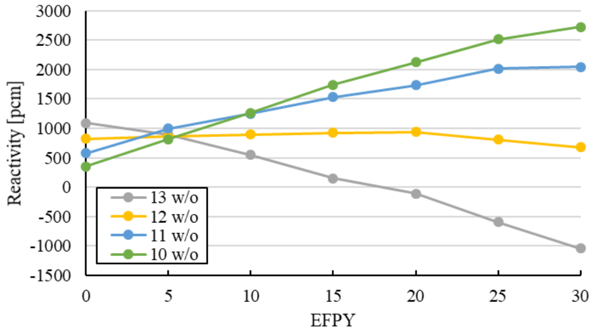

Fig 6. Reactivity change for the simplified reactors

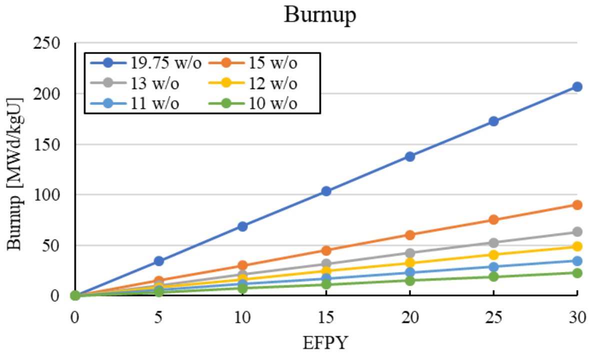

Fig 7. Burnup increment for simplified reactors

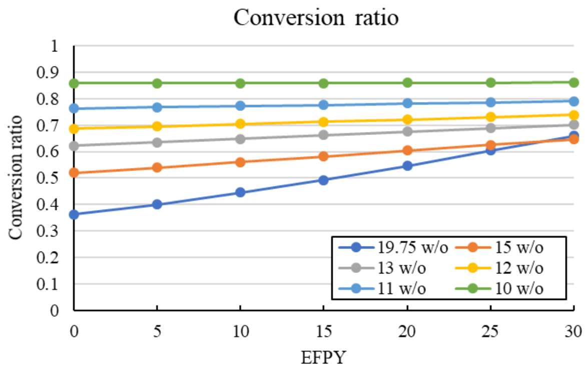

Fig 8. Conversion ratio change for simplified reactors

Fuel depletion calculation for 30 years has been performed with a condition of 10 MWth power. Figs 5 and 6 show reactivity change of the reactor according to each effective full-power year. One could notice that the extent of reactivity decrement during depletion tends to intensify with high uranium enrichment because of the low conversion ratio stemming from a relatively small fraction of fertile material, i.e., low U-238 proportion. In addition, the reactivity could even escalate during depletion for low enrichment cases due to a noticeable conversion ratio. The burnup increment rate is enhanced with enrichment of the fuel due to the small reactor size and compact fuel volume. With comparisons between the results from various enrichments, it was found that 12 wt.% enrichment gives the smallest reactivity swing which most strongly suggests the possibility for achieving a long-life operation.

Fig. 9 illustrates a more precise design including eutectic molten salt NaCl-$MgCl_2$ above the active core, where its volume is set to be identical to that of the metallic fuel. In addition, the diameter of the core and the height of fuel and height of molten salt are postulated to be the same. The Hastelloy-N that comprises the reactor vessel has 5 cm thickness, and the stainless-steel reflector has 40 cm thickness. The eutectic U-Fe with 12 wt.% enrichment U has been used for the fuel, and the diameter for obtaining criticality is estimated to be about 59.6cm, the multiplication factor of BOL is 1.00166 ± 34 pcm, and the initial fuel inventory is 2,267 kg.

To verify the possibility of long-life operation, fuel depletion calculation has been performed with 10MWth and 40 years period. With excess reactivity of 170 pcm, the results from Fig. 10 to 12 plainly attest to the feasibility of obtaining an operation period of about 30 years with moderate spatial power distribution.

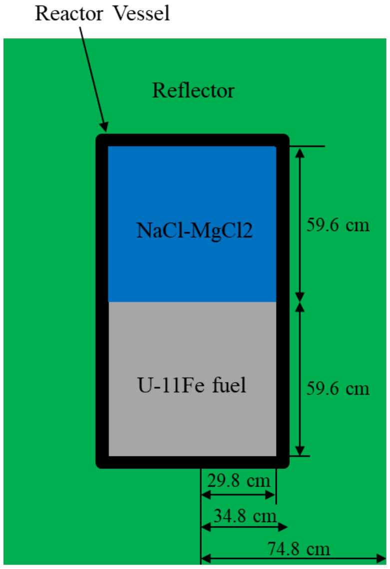

Fig 9. Configuration of MSMR for computational analysis

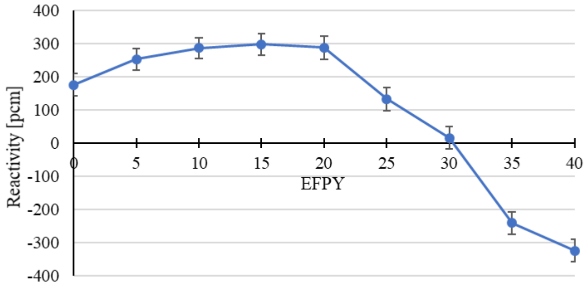

Fig 10. Reactivity change of MSMR operating 30 years

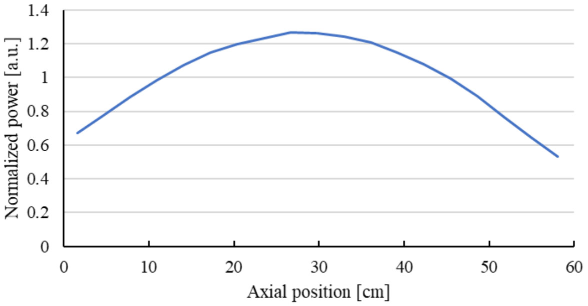

Fig 11. Axial power distribution of MSMR at BOL

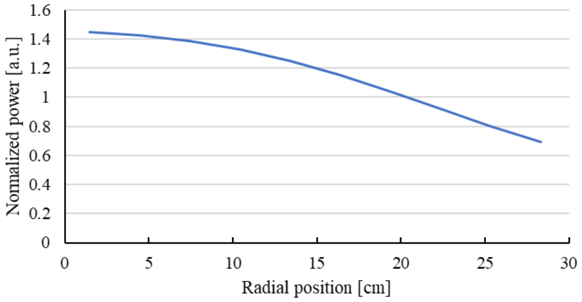

Fig 12. Radial power distribution of MSMR at BOL

4. Summary and Conclusions

The proposed concept of MSMR, which exploits a unique coalescence of layers of metallic fuel and molten salt gives a higher conversion ratio through compact usage of nuclear fuel. The evaluated size of the MSMR is small enough to be loaded in a container, i.e., could be miniaturized as a micro-reactor. The preliminary analysis result suggests an optimal enrichment for minimum reactivity swing to be found 12 wt.%, where the diameter of the reactor is estimated at about 60 cm. The depletion analysis exhibits the possibility of the 10MWth MSMR reactor to be operated for 30 years without any refueling. As aforementioned, the novel MSMR concept allows an extremely simplified structural design and it is expected to be deployed as a mobile power generator in various industry fields including space, reducing dependencies on fossil fuels.

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