# Sensitivity Evaluation of Criticality Uncertainty for Small MSFR Core Design

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## 1. Introduction

The Molten Salt Fast Reactor (MSFR), one of the six candidate reactors selected by the Generation IV International Forum (GIF), has many exceptional benefits and features for advanced nuclear fuel utilization.

The high core power density of MSFR, combined with the use of flowing fuel without any solid moderators inside core, makes it suitable for use as an ultra-small nuclear power plant [1,2]. It can be installed immediately in a module unit and transported to construction sites using trucks, trains, ships, and so on. However using liquid fuel introduces significant uncertainty into nuclear core design. In SMR design, even a minor manufacturing error can have a significant impact on the initial composition, density, cross-section, and core design as a whole, necessitating a complete revision [3]. The impact of those uncertainties is further exacerbated when taking into account the circumstances of continuous removal of fission product or online feeding. In this paper, the largest uncertainty factors were assumed to be the initial molten salt composition mismatch and inaccurate fuel density. To assess the impact of uncertainty, a criticality sensitivity study was carried out.

## 2. Sensitivity Evaluation and Result

### 2.1 Reference Core design

Due to its low melting temperature and soluble actinide isotopes, chloride salt enriched in Cl-37 (99% of Cl-37 and 1% of Cl-35) with a eutectic temperature of 424°C is chosen among numerous molten salt options. The initial fuel salt is composed of $62NaCl\text{-}18MgCl_2\text{-}20TRUCl_3$, with this fraction remaining constant throughout reactor operation. It is assumed that the total fuel salt volume is divided in half and distributed in the core and half in the external fuel circuit. Figures 1 and 2 show a schematic drawing of the preliminary core design. The core of the MSFR was modeled as a simple compact cylinder (1.06 m high x 1.06 m diameter), where nuclear reactions occur within the liquid chloride salt, which acts as both fuel and coolant. The external core structures are protected by 40 cm thick Stainless Steel 304LN reflectors. Considering the use of off-the-shelf transportation casks or trucks, the reactor core was determined to be smaller than the cylindrical space of 2m radius and 2m height.

Goals of nuclear core design are to meet cycle length of 5 effective full power year (EFPY) with target power of 6MWth without refueling.

OpenMC, a Monte Carlo neutron transport code, carried out the criticality sensitivity evaluation. At this stage, the calculation model assumed stationary fuel at BOC by using the ENDF/B-VII.1 cross-section library.

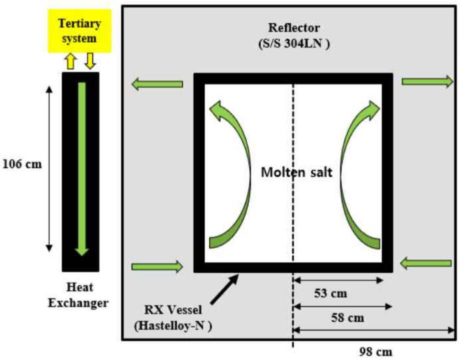

Fig. 1. Radial core layout of reference core.

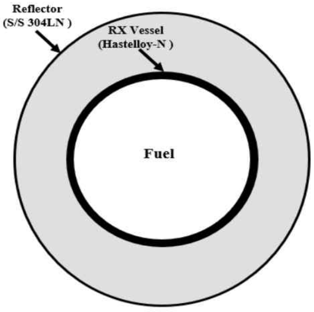

Fig. 2. Top view of reference core layout.

### 2.2 Uncertainty impact of initial TRU mole fraction

It is difficult to produce molten salt fuel with consistent composition with different burnup histories of spent nuclear fuel. Uncertainty of molten salt quality arises technical issues not only for the method of measuring individual nuclides in fuel but also for core design and optimization.

To assess the sensitivity of the above conditions, the mole fractions of NaCl, $MgCl_2$, and $TRUCl_3$ in the initial molten salt fuel were divided by the average fuel temperature. The TRU mole fraction was calculated by increasing the TRU mole ratio by 1% from 15% to 25%, and the average operating temperature was calculated by increasing by 5°C from 575°C to 650°C.

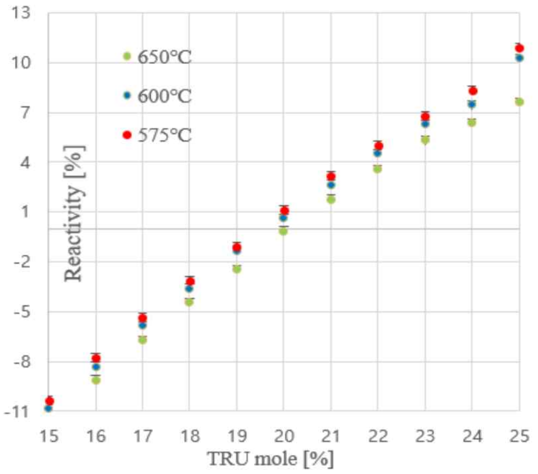

Fig. 3. Reactivity  curve according to TRU mole fraction.

As shown in Fig. 3, the reactivity tends to increase consistently as the fissile density of the molten salt fuel increases in proportion to the increase of the TRU mole fraction. Based on the liquid fuel expansion characteristics, the temperature feedback coefficient was calculated to be high up to 0.02%/°C and gradually increased as the TRU mole fraction increased. The average temperature feedback coefficient was then calculated to be approximately 0.04%/°C, or twice as much as the 25% TRU mole fraction.

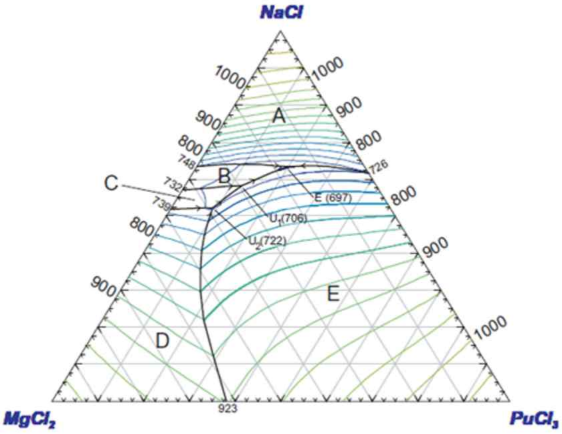

Fig. 4. Calculated liquidus surface of the NaCl-$MgCl_2$-$PuCl_3$ system.

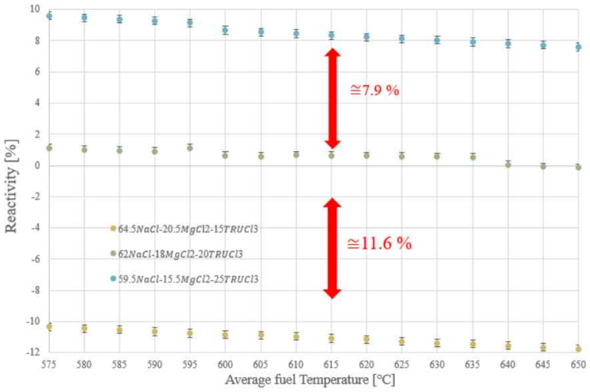

Fig. 5. Reactivity letdown curve according to operation temperature.

The graph above depicts temperature on the x-axis and reactivity on the y-axis. As expected, as the temperature rises, a large negative reactivity is introduced, which is then reduced by the temperature feedback. The curve with the same pattern increases only absolute value with rising fissile density as the TRU mole fraction rises.

Based on the above findings, fuel composion was changed to 62NaCl-08$MgCl_2$-30$TRUCl_3$ on the same eutectic temperature line showed in Fig.4. Then the size of the core was reduced by 26 cm from 106 cm in diameter to 80 cm, and the fuel inventory was reduced by 1225.96 kg, which was approximately half of the 20% of TRU case. Criticality could also be increased by 2.1% when compared to the reference core.

### *2.3 Uncertainty impact of fissile density*

Table I: Criticality Sensitivity Evaluation of Uncertainty

| Molten Salt<br>(NaCl:MgCl2:TRUCl3) | Temperature [°C] | Core size (D/H = 1) | Difference [pcm] | Note |
|---|---|---|---|---|
| 62:08:30 | 610 | 80 | - | Reference<br>Keff = 1.0277±0.00023 |
| | | | -139 | TRU density uncertainty of -0.5% |
| | | | -347 | TRU density uncertainty of -1.2%<br>(Initial fuel loading reduced at -0.5 % ) |
| | | | -690 | TRU density uncertainty of -1.6% |
| | | | -107 | Pu density Uncertainty of -0.5 % |
| | | | -206 | Pu density Uncertainty of -1.0 % |
| | | | -449 | Pu density Uncertainty of -2.0 % |

The above table evaluated how much the criticality would be impacted if the density measurement error of TRU constituting the molten salt and the number density of Pu in TRU composition were both measured incorrectly. The target criticality uncertainty was set as 500 pcm relative to the reference core, and the corresponding TRU density and Pu density uncertainties were investigated. With TRU density uncertainties of 0.5%, 1.2% and 1.6%, the criticality uncertainties are 139 pcm, 347 pcm, and 690 pcm, respectively. For nuclear core design, TRU must be precisely measured to within 1.6%.

In case of uncertain Pu number density, 449 pcm is inserted in comparison to the reference core, while the number density is increased by about 2%.

## 3. Conclusions

A criticality sensitivity study was carried out to assess the impact of uncertainty on the initial TRU mole fraction of molten salt fuel and fissile density. If the TRU mole fraction changes by about 1%, the reactivity changes by about 2%. This is significant enough to reduce core size by 26 cm by increasing the TRU mole fraction by 5%. Additionally, the molten salt fuel inventory was cut in half. Temperature coefficient was estimated to be as high as 0.02%/°C and gradually rose with rising TRU mole fraction. and it reached twice as high around 0.04%/°C in 25% TRU mole fraction. In order for the TRU density uncertainty to differ from the reference case of about 500 pcm, it is limited to having an uncertainty within about 1%. In case of Pu density, the uncertainty must be within 2%. The results presented in this paper are based on preliminary study prior to detailed core design and optimization. As a result, further works should be completed later.

## ACKNOWLEDGMENTS

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