FUEL CYCLE PERFORMANCE OF FAST SPECTRUM MOLTEN SALT REACTOR DESIGNS

Andrei Rykhlevskii[1], Benjamin R. Betzler[2], Andrew Worrall[2], and Kathryn Huff[1]
[1]Dept. of Nuclear, Plasma, and Radiological Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801

[2]Oak Ridge National Laboratory
1 Bethel Valley Road, Oak Ridge, TN, USA

andreir2@illinois.edu, betzlerbr@ornl.gov, worralla@ornl.gov, kdhuff@illinois.edu

ABSTRACT

Use 8.5×11 paper size, with 1" margins on all sides. A required 200-250 word abstract starts on this line. Leave two blank lines before "ABSTRACT" and one after. Use 11 point Times New Roman here and single spacing. The abstract is a very brief summary highlighting main accomplishments, what is new, and how it relates to the state-of-the-art.

KEYWORDS: molten salt, fast reactor, depletion, fuel cycle, salt treatment, salt separations

1. INTRODUCTION

A liquid-fueled Molten Salt Reactor (MSR) concepts promise one of the most desirable and competitive, sustainable energy among of many advanced reactor systems [1]. In MSR fissile and/or fertile materials are dissolved in carrier molten salt (e.g., LiF, NaCl) which leads to immediate advantages over traditional, solid-fueled, reactors. These include near-atmospheric pressure in the primary loop, relatively high coolant temperature, outstanding neutron economy, a high level of inherent safety, reduced fuel preprocessing, and the ability to continuously remove fission products and add fissile and/or fertile elements without shutdown [2].

Historically, researchers focused on thermal spectrum MSR concepts with solid graphite moderator. Oak Ridge National Laboratory (ORNL) operated ≈8 MW_{th} Molten Salt Reactor Experiment (MSRE) pilot reactor from 1965 to 1969 to test approaches/materials, demonstrate fissile recycle (both ^{233}U and ^{235}U), and determine generic MSR operational characteristics [3]. Obtained experience plus promising breakthrough in reprocessing technology [4] chained ORNL attention to the simply configured, also graphite-moderated (i.e., thermal or epithermal), single-fluid Molten Salt Breeder Reactor (MSBR) by the end of the 1960s. The primary weakness of all one-fluid thermal MSR concepts is the fact that the hundreds tons (≈300 t for MSBR [5]) of expensive, radiologically contaminated, neutron-damaged graphite would have to be replaced every 4-10 years, which raises significant waste and economical issues.

In contrast, consistent with Generation IV International Forum (GIF) sustainability and safety goals [6], unmoderated (no graphite), one- or two-fluid (blanket equipped) fast spectrum MSR concepts eventually became the EUROATOM Consortium's "reference" MSR [7]. Other identified advantages of fast MSR systems comparing with conventional reactors include: (1) they can operate in breeding (CR*>1) [7–9], fertile-free transuranic waste (TRU) burning, or U/Th-supported TRU burning [10] regime; (2) they can potentially work in both ^{232}Th/^{233}U and ^{238}U/^{239}Pu fuel cycles (i.e., thermal MSR supports only Th/U); (3) they can be operated in ways that would generate very little long-lived TRU waste, and (4) they would use less natural resources (e.g., natural uranium, natural thorium) per unit energy generated. To quantitatively estimate benefits of these capabilities fuel cycle performance analysis for various fast spectrum MSR concepts is necessary.

Much of the analysis herein uses unit cell representations of four different fast MSR designs: (1) European Molten Salt Fast Reactor (MSFR) [7]; (2) Molten Chloride Salt Fast Reactor (MCSFR) [8]; (3) REBUS-3700 [9]; (4) Molten Salt Actinide Recycler and Transmuter (MOSART) [10]. Some of these designs are two-fluid (1, 2), operate in thorium fuel cycle (1,4), or use TRU as start-up fissile material. The concepts (2) and (3) use chloride salts† while (1) and (2) employ fluorides. This paper discusses the depletion simulation of different fast MSRs to identify fuel cycle performance for deployment of this reactor technology.

2. METHODS

To determine Fuel Cycle Performance parameters four different fast spectrum MSRs were selected. Table 1 contains summary of principal data of these designs. Fuel cycle performance analysis required depletion simulation for each reactor concept over the whole system lifetime which in this work assumed to be 60 years‡. Full-core 60-years depletion computation for MSR model required massive computing power. Computation time can be significantly reduced by performing depletion simulation for simplified unit cell representation instead of full-core one with sophisticated geometry.

2.1. Subsection Title: First Character of Each Non-trivial Word is Uppercase

Double-space before and after secondary titles is automatic. Figures and tables should appear as close as possible to where they are first cited, e.g., Fig. **??**, in the text. Figures are numbered in Arabic numerals, with the caption centered below the figure, in **boldface**. For a better arrangement it is strongly recommended that all the figures must be placed in the"Figures" folder. Triple-space before the figure, and after the figure caption.

3. RESULTS

When importing figures or any graphical image please verify two things:

*Conversion ratio (CR) $\equiv$ fissile generated/fissile consumed: if CR<1 the reactor is a "converter"; CR$\equiv$1, an "isobreeder"; CR>1, a "breeder".

†The chlorine in the MCSFR is fully enriched in ^{37}Cl because ^{35}Cl (76% abundance) is a very strong neutron poison in fast neutron energy range.

‡Lifetime for fast MSR limited by neutron damage on the reactor vessel. Further R&D activities should be performed to evaluate maximum fast neutron fluence and assess structural materials choice. Moreover, MOSART concept has graphite reflector which should be replaced every 4 years.

Table 1: Principal data of selected fast spectrum MSRs designs.

Parameter	MSFR	MCSFR	REBUS-3700	MOSART
Thermal power, MW	3,000	6,000	3,700	2,400
Fuel salt volume (in/out of core)	18 (9/9)	38 (16/22)	55.6 (36.9/18.7)	49.05 (32.7/16.35)
Fertile salt volume (in/out of blanket)	7.3 (7.3/0)	75 (55/22)	—	—
Fuel and fertile salt initial composition (mol%)	LiF-ThF_4-$^{233}UF_4$ (77.5-19.9-2.6) LiF-ThF_4 (77.5-22.5)	NaCl-UCl_3-$^{239}PuCl_3$ (60-36-4) NaCl-UCl_3 (60-40)	55 mol%NaCl+ 45 mol%(natU+ 16.7at.%TRU)Cl_3	LiF-BeF_2-ThF_4-$TRUF_3$ (69.72-27-1.28)
Fuel cycle	Th/^{233}U	U/Pu	U/TRU	Th/^{233}U
Initial fissile inventory, t	5.060	9.400	18.061	9.637

- Any number, text or symbol is in Times font and is not smaller than 10-point after reduction to the actual window in your paper
- That it can be translated into PDF

Equations, such as Eq. (1), should be centered and sequentially numbered to the flush right of the formula.

$$\text{Speedup} = \frac{1}{\frac{f}{p} + (1 - f)} \tag{1}$$

The continuation of a paragraph after an equation should not be indented. All paragraphs, as well as section or subsection headings, are separated by just one single empty line.

3.0.1. Sub-subsection level and lower: only first character uppercase

See Table 2 for a sample table. The “tabls” package is recommended for improved row and column spacing. Notice the caption appears above the table by setting the `\caption` command immediately after the `\begin{table}`. Tables are numbered in Roman numerals, with the caption centered above the table, in **boldface**. Triple-space before and after the table.

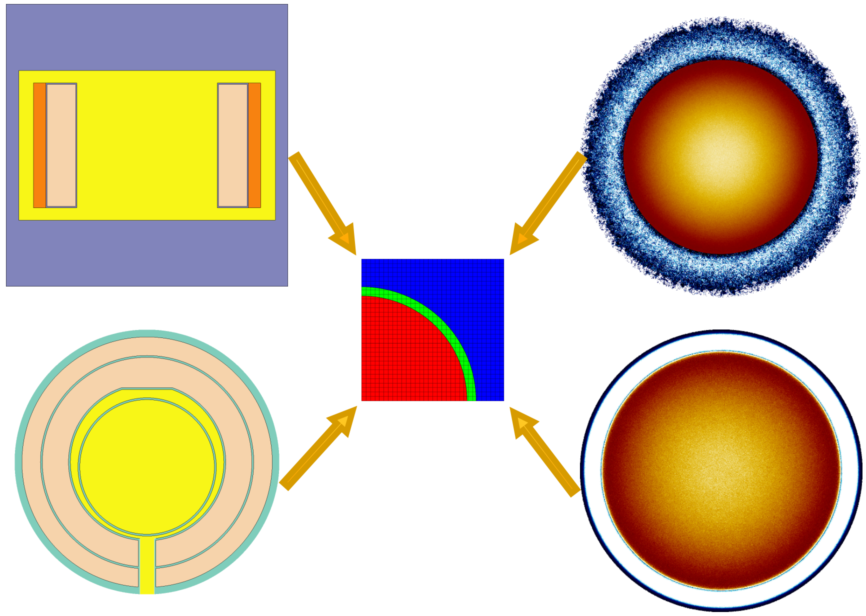

Figure 1: Full-core 3D models of MSFR (upper left), MCSFR (lower left), REBUS-3700 (upper right), MOSART (lower right), and 2D unit cell model (center) showing fuel salt (red), fertile salt (green), structural material (blue).

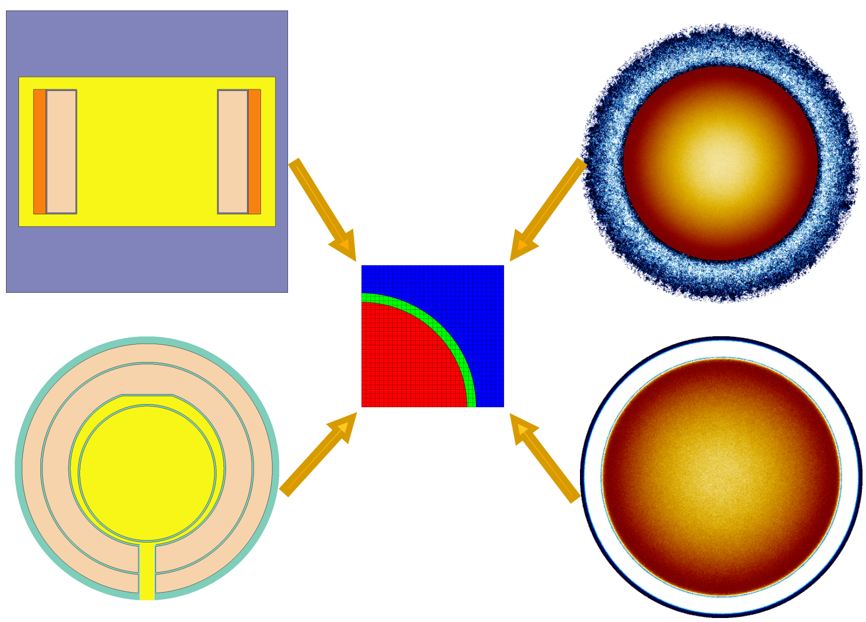

Figure 2: Neutron flux energy spectrum for full-core and unit cell models for two-fluid MSFR (left) and MCSFR (right).

4. CONCLUSIONS

Present your summary and conclusions here.

Table 2: Parallel Performance for the Sample Problem

Parameter MSFR	(T_s/T_p)	(%)	
1	100.0	—	—
2	52.6	1.9	95.0

NOMENCLATURE

If variables are extensively used in the text, a Nomenclature section would be helpful to the readers.

ACKNOWLEDGEMENTS

Acknowledge the help of colleagues and sources of funding, as appropriate.

As an example: The format for this template was adapted from the LaTeXtemplate for the PHYSOR-2018 conference posted and available on the Internet and most of the LaTeX format definitions contained in this were already defined. The M&C 2019 organizing committee deeply thank the PHYSOR-2018 technical committee for this great support.

REFERENCES

[1] D. D. Siemer. "Why the molten salt fast reactor (MSFR) is the best Gen IV reactor." *Energy Science & Engineering*, **volume 3**(2), pp. 83–97 (2015).

[2] D. LeBlanc. "Molten salt reactors: A new beginning for an old idea." *Nuclear Engineering and Design*, **volume 240**(6), pp. 1644–1656 (2010). URL http://www.sciencedirect.com/science/article/pii/S0029549310000191.

[3] H. G. MacPherson. "The Molten Salt Reactor Adventure." *Nuclear Science and Engineering*, **volume 90**(4), pp. 374–380 (1985). URL http://moltensalt.org/references/static/downloads/pdf/MSadventure.pdf.

[4] M. E. Whatley, L. E. McNeese, W. L. Carter, L. M. Ferris, and E. L. Nicholson. "Engineering development of the MSBR fuel recycle." *Nuclear Applications and Technology*, **volume 8**(2), pp. 170–178 (1970).

[5] R. C. Robertson. "Conceptual Design Study of a Single-Fluid Molten-Salt Breeder Reactor." Technical Report ORNL–4541, comp.; Oak Ridge National Lab., Tenn. (1971). URL http://www.osti.gov/scitech/biblio/4030941.

[6] GIF. "Generation IV International Forum 2015 Annual Report." Technical report, Generation IV International Forum (2015).

[7] "Final Report Summary - EVOL (Evaluation and Viability of Liquid Fuel Fast Reactor System) | Report Summary | EVOL | FP7| European Commission." Final report 249696, France (2015). URL https://cordis.europa.eu/result/rcn/159411_en.html.

[8] W. E. SIMMONS and J. SMITH. "AN ASSESSMENT OF A 2500 MWe MOLTEN CHLORIDE SALT FAST REACTOR." Technical Report AEEW-R956, United Kindom Atomic Energy Authority (1974).

[9] A. Mourogov and P. M. Bokov. "Potentialities of the fast spectrum molten salt reactor concept: REBUS-3700." *Energy Conversion and Management*, **volume 47**(17), pp. 2761–2771 (2006). URL http://www.sciencedirect.com/science/article/pii/S0196890406000549.

[10] V. Ignatiev, O. Feynberg, I. Gnidoi, A. Merzlyakov, V. Smirnov, A. Surenkov, I. Tretiakov, R. Zakirov, V. Afonichkin, A. Bovet, V. Subbotin, A. Panov, A. Toropov, and A. Zherebtsov. "Progress in development of Li,Be,Na/F molten salt actinide recycler and transmuter concept." In *Proceedings of ICAPP 2007* (2007). URL http://inis.iaea.org/Search/search.aspx?orig_q=RN:39090717.