IMPACTS OF FAST-SPECTRUM MOLTEN SALT REACTOR CHARACTERISTICS ON FUEL CYCLE PERFORMANCE[1]

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The System Analysis and Integration Campaign nuclear fuel cycle evaluation and screening study was conducted to outline the potential benefits and challenges of nuclear fuel cycle options. The study identified continuous recycle in fast critical reactors as a common characteristic shared among some of the most promising future nuclear fuel cycles. This study was technology agnostic to focus on the underpinning physics that drives fuel cycle outcomes. This process used an analysis example to generate a physics-based understanding of the fuel cycle, and it yielded performance metrics over ranges rather than comparing absolute numbers. While no fast-spectrum molten salt reactor (MSR) has ever been built, several concepts exist using different fuels and carrier salts, many of which target high-burnup objectives, such as light-water reactor nuclear waste consumption. Putting the resulting fuel cycle impacts of these reactor choices (e.g., fuel and neutron spectrum) into perspective is informative for our current understanding of a given fuel cycle's performance, and it also demonstrates the applicability of MSRs to different fuel cycles. It has been established that in a fuel cycle transition, performance of a given fast-spectrum MSR depends in part on the initial fuel loading requirements and processing methods.

I. INTRODUCTION

In support of the Systems Analysis and Integration Campaign that was implemented by the US Department of Energy Office of Nuclear Energy (DOE-NE), fast-spectrum molten salt reactors (MSRs) were analyzed to assess performance of the reactor technology in various fuel cycles. These analyses are part of a larger study DOE-NE chartered to evaluate and screen nuclear fuel cycle options. This evaluation and screening (E&S) study provides information about the potential benefits and challenges of nuclear fuel cycle options, including the complete nuclear energy system, from mining to disposal. This information was intended to strengthen the basis and provide guidance to DOE-NE activities in the Fuel Cycle Research and Development Program [1]. A technology-agnostic approach was followed to avoid focusing on specific fuel cycle technologies such as specific reactor designs. Instead, characteristics were studied that could be shared by several reactor designs. A common characteristic among some of the most promising future nuclear fuel cycles was continuous recycle in fast critical reactors.

Liquid-fueled MSRs were originally conceived in the years of early reactor technology development at Oak Ridge National Laboratory (ORNL), culminating in the design and operation of the Molten Salt Reactor Experiment (MSRE) [2]. Liquid-fueled MSR concepts have seen increased interest due in part to the recent private investment in advanced reactor technology [3]. Some of these concepts note enhanced fuel cycle outcomes (e.g., reduction of actinide waste per MW generated and increased resource utilization) obtained based on the potential characteristics of MSRs, including low excess reactivity, online refueling, and fission product removals.

While critical liquid-fueled MSRs were used as the analysis example for 2 of the 40 evaluation groups (EGs) within the E&S study (Table I), this technology could be deployed as the analysis example for many of the other 38 EGs due to the flexibility in MSR design space (e.g., a fast-spectrum MSR could serve the same function as a sodium fast reactor [SFR]). In many cases, reactor types for analysis examples were chosen to ensure a straightforward physics-based assessment without significant tool development. Such analysis examples include

TABLE I. Selected EGs from the E&S Study

EG	Description	Analysis Example
01	Once-through using enriched-U fuel in thermal critical reactors	PWR
10	Limited recycle of ^{233}U/Th with new Th fuel in fast and/or thermal critical reactors	MSR
23	Continuous recycle of U/Pu with new natural-U fuel in fast critical reactors	SFR
24	Continuous recycle of U/TRU with new natural-U fuel in fast critical reactors	SFR
26	Continuous recycle of ^{233}U/Th with new Th fuel in thermal critical reactors	MSR
28	Continuous recycle of ^{233}U/Th with new Th fuel in fast critical reactors	SFR

pressurized water reactor (PWR), sodium fast reactor (SFR), and high temperature gas reactor (HTGR) designs.

Previous analyses on the fuel cycle performance of selected thermal and fast MSRs show that the overall fuel cycle performance assessments align within that of the analysis examples, with an underperformance in fuel cycle metrics dependent on the perceived large flow rates required to continuously process fuel salt material [4]. This paper discusses the approach and results from fuel cycle analyses for five fast-spectrum MSRs from literature.

II. MOLTEN SALT REACTOR SYSTEMS

In liquid-fueled MSRs, molten salt fuel is continuously circulated through the core, undergoing irradiation, chemical treatments and separations, and feeds (fueling) simultaneously. This presents a challenge for modern neutron transport and depletion tools designed for analysis of solid-fueled systems, where the fission products, actinides, and activated isotopes physically remain within a fuel rod or assembly. The MSR design space is very broad, including many different designs: thermal and fast-spectrum designs; designs using fluoride or chloride salts; multiple-spectrum designs; multiple-fluid designs; and burner, break-even, and breeder designs. The analyses herein rely on fast-spectrum MSR designs from literature to understand their performance within the context of the E&S study.

Five existing fast-spectrum MSR concepts with sufficient design information to build a reactor physics–based fuel cycle model were selected for this analysis (Table II):

1. Molten Chloride Fast Breeder Reactor (MCFBR) [5],
2. European Molten Salt Fast Reactor (MSFR) [6],
3. Molten Chloride Salt Fast Reactor (MCSFR) [7],
4. REBUS-3700 [8],
5. Molten Salt Actinide Recycle and Transmuter (MOSART) [9].

II.A. Molten Chloride Fast Breeder Reactor

The MCFBR design [5] is a 2,000 MWt two-fluid reactor concept with a NaCl carrier salt. The two salts are a stationary $PuCl_3$-NaCl fuel salt and a flowing UCl_3-NaCl coolant salt. The fuel salt is located at the center of the cylindrical reactor. It circulates within the core region, meaning that it does not flow to a heat exchanger, and it provides most of the power in the reactor. The core region contains an array of 1.26 cm diameter tubes on a 1.38 cm pitch through which coolant salt circulates from the blanket region. The coolant salt is located in the annular blanket that surrounds the core region axially and radially.

This coolant salt flows through the coolant tubes in the core region and to the heat exchanger. Due to the large blanket region, only a small fraction of coolant salt is estimated to be outside the core during operation.[1] Neutronically, this is a highly absorptive composition that converts ^{238}U to ^{239}Pu. The volume of this coolant salt is 13–14 times larger than the fuel salt (i.e., the axial and radial blankets are very large). The two streams are kept separate during operation, only communicating through plutonium feed. During operation, this reactor has three main ongoing processes: (i) natural or depleted uranium is being fed to the coolant salt, (ii) plutonium is being separated from the coolant salt and immediately fed into the fuel salt, and (iii) salt treatment and separations are ongoing for the fuel and coolant salts. With a very high density and quality fuel driver salt, only a small amount of fissile inventory is required at start up.

[1] The exact fraction is not provided in design documents.

II.B. European Molten Salt Fast Reactor

The European MSFR is a 3,000 MWt two-fluid reactor concept with a LiF carrier salt. The two salts are a flowing UF_4-ThF_4-LiF fuel salt and a stationary ThF_4-LiF blanket salt. The blanket salt is located at the periphery of a cylindrical fuel salt core region (Fig. 1). A reflector sits radially adjacent to this blanket salt.

The primary fuel salt flows to the heat exchanger. Approximately half of this flowing fuel salt is outside the core during operation. At startup, the primary fissile material is ^{233}U within the fuel salt. The blanket salt shields neutrons from secondary side components and breeds fissile ^{233}U from fertile ^{232}Th. During operation, this reactor has three main ongoing processes: (i) ^{232}Th is being fed into the fuel and blanket salts, (ii) ^{233}U is being separated from the blanket salt and immediately fed into the fuel salt, and (iii) salt treatment and separations are ongoing for the fuel and coolant salts.

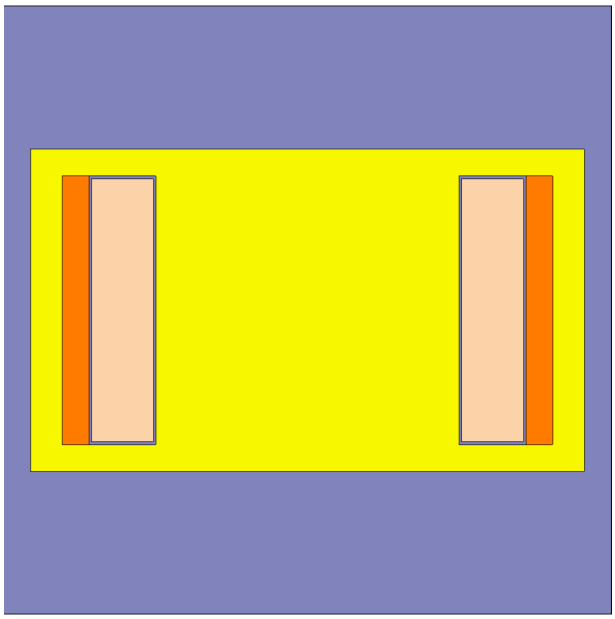

Fig. 1. Representative full-core *rz* geometry for the MSFR, showing the fuel salt (yellow) and blanket salt (peach).

TABLE II. Principal data of selected fast spectrum MSR designs.

Parameter	MCFBR	MSFR	MCSFR	REBUS-3700	MOSART
Thermal power, MW	2,000	3,000	6,000	3,700	2,400
Fuel salt volume (in/out), m^3	3.7 (3.4/0.3)	18 (9/9)	38 (16/22)	55.6 (36.9/18.7)	49.05 (32.7/16.35)
Fertile salt volume (in/out), m^3	46 (42/4)	7.3 (7.3/0)	75 (55/22)	—	—
Fuel salt initial composition, mol%	$PuCl_3$-NaCl (16-84)	LiF-ThF_4-$^{233}UF_4$ (77.5-19.9-2.6)	NaCl-UCl_3-$^{239}PuCl_3$ (60-36-4)	NaCl + (natU + 16.7at.%TRU)Cl_3 (55-45)	LiF-BeF_2-ThF_4-$TRUF_3$ (69.72-27-1.28)
Fertile salt initial composition, mol%	UCl_3-NaCl (65-35)	LiF-ThF_4 (77.5-22.5)	NaCl-UCl_3 (60-40)	—	—
Fuel cycle	U/Pu	Th/^{233}U	U/Pu	U/TRU	Th/^{233}U
Initial fissile inventory, t	3.150	7.726	9.400	18.061	9.637

II.C. Molten Chloride Fast Reactor

The MCSFR is a 6,000 MWt two-fluid reactor concept with an NaCl carrier salt. The two salts are a flowing (U/Pu)Cl_3-NaCl fuel salt and a flowing UCl_3-NaCl blanket salt. The fuel salt resides within a central spherical core, with the blanket salt within a spherical shell outside of this active core region. The spherical shell geometry is neutronically ideal (Fig. 2).

Both salts flow to heat exchangers, with a significant amount of each salt being outside the core during operation: over half of the fuel salt and nearly a third of the blanket salt. Like the MCFBR, the primary fissile material at startup is Pu, but with the reduced molar fraction of fissile plutonium within the fuel salt, a larger initial fissile inventory is required.

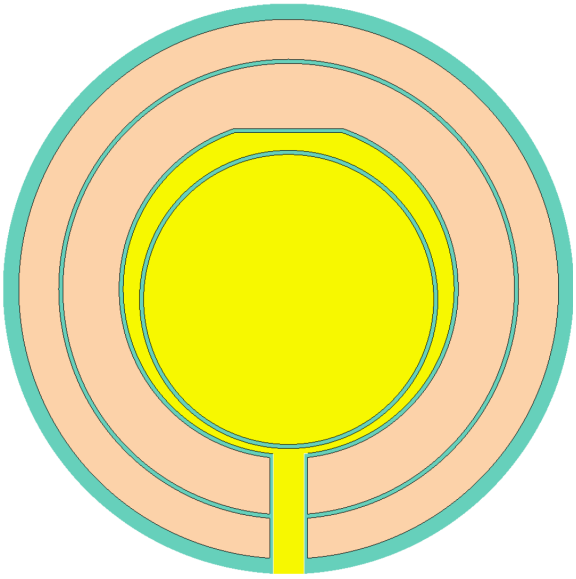

Fig. 2. Representative full-core *rz* geometry for the MCSFR showing the fuel salt (yellow) and blanket salt (peach).

The blanket salt absorbs neutrons from the central core driver region, breeding fissile ^{239}Pu and shielding secondary side components. During operation, this reactor has three main ongoing processes: (i) natural uranium is being fed into the fuel and blanket salts, (ii) plutonium is being separated from the blanket salt and immediately fed into the fuel salt, and (iii) salt treatment and separations are ongoing for the fuel and coolant salts.

II.D. REBUS-3700

The REBUS-3700 is a 3,700 MWt single-fluid reactor concept with an NaCl carrier salt. This single (U/TRU)Cl_3-NaCl fuel salt contains both fissile and fertile material. This fuel salt fills a graphite-reflected cylindrical core vessel (Fig. 3).

The salt flows through the active core and to the heat exchangers, with approximately one third of the total salt volume outside the core during operation. Due to the co-mingled fissile and fertile material and the size of the cylindrical reactor system, the required initial fissile material inventory is relatively high. At startup, the primary fissile material is obtained from reprocessed spent fuel; using a different initial fissile material inventory is not expected to change the overall fuel cycle performance within the context of the E&S Study. Fertile ^{238}U within the fuel salt absorbs neutrons and transmutes to ^{239}Pu, which is immediately available to drive fissions within the fuel salt. During operation, this reactor has two main ongoing processes: (i) natural uranium is being fed into the single salt and (ii) salt treatment and separations are ongoing for the fuel and coolant salts.

II.E. Molten Salt Actinide Recycle and Transmuter

MOSART is a 2,400 MWt single-fluid reactor concept with a LiF-BeF_2 carrier salt. The single (TRU/Th)F_4-BeF_2-LiF fuel salt contains both fissile and fertile material. This fuel salt fills a metal-reflected cylindrical vessel (Fig. 4).

Like the REBUS-3700 reactor, this single salt flows from the active core to the heat exchangers, with approximately one third of the salt outside the core during operation. Co-mingling of the fissile and fertile materials increases the initial fissile material loading, which consists of TRU from reprocessed spent fuel. Fertile ^{233}Th within the fuel salt absorbs neutrons and transmutes to ^{233}U, which is immediately available to drive fissions within the fuel salt. Three processes occur during operation: (i) ^{232}Th is being fed into the single salt, (ii) LWR TRU is being fed into the single salt, and (iii) salt treatment and separations are ongoing for the fuel and coolant salts. Unlike the others, this reactor is designed as an LWR waste transmuter, taking in additional fissile material from the LWR TRU vector.

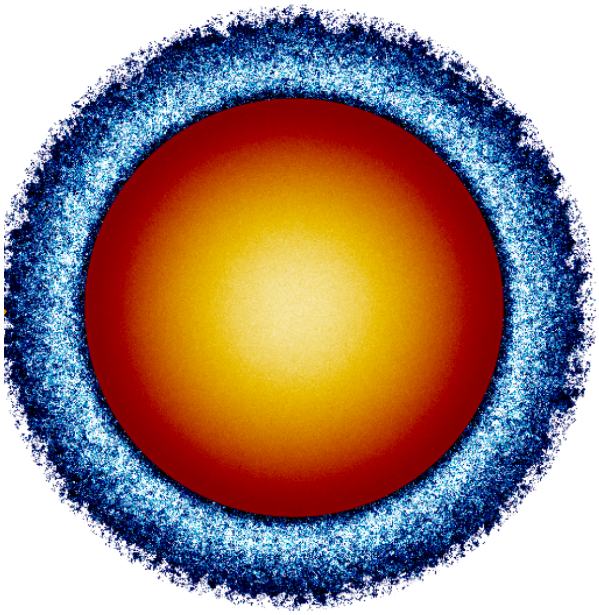

Fig. 3. Representative full-core *xy* geometry for the REBUS-3700 showing the fission density in the fuel salt (orange) and reflector neutron flux (blue).

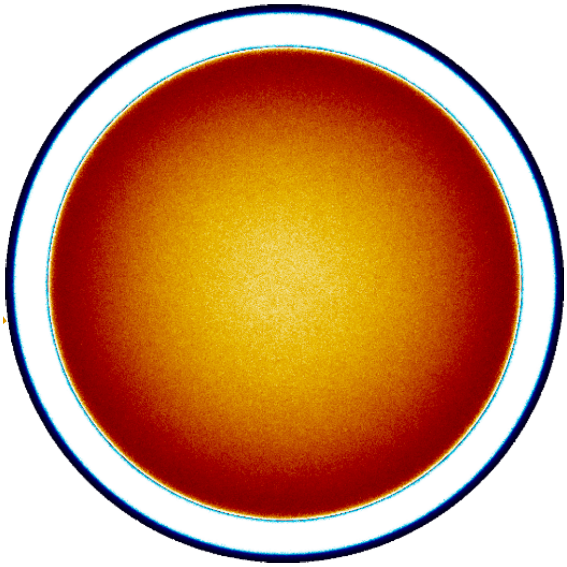

Fig. 4. Representative full-core *xy* geometry for MOSART showing the fission density in the fuel salt (orange).

II.F. Design Summary

These concepts include different fuel materials (Th, TRU, Pu, and NU), single-fluid (REBUS-3700 and MOSART) and two-fluid (MCFBR, MSFR, and MCSFR) systems, and several carrier salt types (NaCl, LiF, and BeF_2-LiF). The fuel cycle designs of the MCFBR and MCSFR fall into EG23, provided continuous recycling is performed (Figs. 5 and 6). For REBUS-3700, the fuel cycle design falls into EG24, provided continuous recycling is performed (Fig. 7). The fuel cycle design of the MSFR and MOSART fall into EG28, provided continuous recycling is performed (Figs. 8 and 9).

These five designs were not selected to represent the entirety of the fast-spectrum MSR design space. The ranges in heavy metal salt densities, initial fissile material inventory, and ex-core salt volumes have a large impact on transitions and starting up additional reactors [10, 11]. The initial fissile material inventories do not scale with thermal power density due to the different ex-core volumes and power density, which is theoretically not as limited as in solid fueled reactors. In addition, higher coolant temperatures would lead to a higher energy conversion efficiency than typical LWRs.

III. FUEL CYCLE SIMULATIONS

Each concept has been assessed using SCALE in a systematic approach for modeling the fuel cycle [4, 12, 13, 14]. Performance metrics extracted from these simulations are used to categorize each system according to the E&S study and then to determine the relative performance for an abbreviated set of metrics. For this fuel cycle analysis, the reactor physics behavior of each design was approximated with unit cell models (Fig. 10) that are designed to preserve flux spectra and reaction rates of higher fidelity models [4, 14]. These approximations are appropriate for fuel cycle simulations and would not impact results shown herein.

A Python script known as ChemTriton [12] is used to model the operation of the MCFBR. ChemTriton is a tool developed at ORNL that is capable of modeling the changing isotopic composition of a fuel salt during reactor operation with SCALE. This tool models salt treatment, separations, discards, and fueling using single- or multi-zone transport models. ChemTriton builds on earlier ORNL efforts that modeled MSRs with SCALE [15] by updating to the latest version of SCALE and expanding the capabilities offered for MSR models.

The operation of the other four fast-spectrum reactors leverage new continuous removal and tracking capabilities implemented in the SCALE/TRITON module [16]. These implementations have been developed and tested using analytic solutions and use case problems and are capable of efficiently generating reactor physics and fuel cycle behavior over the lifetime of an MSR. The SCALE-integrated tools compare well with ChemTriton simulations considering the differences

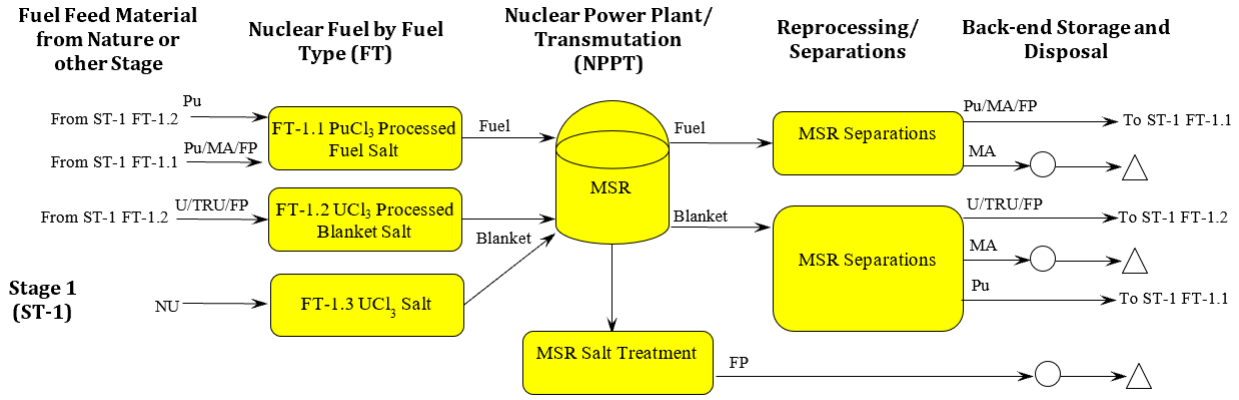

Fig. 5. Fuel cycle flow diagram for the MCFBR with continuous recycling (EG23).

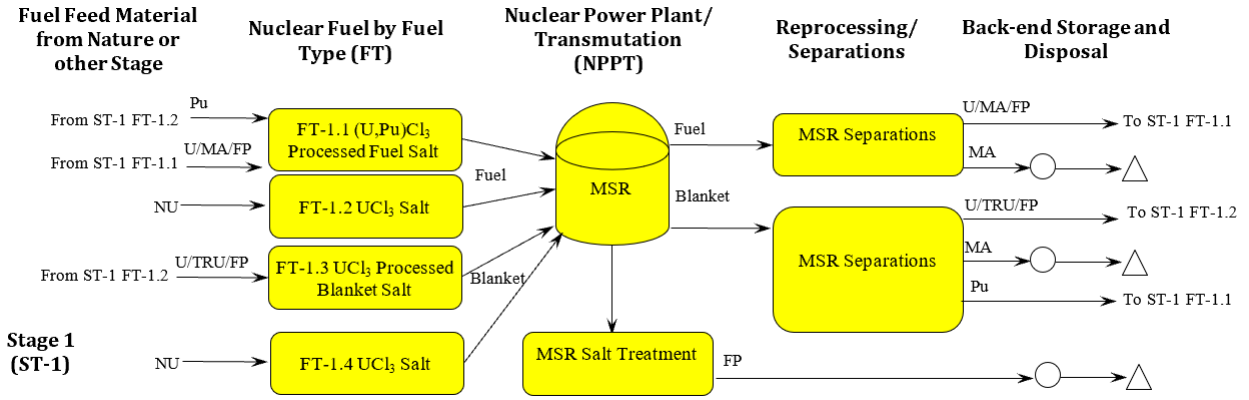

Fig. 6. Fuel cycle flow diagram for the MCSFR with continuous recycling (EG23).

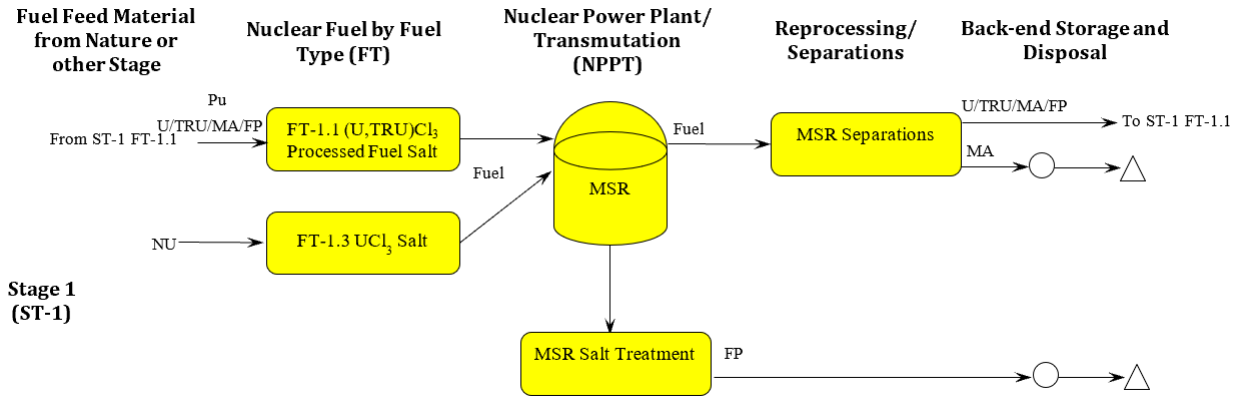

Fig. 7. Fuel cycle flow diagram for the REBUS-3700 with continuous recycling (EG24).

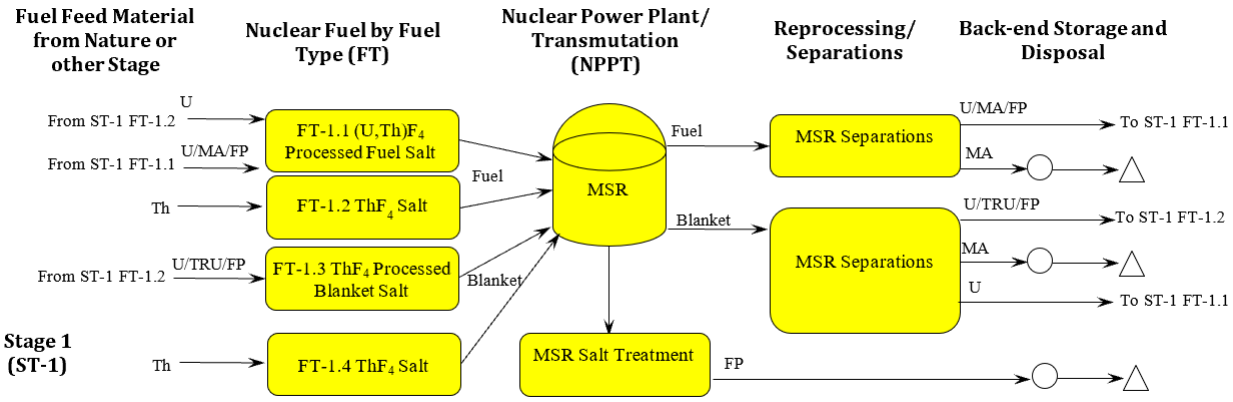

Fig. 8. Fuel cycle flow diagram for the MSFR with continuous recycling (EG28).

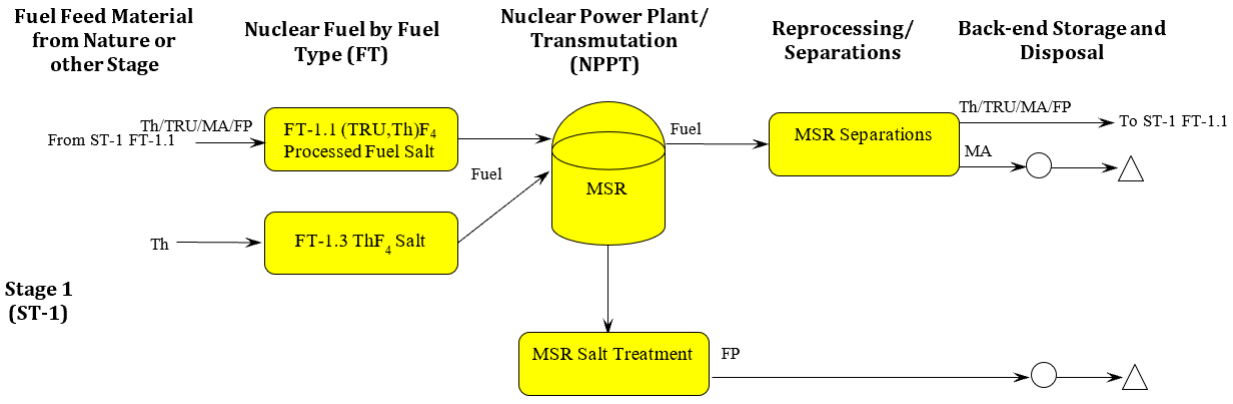

Fig. 9. Fuel cycle flow diagram for the MOSART with continuous recycling (EG28).

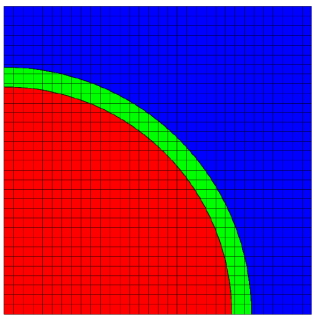

Fig. 10. Representative unit cell models for fuel cycle simulations.

and approximations inherent to the ChemTriton methodology.

Each SCALE/TRITON simulation is the result of running several simulations to refine the a priori time-dependent feed rate and pattern necessary to maintain a critical configuration throughout the reactor lifetime.

IV. FUEL CYCLE METRICS

For each analysis, the evolution of the fuel salt was simulated for a projected core lifetime of 60 years, and the fuel cycle analysis was performed at the end of the simulation. Fuel cycle metrics for these five MSRs were calculated to be consistent with the E&S study; these fuel cycle metrics correspond to an equilibrium condition in the reactors. Calculated metrics are categorized on a scale from A–E, with A representing higher performance [1].

Because MSR technology is significantly different than that of solid-fueled reactors, it is difficult to appropriately quantify fuel cycle impact and compare it directly to solid-fueled systems. For example, the fuel salt consistently flows and may undergo continuous processing, increasing the material flow rates and impacting fuel cycle metrics. Thus, it is more important to note the reasons for differences in individual metrics rather than using metrics to make an overreaching statement on the performance of MSRs relative to other reactor technologies. In addition, due to continuous salt treatments and processing, MSRs may be more suitable in limited recycle fuel cycles from a performance and physics standpoint, though this is not explored here.

For fuel cycle metrics based on processing flow rates (e.g., carbon emissions), these fast-spectrum MSRs underperform other solid-fueled fast-spectrum technologies. However, scaling these flow rate metrics in the same manner that is used for solid-fuel flow rates does not capture the actual differences in the physical processes required to maintain a molten fuel salt. Without significant detail on this physical process design, generating a more physically informed metric is not feasible.

Overall, fast-spectrum MSRs perform on par with their EG analysis example counter parts for natural uranium and thorium utilization; mass of depleted uranium (DU), recovered uranium (RU), and recovered Th (RTh) disposed; and mass of spent nuclear fuel (SNF) and high level waste (HLW) disposed (Table III). For these metrics, each design falls within the highest performance bin. This high performance is due to the fast spectrum in these designs, which increases the breeding ratio, lowers the feed requirements, and effectively achieves a very high burnup. Within the context of the E&S Study, these findings support (1) the EG classification using fuel type, spectrum, and identifying critical reactors and (2) the choice of analysis example as representative of technologies exhibiting the characteristics identified within that classification.

These fuel cycle metrics do not capture the benefit of fuel cycle transition using MSRs [11]. In MSRs, the liquid fuel is continuously circulated through the core and is processed online. The fuel spends a minimal amount of time in discharge, reloading, reprocessing, or fabrication states; the actual holdup time varies by design. The operation of a typical solid-fueled breeder reactor consists of several steps: load fissile material at the beginning of cycle; burn fuel until end of cycle; discharge, cool, and reprocess spent fuel; and fabricate new fuel from recovered fissile material. Therefore, the out-of-core time for MSRs is notably lower, which results in much lower doubling times than other breeder systems. However, the evolving fuel salt composition in MSRs influences breeding ratios and doubling times, as fission products and actinides build up in the core during operation. In addition, the performance in a transition scenario is highly dependent on the total initial fissile material inventory [10], which varies between designs. In some cases, the initial fissile material inventory may be larger than that of a typical solid fueled reactor if large volumes of salt are retained within the primary loop and additional processing systems.

V. DISCUSSION

Liquid-fueled MSRs may fit into many fuel cycle EGs within the E&S study because of their design flexibility. Due to continuous online separations, low excess reactivity, and online fuel feed, MSRs have a favorable neutron economy. Combined with a higher thermal efficiency due to higher operating temperatures and possible utilization of more efficient thermal cycles such as Brayton cycles, the improved neutron economy in MSRs tends to result in positive fuel cycle outcomes, with improved resource utilization and waste management. For fast-spectrum MSRs, these characteristics and the hardened spectrum lead to low resource utilization and low waste generation metrics on par or better than their fast-spectrum solid-fueled reactor counterparts. Within the context of the E&S study, the performance of these fast spectrum MSRs is consistent with the EG solid-fueled analysis examples. This consistent performance reaffirms the E&S technology-agnostic approach.

Additional fuel cycle metrics show that MSRs are impacted by the large flow rates required to continuously process fuel salt material. Larger flow rates may lead to lower specific power densities and larger material losses in processing, although details on these processes remain uncertain. Salt separations processes could be developed or applied to reduce mass flow rates in the analyses in this study. These metrics do not highlight the strengths of MSRs in transition scenarios, which are quantified by shorter doubling times for MSRs.

TABLE III. Fuel cycle characteristics and performance ofr fast spectrum MSR designs.

Parameter	MCFBR	MSFR	MCSFR	REBUS-3700	MOSART
Evaluation group	23	28	23	24	28
Natural uranium utilization	A	—	A	A	—
Natural thorium utilization	—	A	—	—	A
Mass of DU+RU+RTh disposed	A	A	A	A	A
Mass of SNF+HLW disposed	A	A	A	A	A

VI. ACKNOWLEDGMENTS

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