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Government Sector Activities to Reduce Thermal-Spectrum Molten Salt Breeder Reactor Investment Risk

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Changing the World's Energy Future

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Idaho National Laboratory

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Thermal-spectrum molten-salt breeder reactors (TS-MSBRs) have long been recognized as having high potential for clean, safe, large-scale, cost-effective energy production for the foreseeable future. U.S. government support for TS-MSBR development was stopped half a century ago believing they were too technically difficult. Technology progression over the past several decades as well as the pressing need for clean power on-demand provides incentives to reconsider the development program cancellation. Limited, early-stage, government sector activities have the potential to sufficiently reduce investor risk to trigger the private sector investment necessary to commercialize the reactor class. These activities are summarized in this article.

1 Background

Thermal-spectrum molten salt breeder reactors (TS-MSBRs) potentially have highly desirable characteristics for cost-effective energy production including not requiring high-assay low-enriched uranium (HALEU) - or uranium enrichment at all following fuel-cycle start-up. In addition, these reactors will operate at low-pressure, have strong passive safety characteristics, as well as strong proliferation resistance, an insubstantial actinide waste stream, abundant fuel, and (like other molten salt reactors [MSRs]) the highest exergy (i.e., the ability to do work) of any reactor class. However, the required technology remains immature with unresolved technical issues that will require significant, sustained resources to overcome.

The U.S. government supported TS-MSBR development from the late 1940s through the mid-1970s. The program was stopped in the mid-1970s due to the relative technology immaturity and estimated remaining resources required to commercialize the reactor class. Simultaneously, proliferation resistance became a necessary element for all reactor technologies, and the planned TS-MSBR fuel cycle included several steps that would have provided relatively direct access to unacceptably high fissile content materials. Decreased load growth combined with the availability of large quantities of inexpensive fossil fuels inhibited subsequent reconsideration of the reactor class including the redesign of its fuel cycle.

2 Introduction

The current need for large quantities of dispatchable clean energy combined with limited domestic capacity for uranium enrichment (especially HALEU with ^{235}U enrichments above 10 wt%) along with the high costs associated with adequately safe, large light-water-cooled reactors (LWRs) is driving the reconsideration of a broader set of advanced reactor technologies. The continuing issue of high-level waste storage and disposal increases the incentive for reactor concepts that do not generate substantial actinide waste streams. The purpose of this paper is to assess government sector activities that would efficiently reduce the investment risk for commercializing TS-MSBRs.

In the United States, energy production is a private sector responsibility. Consequently, advanced reactor commercialization will be primarily performed within the private sector. Part of the reason for reevaluating TS-MSBRs is that, since the historic government program was terminated, their most likely development pathway has changed from a primarily public sector activity to a private-sector-led activity spurred by government activities and incentives. The government sector, however, maintains unique roles in enabling private-sector-led development. The government, also, has non-financial objectives including promoting a clean and healthy environment, creating high value jobs, as well as reclaiming U.S. leadership in nuclear energy technology and developing advanced nuclear fuel cycles.

TS-MSBRs have the potential to accomplish all the Generation IV nuclear energy goals, notably including the potential to "have a clear life-cycle cost advantage over other energy sources" [1]. TS-MSBRs, however, will require substantial development resources for several years to achieve their potential. Development and deployment are likely to occur progressively from small to large size and simple to complex plant configurations and fuel cycles, as well as progressively introducing more advanced materials. A staged development approach forms the basis of the plans described in this discussion. Some development stages may be commercially viable even though they do not achieve all the class capabilities. For example, non-breeding thermal-spectrum MSRs could only have limited, quasi-inherent, on-site fuel salt chemical processing but would generate actinide-bearing wastes and would have a continuing need for low-enrichment uranium (LEU). With current uranium reserves, breeding additional fissile material only becomes necessary if nuclear power begins to provide a substantial fraction of the world's energy for an extended period (multiple decades) [2]. Non-breeding thermal-spectrum MSRs could provide a useful, nearer-term bridge capability while fuel salt processing technologies are matured.

Both non-U.S. national programs and private sector developers within and outside the United States are currently pursuing TS-MSBR development. To date, U.S. developers have not been successful in raising sufficient funding to adequately mature TS-MSBRs. However, both substantial high-temperature reactor relevant technology development and regulatory changes have occurred over the past half-century altering the TS-MSBR commercialization landscape. Nuclear power plant (NPP) regulations in the United States are currently reflective of the vulnerabilities and risk characteristics of the current fleet (e.g., of large LWRs). While the strong safety characteristics of MSRs decrease the difficulty in showing that TS-MSBRs would not present an unacceptable hazard, substantial effort will be required to comply with (or to obtain exemptions, where appropriate, from) the existing, highly prescriptive set of regulations.

3 Fuel Cycle Configuration

Liquid fuel enables many different plant configurations, and the purpose of this evaluation is not to recommend a particular design. For example, heat transfer from the fuel salt can take place within the core (fuel salt within tubes or between plates), within the vessel (integral), or exvessel (loop) and the fuel, the coolant, or both can be pumped. The common plant characteristics for the configurations evaluated herein include (1) achieving breeding gain, (2) not employing material that cannot meet the International Atomic Energy Agency (IAEA) definition of the longest time for conversion to non-peaceful uses, and (3) not generating a substantial actinide-bearing waste stream.

A neutron yield per absorption greater than the number needed to sustain criticality provides excess neutrons that can be used to breed additional fissile material. At relevant fuel salt temperatures (~1000 K), only ^{233}U has sufficiently high neutron production to result in breeding gain. The central challenge to breeding additional ^{233}U is that its ^{232}Th precursor feedstock requires exposure to neutrons to initiate the transmutation chain into ^{233}U, yet the intermediate product, ^{233}Pa, has a roughly 27-day half-life and a sufficiently high neutron absorption cross section that cannot be exposed to a significant neutron fluence. Moreover, some fission products have significant neutron absorption cross sections for thermal neutrons (e.g., ^{135}Xe and ^{149}Sm), necessitating intensive fuel salt processing to achieve substantial breeding gain. Core physics design includes several other considerations, such as the need for a heterogenous configuration to enable fast neutrons to thermalize away from the resonance absorption energy region.

Pure ^{233}U would be an unacceptably attractive nuclear material. The IAEA detection timeliness table, from its safeguards-glossary [3], indicates that isotopic mixtures of uranium containing a total of less than 20% of ^{233}U and ^{235}U remain at the highest conversion time interval. In other words, maintaining a non-fissile uranium concentration over 80% results in the highest conversion time. One means to separate ^{233}Pa from ^{232}Th, while not generating a separated stream of fissile material, is to co-separate the actinides from the fuel salt. Conocar et al. have demonstrated (at a laboratory level of maturity) an aluminum-based method to strip actinides from fluoride salts [4]. Once the actinides have been stripped from the salt, the fission and corrosion products can be stripped from the salt prior to returning reconstituted barren salt to use. Once the ^{233}Pa has decayed into ^{233}U, sufficient fissile material to maintain criticality (most of the co-separated actinide mixture) would be returned to the salt. The remainder of the co-separated actinide mixture would be retained to use as startup fuel for future TS-MSBRs. The ^{239}Pu, bred from the ^{238}U employed to denature the ^{233}U, remains at low concentration due to its efficient consumption and is never separated from the other actinides. TS-MSBRs lack technology capable of separating ^{239}Pu from other actinides. Plutonium-239 production decreases with the decreasing uranium concentration as the primary fissile material transitions from ^{235}U to ^{233}U. Second generation (those started on fissile material bred in first generation TS-MSBRs) and subsequent generations of TS-MBSRs will begin operation with higher, non-fissile heavy actinide content as well as lower ^{239}Pu production. Non-fissile heavy actinides gradually build up to equilibrium concentrations in the fuel salt [5]. Figure 1 provides a conceptual diagram of a potential reactor configuration and candidate fuel cycle process steps for a TS-MSBR.

Figure 1 – TS-MSBR and fuel cycle conceptual diagram

The TS-MSBR fuel cycle could be started with LEU (5% ^{235}U) along with sufficient thorium to initiate ^{233}U production while maintaining criticality. Information about the thermophysical properties of quaternary mixtures of LiF-BeF_2-UF_4-ThF_4 was developed early in the historic MSBR program providing confidence that useful compositions (those with less than 20 mole% actinides) will have sufficiently low melting points and viscosities to be useful as fuel salts [6]. At startup, TS-MSBRs will not be a breeder as all the fissions are from ^{235}U. Breeding gradually increases as the fuel salt fissile material transitions to a mixture of ^{233}U along with a smaller amount of ^{239}Pu. The fuel salt uranium concentration needs to be higher during fuel cycle startup to provide sufficient excess neutrons to initiate ^{233}U breeding due to the lower neutron yield of the ^{235}U and to compensate for neutron absorptions in ^{238}U. As increasing amounts of ^{233}U are produced, the fuel salt uranium to thorium concentration ratio can be lowered, which minimizes ^{239}Pu production, while still providing sufficient excess neutrons to transition to a breeding fuel cycle.

Consuming the excess ^{238}U (i.e., the non-fissile uranium beyond that required to maintain low material attractiveness) from the LEU needed to maintain criticality during the transition to ^{233}U operation will take multiple years. Figure 2 provides the evolution of the transuranic actinide content for each batch of fuel salt starting on 5 weight-% ^{235}U. The TS-MSBR transition time to producing fuel salt for progeny reactors would be decreased by employing higher ^{235}U enrichment during the fuel cycle startup due to the decreased amount of ^{238}U buildup. Starting up on 19.75% enriched uranium fuel salt would enable TS-MSBRs and would altogether avoid the need to burn out excess ^{238}U.

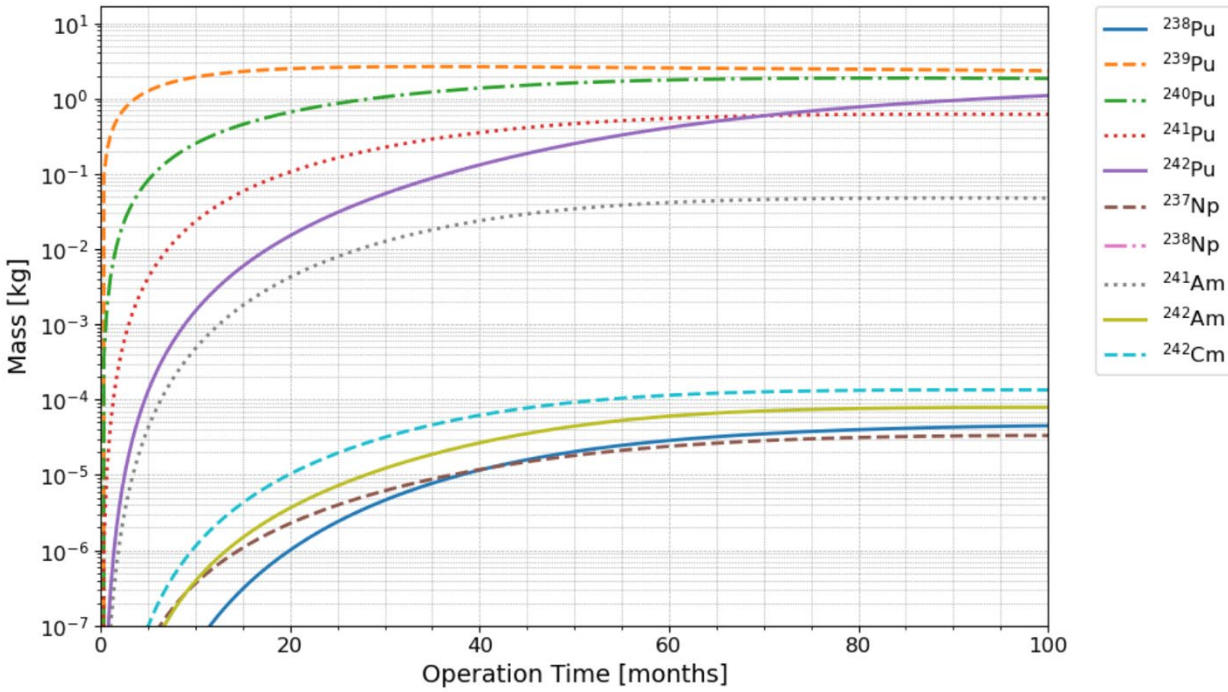

Figure 2 - Evolution of transuranic isotope content of each fuel salt batch of 5-weight% ^{235}U started TS-MSBR

U.S. production capability for higher assay uranium (especially enrichments above 10%) is currently extremely limited. Moreover, substantial quantities of natural uranium continue to be available at reasonable cost, decreasing the importance of the time to transition to rapid breeding. The use of LEU+ (5% < ^{235}U < 10%) to initiate the TS-MSBR fuel cycle may represent a reasonable compromise of relying on more readily available uranium enrichment while decreasing the amount of time necessary to transition to the production of fuel salt for progeny reactors. Holcomb and Tano [7] provides more details on the fuel cycle and breeding performance of one potential TS-MSBR design. Figure 3 provides a graphical representation of TS-MSBR performance characteristics.

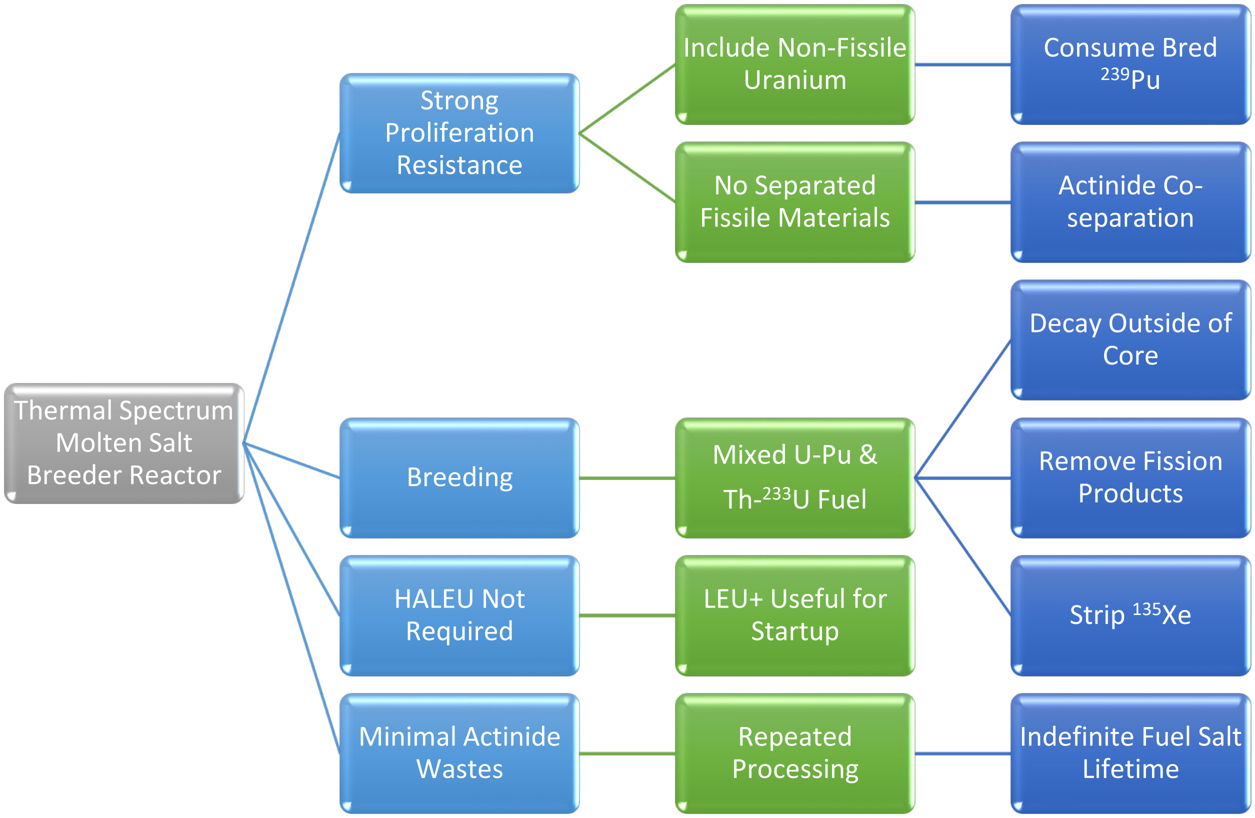

Figure 3 Hierarchical representation of TS-MSBR performance characteristics

The ex-core holdup of the fissile material during processing results in requiring several fuel salt volumes at the plant providing incentive to employ a design that minimizes active fuel salt volume, e.g., fuel in tube. Fissile material requirements, however, are substantially reduced by the frequent removal of parasitic absorbers and fuel addition (i.e., does not employ neutron poisons) as well as the reduced self-shielding due to the lower (as compared to solid fuel) actinide loading of the fuel salt. Moreover, the core of a TS-MSBR would be optimally moderated, avoiding the potential for substantial reactivity accidents.

The size and complexity of an integrated TS-MSBR including its fuel salt processing and waste handling equipment are, so far, unknown. Multiple stages of actinide separations from the fuel salt would be implemented sequentially resulting in essentially complete actinide separation. The fuel salt processing is less mature than the reactor technology, and no integrated demonstration has ever been performed. The fuel salt processing appears likely to be the larger, more complex portion of the plant. However, until all aspects of plant have reached sufficient maturity, the costs, development timeline, and overall system potential will remain speculative.

4 Assessment

The basic assessment methodology employed is to map the elements of the private sector investment decision process against TS-MSBR technology and deployment requirements to understand the remaining tasks and which have the highest potential impact. The fundamental set of evaluation metrics that guide any investment decision are (1) solid management, (2) size of the market, (3) advantageous product characteristics, and (4) risks [8].

4.1 Solid Management

The U.S. government has a limited role in enabling assessment of management, chiefly by providing an independent review of whether performance claims are reasonable and supported by evidence. However, perhaps the largest impediment to future investments in advanced reactors is that advanced reactors have no examples of prior successful commercial deployment. Commercially deployed advanced reactors have not performed well leading to substantial, well-justified investor skepticism. Previous government-led advanced-reactor-deployment efforts (e.g., the Clinch River Breeder Reactor) have seen massive cost escalations and schedule delays. The historic advanced reactor project failures have their origins in not adequately understanding the full set of technology, regulatory, and deployment issues and consequent costs early on.

One of DOE-NE's goals is to enable the deployment of advanced reactors [9]. Performing technology maturity assessments and development activity planning are supporting elements of accomplishing the goal. Peer review by independent experts remains the best available method to assess technology issues and maturity levels. The U.S. Atomic Energy Commission's (AEC's) Division of Reactor Development and Technology performed a detailed evaluation of TS-MSBRs in 1972 [10]. While the review is dated and occurred prior to proliferation resistance becoming a baseline requirement for all fuel cycles, it provides detailed, expert analysis that increases the confidence that the key technology issues necessary to be resolved have been identified.

The combination of very high potential, complexity, and substantial technology divergence from other advanced reactors makes TS-MSBRs especially vulnerable to overly simplistic analysis. Overly simplistic analysis can result in either the technology being oversold, glossing over significant unresolved technical and regulatory issues, or being subjected to specious criticism. TS-MSBRs will be highly integrated systems requiring cross-disciplinary expertise for effective evaluation. Creating and periodically updating a TS-MSBR deployment issue identification and technology maturity status information resource would be a valuable government sector contribution toward enabling private sector evaluation of performance claims and cost estimates.

4.2 Size of the Market

A primary motivation for TS-MSBR development and deployment is the size of the potential market. TS-MSBRs have the potential to supply a major fraction of the world's energy safely and economically for the indefinite future (millennia). Their equilibrium fuel feedstock is a mixture of natural uranium and thorium. Moreover, the high exergy of MSRs enables them to support a broader set of industrial processes than any other reactor class, while their liquid fuel facilitates medical and industrial isotope production. However, much of the TS-MSBR value does not accrue to investors, but to society—clean air and water, economic development, good jobs, as well as plentiful and reliable energy.

An analysis of electricity production market size for the TS-MSBR is performed via an elastic growth analysis and presented in Figure 3. In the blue line, the figure shows the expected market size growth for nuclear electricity, assuming 30% of the worldwide electricity production comes from nuclear sources [11]. The red line is the expected growth for conventional nuclear. The orange line shows the available market share, i.e., the current market share minus the one already occupied by conventional nuclear electricity production. The green line is the expected market share captured by a potential deployment of the TS-MSBR. While TS-MSBRs have advantageous characteristics, other advanced reactor types are also anticipated to be deployed, and substantial uncertainty remains as to which reactors will capture particular market shares. This follows an elastic development analysis with a learning rate in the levelized cost of energy (LCOE) of 0.5$/year and a market elasticity of 40 GW/year [12]. In brief, this analysis shows the potential for the deployment of the TS-MSBR for electricity production. Further analysis is needed to better refine the potential deployment scenarios.

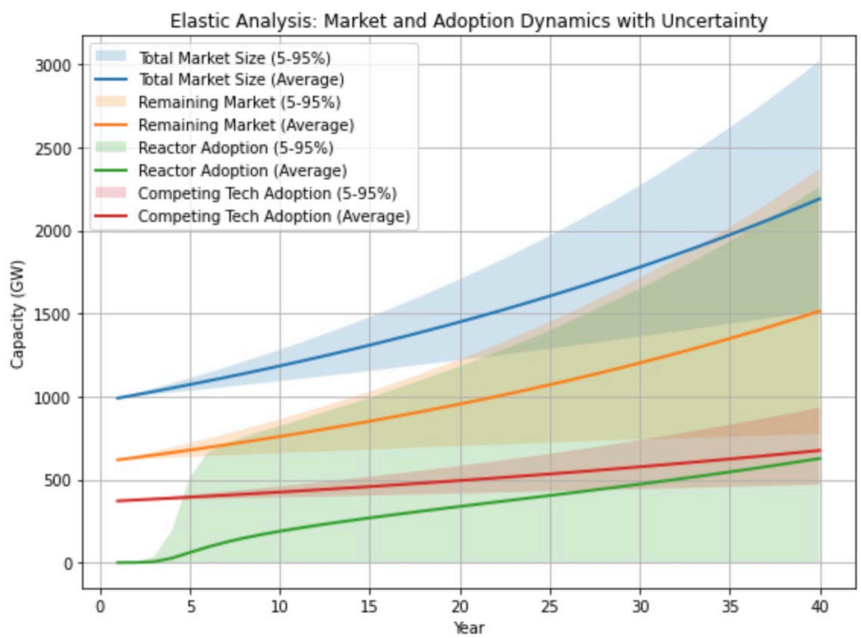

Figure 4 Current market size for nuclear electricity production, assuming 30% of the electric production worldwide comes from nuclear sources, current nuclear production, remaining market share, and modeled growth for the TS-MSBR.

4.3 Advantageous Characteristics and Consequent Rationale for Government Support

TS-MSBRs have the potential for highly advantageous characteristics including the potential for a clear lifecycle cost advantage (see Section 4.3.1) over other energy production technologies. Notably, they are the only high-temperature thermal-spectrum reactor that can achieve significant breeding, and unlike fast-breeders, they do not require HALEU for startup. Further, TS-MSBRs will not emit combustion products into the air or produce substantial quantities of high-level nuclear waste. Nuclear fuel only becomes waste when it can no longer perform its functions. The content of TS-MSBR fuel salt would ordinarily be adjusted as part of normal operations to remove parasitic neutron absorbers and other contaminants, add fertile material, and remove bred fissile material. The non-fissile heavy actinides remain in the fuel salt and build up to equilibrium concentrations [5]. Figure 5 shows the time evolution of the mass of transuranic actinides in each batch of TS-MSBR fuel for startup with 7-weight% ^{235}U. Ionic liquids (such as fuel salt) are not vulnerable to radiation damage. In short, TS-MSBR fuel salt has an indefinite lifetime and only directly results in fission and activation product radioactive wastes. Fuel salt, however, never ceases to contain actinides, and all the actinides within the fuel salt would become high-level waste if not useful to future reactors.

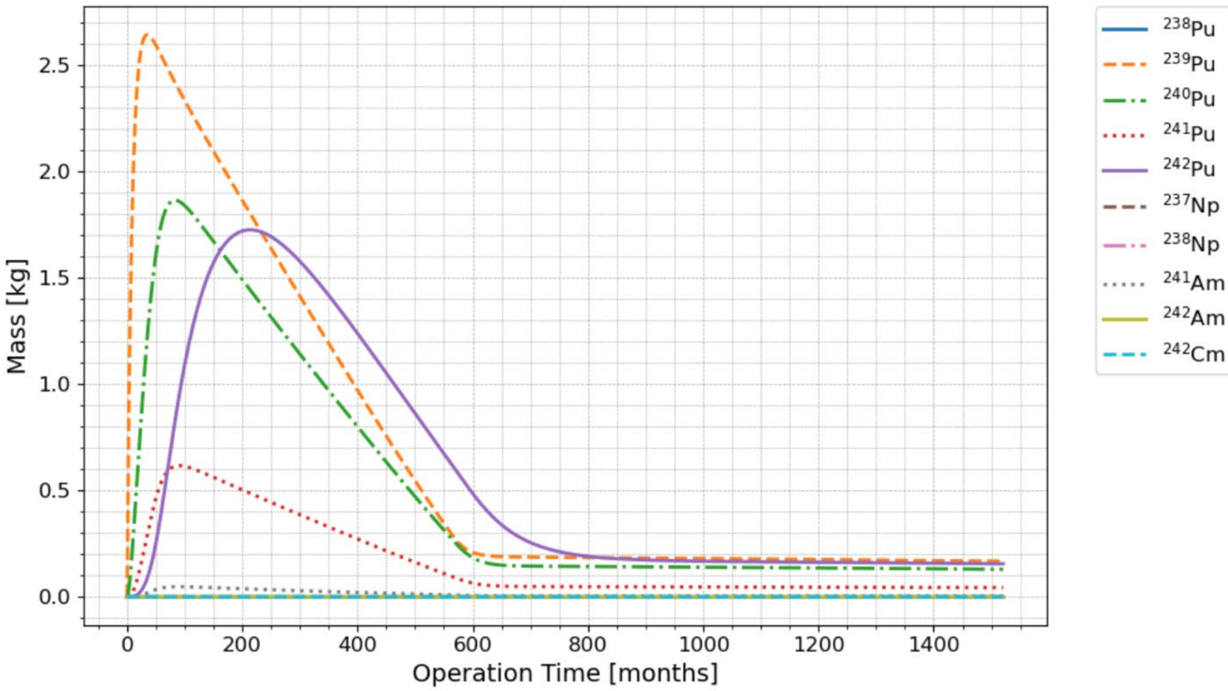

Figure 5 – Evolution of mass of transuranic isotopes in each batch of TS-MSBR fuel starting with 7-weight% ^{235}U

Operating TS-MSBRs will produce limited-quantities of actinide wastes. Solid material in contact with the fuel salt will become damaged by the operating environment resulting in a limited lifetime and will have actinides deposited onto its surfaces. Fuel salt processing equipment when it reaches end of life will be heavily contaminated with fuel salt materials (actinides, fission products, and activated material). Fuel salt separations will need to be sufficiently effective so that the actinide content of direct fuel waste streams meet regulatory requirements for shallow land disposal.

TS-MSBRs have multiple advantageous safety characteristics. MSRs operate at low-pressure, so lack a driving force to cause radionuclides to disperse into the environment and consequently do not require massive pressure retaining structures. TS-MSBRs, however, will be within robust structures or located below grade to withstand external events (e.g., wildfires, floods, tornadoes, and aircraft impact). The fuel salt chemically retains most radionuclides. Those that are released during normal operations (e.g., fission gases, aerosols, and vapors) would ordinarily be trapped away from the core, so would not be vulnerable to release during reactor accidents. The reactor rapid reactivity feedback coefficients are all strongly negative. TS-MSBRs operate hundreds of kelvins from the fuel salt boiling temperature, operate near optimal moderation, and have no cliff-edge-type phenomena (i.e., no departure from nucleate boiling and no hypothetical core disruptive accidents); so they have no need for fast acting safety systems. Liquid fuel salt cannot be mechanically damaged, enabling the reactor to withstand large reactivity transients without harm. Fuel salt provides strong buoyancy-driven convective heat transfer simplifying passive decay heat removal under loss-of-forced flow accident conditions. Liquid fuel salt flows similarly to other low-viscosity Newtonian fluids, enabling defueling the reactor as part of an accident response. Conceptually, liquid fuel can be displaced from a critical configuration as an alternative to moving neutron absorbers (e.g., control rods) into the critical region. Design features, such as a sloped fuel salt catch pan below the reactor vessel to direct fuel salt spills to cooled, highly subcritical drain tanks, enable the plant to withstand even large fuel salt spills or reactor vessel failure without challenging containment. No uncontainable accidents have been identified for MSRs, enabling a simpler, containment-focused safety-adequacy assessment.

TS-MSBRs can start on LEU (will never require HALEU) and will not require uranium enrichment at all following fuel cycle startup. Their equilibrium fertile feedstock will be a combination of natural enrichment uranium (U_{nat}) and thorium (Th). While breeder reactors can supply abundant energy for the indefinite future, a once-through LEU U-Pu fuel cycle remains the leading candidate fuel cycle to minimize system complexity in first generation deployment. A once-through U-Pu fuel cycle at MSRs will have the same fuel cycle advantages and challenges as the once-through U-Pu fuel cycle at LWRs, namely because it requires the continuous addition of LEU to maintain criticality and results in an actinide-bearing waste stream. Initially, implementing an as-simple-as-possible fuel handling system decreases the probability of unanticipated cost escalation and schedule slippage. Cost and schedule remain dominant issues in nuclear power deployment. Growth in nuclear power deployment is currently primarily constrained by cost. While TS-MSBRs characteristics (e.g., low-pressure and high degrees of passive safety) provide the opportunity for lower costs in mature systems, the complexity of the fuel cycle processes substantially increases the risks of higher costs and poor overall reliability in initial deployments.

TS-MSBRs will employ liquid fuel. Liquid fuel provides multiple advantages, such as not requiring precision fuel fabrication with nuclear-grade quality assurance and its attendant costs. Adequate quality control for incoming fuel salt can be provided through measuring its composition. Further, the fuel salt composition would ordinarily be adjusted during use to maintain the composition within an acceptable range.

TS-MSBRs, like all nuclear reactors, would be anticipated to be dispatchable, would have high availability, and could schedule maintenance outages at times of lower demand. The nuclear portion of TS-MSBRs would be able to rapidly load follow. However, given that their marginal cost to operate is minimal and thermal cycling plant systems has the potential to significantly shorten component lifetimes, it is anticipated that a thermal reservoir would be employed to buffer demand variability and facilitate product switching. TS-MSBRs, as with other reactors, will require much lower quantities of land and materials than diffuse, environmentally scavenged power (e.g., solar and wind) and could be located near the energy demand, decreasing transmission costs. High-temperature systems, such as MSRs, can more easily employ air (water would be preferred where available) as their ultimate heat sink, allowing siting away from valuable shorelines.

Liquid salt cooling enables the generated energy to be delivered over a narrow, high-temperature range, resulting in the highest exergy (or the ability to do work) of any reactor class and enabling

MSRs to efficiently support a broader set of thermochemical cycles (notably thermochemical hydrogen production [13]) than other reactor classes.

4.3.1 Economic Competitiveness

The analyses are performed for a 300 MWth plant. The LCOE is a widely used metric to evaluate the economic feasibility of energy generation technologies. It represents the cost per unit of electricity generated over the lifecycle of a project, considering all associated expenses. The LCOE is calculated using the formula:

$$LCOE = \frac{\sum_{t=1}^{T} \frac{C_{cap}(t)+C_{op}(t)+C_{fuel}(t)+C_{dec}(t)}{(1+r)^t}}{\sum_{t=1}^{T} \frac{E(t)}{(1+r)^t}}.$$

In this equation, T represents the financial payback time, assumed to be 40 years [14]. The discount rate, r, varies between 3% and 10% to account for different financial conditions [15]. Capital costs, $C_{cap}(t)$, are amortized over the reactor's lifetime using the capital recovery factor (CRF). Operational and maintenance (O&M) costs, $C_{op}(t)$, fuel costs, $C_{fuel}(t)$, and decommissioning costs, $C_{dec}(t)$, are included as discounted cash flows. Energy generation, $E(t)$, is similarly discounted to represent the time value of electricity produced. Additionally, the analysis incorporates carbon credits, which account for avoided greenhouse gas emissions and are modeled as negative cost components.

The cost estimates are performed with the FORCE (Financial Opportunity and Risk Calculating Evaluation) framework at Idaho National Laboratory (INL) [16], which provides a comprehensive financial analysis for advanced nuclear reactors by evaluating capital costs, operation and maintenance (O&M) costs, fuel costs, decommissioning costs, and potential revenue from carbon credits. It estimates capital expenditure by considering site preparation, equipment, materials, labor, and engineering services. For O&M costs, it accounts for staffing, routine maintenance, repairs, and regulatory compliance over the reactor's lifecycle. Fuel costs are calculated based on raw material acquisition, fuel fabrication, transportation, storage, and refueling frequency. Decommissioning costs are projected by analyzing the complexity of dismantling the facility and managing radioactive waste. Additionally, FORCE incorporates potential revenue from carbon credits, evaluating their market value and estimating credits earned by reducing greenhouse gas emissions. This integration enables the financial projection of the reactor development, aiding stakeholders in understanding the economic viability and risks of advanced nuclear reactor projects.

The capital cost represents the initial investment required to construct the reactor. For this study, the baseline value is computed by combining the main components of the reactor plant at \$5,512/kW, which aligns with estimates for advanced nuclear reactors utilizing optimized designs [17]. The main cost advantages of the concept are related to the lower operating pressure of the reactor core, which relaxes mechanical requirements in the main structures of the core loop and reduces the containment requirements due to a lower internal pressure in case of accidents. The cost is annualized using the CRF:

$$CRF = \frac{r(1+r)^T}{(1+r)^T - 1}.$$

This factor ensures consistent treatment of capital expenditures over the reactor's operational lifespan. To account for uncertainties in first-of-a-kind reactors, capital costs are modeled with a uniform distribution ranging from 81% to 143% of the baseline value. This variability captures potential cost overruns due to supply chain inefficiencies, labor, or material challenges in early deployment phases [18].

O&M costs encompass the expenses required for reactor operation, regular inspections, and maintenance activities. These costs are computed to be $24.9 million/year and are varied between 92% and 133% to reflect possible deviations in operating efficiency [19]. O&M costs are discounted annually over the operational lifespan of the reactor, ensuring accurate incorporation of their present value in the LCOE calculation.

Fuel costs for thorium-based reactors are modeled at $40.1 million/year, with a wide range of variability (51% to 476%). This reflects the significant uncertainty surrounding advanced nuclear fuel cycles, which depend on economies of scale, technological advancements, and the availability of fuel processing infrastructure [20]. The broad range captures potential scenarios where fuel costs either stabilize with mature supply chains or increase due to complexities in online reprocessing and chemical handling [21].

Decommissioning costs, set to a characteristic value of $500 million, are associated with dismantling the reactor, managing residual radioactive materials, and site remediation [22]. These costs are incurred at the end of the operational period and are discounted to present value. To account for uncertainties in regulatory requirements and technological advancements, variability between 50% and 150% of the baseline value is introduced [23][24].

Carbon credits are included to reflect the financial benefit of avoiding greenhouse gas emissions. Assuming 0.5 tons of CO_2 avoided per MWh of electricity generated, credit values range from $0 to $70 per ton of CO_2 avoided, based on market trends and policy scenarios [25][26]. These credits are discounted annually and subtracted from the total costs, effectively reducing the net LCOE. This approach highlights the environmental value of low-carbon energy generation technologies [27].

The LCOE analysis is conducted using a Monte Carlo simulation with 5,000 scenarios to capture the uncertainties in cost components, discount rates, and carbon credits [28]. Each scenario calculates the total discounted costs, discounted energy output, and resulting LCOE. Sensitivity analyses are also performed to assess the contributions of individual cost components—capital, O&M, fuel, and carbon credits—to the overall LCOE. The analysis provides insights into the dominant factors affecting reactor economics and the potential financial benefits of carbon pricing policies [29][30].

This analysis is subject to several limitations. To start with, as a first-of-a-kind reactor, cost assumptions may overestimate expenses due to a lack of economies of scale and the absence of established supply chains [31]. Second, the carbon credit model assumes a linear relationship between avoided emissions and financial credits, which may not fully capture future market complexities [32]. Third, external factors such as regulatory changes, supply chain disruptions, and technological breakthroughs are excluded, though they could significantly impact cost estimates [33]. Finally, the assumed range of discount rates may not capture all country-specific financing conditions, potentially affecting the generalizability of results [34].

A Monte Carlo analysis is performed, where each independent factor affecting the costs in the TS-MSBR was sampled within the uncertainty distribution as specified in the FORCE framework. Each realization of a sample is referred to as a scenario and quantified via a scenario index. The computed LCOE analysis is provided in Figure 6. The blue dots correspond to the capital and decommissioning cost, the overlapping orange dots to operational and maintenance costs, the green dots to the fuel costs, and the red ones to the deductions due to carbon credits. Even though there is a large variability, as expected for a first-of-a-kind reactor, the average LCOE of all scenarios amounts to 48.00 $/MWh, which suggests economic competitiveness when compared with the LCOE of other nuclear facilities. Note also that this is a conservative estimate on the LCOE as longer operation periods, value produced by the net production of fuel at later stages, and the innovations in autonomous operation and maintenance, among others, will drive down the LCOE.

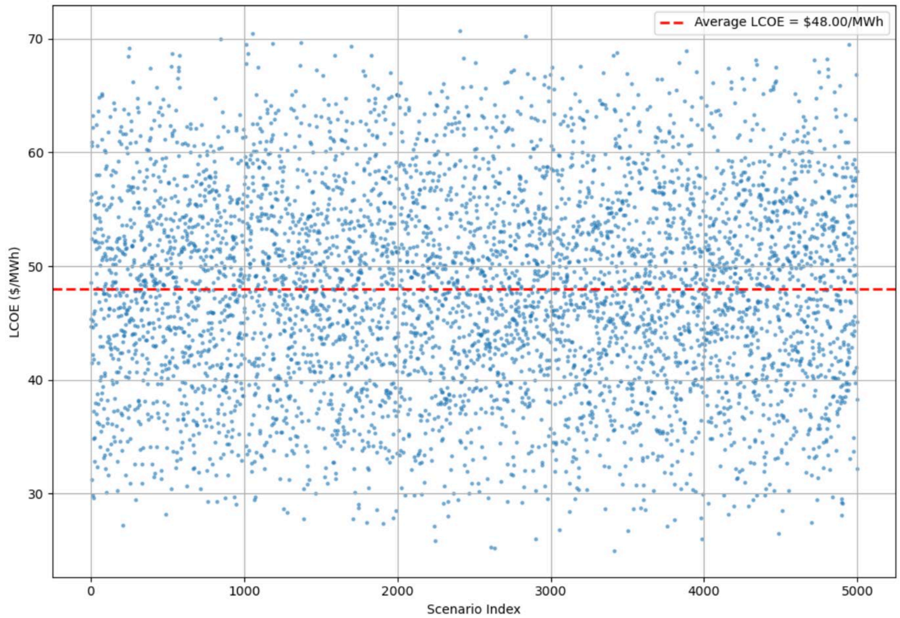

Figure 6 – Scenario analysis for LCOE for the TS-MSBR showing the individual component cost per scenario (above) and total LCOE per scenario and average LCOE (below)

4.4 Risks

The primary risks of TS-MSBRs, in terms of investability, are how much development and deployment will cost and how long they will take. The investment risk can be broken down into four major categories, as follows:

- Legal and regulatory
- Technical maturity
- Financial adequacy—sufficient funds and reasonable timeline
- Investor exit potential and timeframe.

4.4.1 Legal and Regulatory

The legal and regulatory risks can be further subdivided into three subcategories, as follows:

- Market configuration
- Regulatory misalignment
- Liquid fuel confusion—especially of inclusion of thorium in the fuel cycle.

4.4.1.1 Market Configuration

The primary market configuration risk remains the same in that it has largely prevented the development of any advanced reactors for the past several decades. The external costs of fossil fuels are not reflected in their price. Fossil fuels remain cheap and abundant in the United States. Combined cycle natural gas power plants are a mature technology, and hydraulic fracturing has resulted in abundant, inexpensive natural gas supply in the United States for decades to centuries. Mine-mouth coal plants remain among the least expensive means to generate electricity. Without substantial, sustained support, TS-MSBRs will not be able to overcome the first mover advantages of fossil fuels. Further, TS-MSBR technologies remain too immature to confidently predict how well even mature systems will be able to compete against low-cost fossil fuel plants. Lacking adjustment (likely for a limited period) to the relative prices of clean power versus fossil-fuel-derived power to reflect the difference in the harm to the environment, TS-MSBRs will not initially be financially competitive.

One means for adjusting the market to account for the different harm levels of different power options is to establish clean power fraction requirements, thus creating a separate, restricted market for clean power. Some current definitions of clean power require direct scavenging of energy from the environment without removing material. A remaining legal/regulatory risk to TS-MSBR deployment is a definition of clean energy that precludes nuclear power. The situation, however, is beginning to change. For example, Colorado recently enacted legislation that defines nuclear energy as a source of clean energy [35]. In addition, fossil fuel plants coupled with post-combustion carbon capture and sequestration may have lower cost estimates than first-of-a-kind advanced nuclear power. However, neither TS-MSBRs nor large-scale carbon capture and storage are adequately mature to enable a high-confidence assessment of their actual large-scale deployment costs.

Pricing mechanisms that do not include the all-in costs of providing power when and where it is needed disadvantage the dispatchable power production methods that can be located near the demand (e.g., reactors with high degrees of passive safety). Power that cannot be provided on demand or that is not available at the location of demand incurs additional system costs for storage and transmission. Energy storage and transmission costs can constitute much of the all-in power cost [36]. Intermittent, long-distance electrical power transmission is especially costly due to the high capital costs for transmission lines [37]. Currently employed power bid methods (short interval bids) distort a household-focused market perspective by inappropriately favoring power from non-dispatchable power sources, over the intervals for which they function, by not including the additional costs of providing power when and where it will be needed throughout the year (e.g., cold, calm winter nights and hot summer evenings). Not including the cost of developing substantial additional storage or transmission capability into the price of remote power generation also disadvantages local power producers. Moreover, the established regulatory framework for determining where NPPs can be sited is based upon accident potentials that are not relevant to reasonable MSRs (discussed further in regulatory alignment section). An energy market that does not reflect the all-in costs of providing power when and where it is needed represents a key legal/regulatory risk to developing TS-MSBRs.

4.4.1.2 Regulatory Misalignment

The current U.S. NPP regulatory system is based upon providing reasonable assurance of adequate protection from licensed NPPs. All existing commercial NPPs in the United States are large, LWRs. Hence, the risk characteristics reflected in the licensing process are those of large LWRs. A key safety characteristic of large LWRs is that they have the remote potential for accidents that cannot be reasonably contained.

The initial U.S. nuclear power regulatory system was based upon mitigating (by a combination of containment and remote siting) the harm from NPP accidents. However, once it became clear that containment for large LWRs might not hold under some circumstances, the focus for protecting the public from a large release of radioactive material shifted to preventing accidents severe enough to threaten containment. Much of the expansion of the existing regulatory structure, and the nuclear power cost escalation that has accompanied it, is fundamentally based upon the presumption that credible, severe accidents cannot be contained.

The first parts of an application for a commercial NPP license, including for its siting evaluation, require the evaluation of an accident, in which a substantial fraction of the fission products leak from the core into the containment. As having a sloped catch pan guiding a spilled fuel salt flow into passively cooled, subcritical drain tanks would be a typical feature of MSRs, even a complete reactor vessel failure would only drive the plant into a maintenance configuration, with its fuel salt in drain tanks, but would not significantly stress containment. Reasonably designed MSRs lack mechanisms to significantly pressurize containment and can accommodate substantial reactivity excursions. Notably, TS-MSBRs would not have significant quantities of phase change materials (e.g., water) or combustible materials in or near containment. Defueling the reactor into subcritical drain tanks would be a typical response to transients. While reactivity control remains necessary for proper operation, only extreme, non-credible reactivity excursions could challenge containment.

Both the NRC's existing and forthcoming regulatory pathways involve detailed knowledge of all the NPP SSCs to understand and model their role in preventing and mitigating potential accidents. Evaluating the adequacy, quality, construction, and maintenance of containment structures (as well as passive decay heat removal systems) at a TS-MSBR is much simpler than the myriad requirements necessary to provide reasonable assurance that severe accidents will not occur at LWRs. Focusing on adequate accident mitigation avoids the detailed accident prevention information necessary at large LWRs. Many significant requirements, such as the need for skilled operators, much of the requirement for guards to protect external vital areas, as well as substantial portions of the general design criteria in 10 CFR Part 50 Appendix A, are derived directly from the need to prevent accidents (or accident escalation).

Congress has directed the Nuclear Regulatory Commission (NRC) to develop a rulemaking to establish a technology-inclusive, regulatory framework for optional use by commercial advanced nuclear reactor applicants for new reactor license applications [38]. However, the current regulatory development process remains focused on preventing accidents and accident escalation through evaluating the detailed performance requirements of the plant systems, structures, and components (SSCs) rather than providing a simple means to demonstrate containment and decay heat rejection adequacy. Thus, a significant regulatory risk to MSRs is they will be burdened by much more extensive and costly regulatory requirements than the limited set necessary to protect the public and the environment.

4.4.1.3 Liquid Fuel Capability Confusion

Substantial confusion remains about the interrelationship between the capabilities enabled by liquid fuels and the Th-U fuel cycle. The U.S. Department of Energy's Office of Nuclear Energy (DOE-NE) recently recommended not developing the Th-U fuel cycle [39]. However, the rationale underlying the recommendation is only relevant to solid fuel. For example, the lack of a developed infrastructure for thorium fuel fabrication is not relevant to liquid fuel since it is not a fabricated product. Also, liquid fuel qualification is based upon maintaining its composition within an allowable range, so it does not involve extended irradiation testing. Overall, introducing thorium in a solid fuel form to the existing fleet would be costly and technically difficult, as well as providing only limited benefits. However, the benefits increase substantially while the technical challenges are reduced with liquid fuel.

Effective use of the Th-U nuclear fuel cycle requires multiple separations—parasitic absorbers (mainly fission products) from the bulk of the fuel and ^{233}Pa from a high neutron flux. The relative ease of component separations is a primary difference between liquids and solids. The virtues of combining liquid fuel with the Th-U fuel cycle have been apparent since the initial discovery of the properties of ^{233}U. As far back as 1944, L.W. Nordheim proposed a liquid-fueled reactor operating on the Th-U fuel cycle with a three-year doubling time [40]. Two Nobel laureates (Eugene Wigner and Harold Urey) advocated from the earliest days of nuclear power development that nuclear fuel should be liquid largely due to the expense/difficulty of processing solid fuel [41]. Even, Glenn Seaborg, who was a leading proponent of solid-fuel, liquid-metal fast-breeder reactors (LMFBRs), eventually concluded that "Rather than throw such huge resources into a massive LMFBR program with short-term deadlines, the AEC might have done better to initiate a slower and broader program that would have afforded the opportunity to change course as difficulties arose" [42].

The Th-U fuel cycle requires intensive fuel processing to achieve significant breeding gain. The current confusion within the DOE-NE recommendations about the issues of the Th-U fuel cycle as compared to those of liquid reactor fuels is currently a substantial risk to TS-MSBR investment. DOE-NE is the leading agency within the U.S. government charged with both reactor and fuel cycle development. Without DOE-NE support, key TS-MBSR technologies, that are much more difficult to develop outside of secure government facilities, such as fissile materials separations, are unlikely to be adequately developed in the United States for commercial deployment.

TS-MBSR fuel cycles that include the production of unacceptably attractive materials are being pursued outside the United States. Interest in the Th-U fuel cycle is expanding rapidly worldwide, and technology development is currently being pursued by multiple entities across the world. Developing alternative TS-MSBR fuel cycle technology that does not spread technology for production of (or provide access to) unacceptably attractive nuclear material would be beneficial. Moreover, providing a positive alternative that enables peaceful use of abundant thorium reserves to produce large quantities of clean energy would enable the United States to regain a world nuclear energy leadership position. Figure 7 shows the evolution of the fissile content and fissile fractions of each batch of TS-MSBR fuel for a 7-weight% ^{235}U startup fuel.

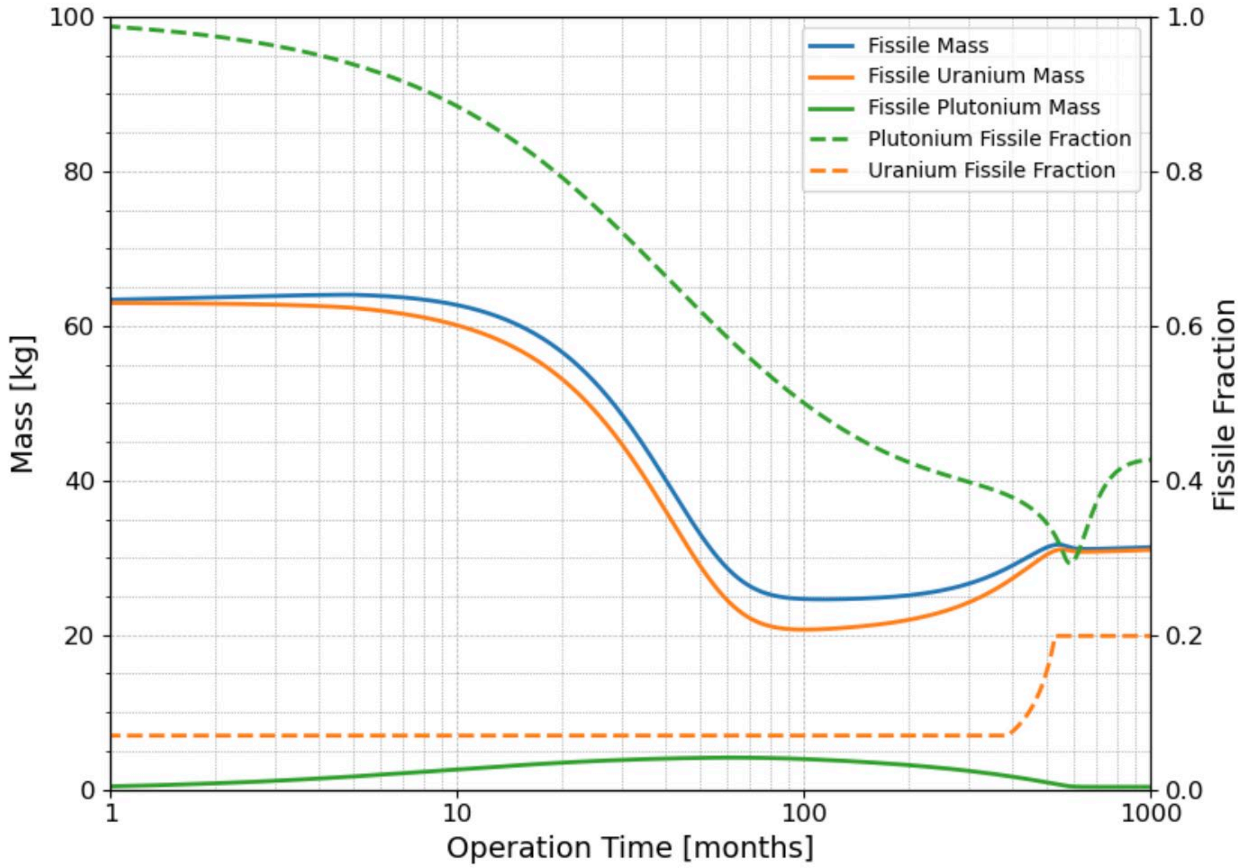

Figure 7 – Evolution of uranium and plutonium fissile masses (per batch) and fissile fractions for TS-MSBR starting with 7-weight% ^{235}U

4.4.2 Technical Maturity

In order to become sufficiently mature to be suitable for private sector investment, both a general understanding of the full set of required technologies and reasonable pathways to adequately mature and validate the technologies need to exist. Investability fundamentally requires understanding how much development and deployment is likely to cost and how long it will take.

The ability to predict development cost and time begins with adequate understanding of the science and technology that enables developing models for the plant throughout its lifecycle. Minimizing the investment risk necessitates sufficient modeling fidelity to capture the cost drivers especially for those materials and components that require specialized production. For example, the Clinch River Breeder Reactor overall project costs were substantially impacted by the decision that a secure fuel fabrication facility would be necessary [43]. Moreover, the modeling needs to include all the stages of the plant lifecycle including construction and waste management as well as O&M.

TS-MSBRs remain immature and will require significant, sustained resources to enable them to become suitable for commercial deployment. TS-MSBRs will incorporate distinctive technologies with no existing market equivalent and, consequently, need to develop their own supply network. TS-MSBRs also lack a recent, resource-loaded, independently reviewed technology maturation roadmap. TS-MSBRs, however, do benefit from a historic 25-year development program that notably included a highly successful test reactor (the Molten Salt Reactor Experiment [MSRE]) and were subject to a detailed, formal expert evaluation (albeit half a century ago). Consequently, a general understanding of the system requirements and development issues exists. Moreover, a substantial amount of useful technology development has occurred over the intervening decades.

Projects in the first nuclear era typically went forward under the combined beliefs that deployment speed was imperative and technical problems that arose would be fixable with reasonable cost and schedule impacts. Today, we have the benefit of hindsight into why prior advanced reactor development and deployment activities experienced such large cost increases and delays. One common element of many of the failures was the lack of adequate performance validation prior to deployment. Root cause analysis of the poor performance and system failures of prior advanced reactors have identified flaws that should have been resolved as part of ordinary engineering diligence. Items like rotating shaft seal leakage and adverse fluid-structure interactions would likely have been identified by experimental validation and resolved through design changes [44][45]. Note, the need for extensive early phase testing and performance validation has been recognized by multiple advanced reactor developers and incorporated into their development plans. Making extensive use of experimental validation along with modeling at early stages limits the possibility of difficult-to-correct issues developing in more expensive later stages or during operation.

Another historic source of delay and cost escalation historically has been the lack of license approval prior to beginning expensive development stages. More recently, licenses have included inflexible technical specifications due to the specific safety analysis employed in the license application. Inflexible technical specifications have resulted in significant delays while the impacts of construction variances were reevaluated. An example of the impact of inflexible safety analysis/license conditions arises from the detailed basemat rebar specification within the Vogtle Electric Generating Plant Units 3 and 4 safety analysis report. The safety analysis report included specifications (via reference to American Concrete Institute standards) for the length of the reinforcement bars embedded into the concrete, which were not met in construction. The required basemat performance, however, could be achieved by increasing the compressive strength of the concrete [46]. Construction was delayed by approximately 6 months during the request for the license amendment to achieve the same performance using a different method (higher strength concrete instead of longer rebar). Employing performance-based safety adequacy evaluation would substantially increase the ability to incorporate changes to most plant components without reopening licensing. More generally, one of the key technical advantages of low-pressure reactors is they do not require the massive, expensive support structures needed with LWRs.

The ability to model/simulate TS-MSBRs has increased dramatically over the past few decades. However, TS-MSBRs do not currently have detailed lifecycle models (digital twins) sufficient to support technology maturity assessment. Reasonable fidelity-integrated TS-MSBR models that incorporate both the fuel salt processing and reactor performance over the plant lifetime are not yet available. Moreover, nuclear power has seen multiple examples of improper modeling and simulation over the past couple of decades that resulted in project cancellations and/or plant closures. The newly constructed Maple Reactors in Canada were experimentally shown to have a positive reactivity coefficient instead of the negative coefficient predicted [47]. Also, the secondary side flow conditions were not appropriately calculated for the San Onofre Nuclear Generating Station replacement steam generators due to a modeling error [48]; even though as a nuclear safety-related component, their modeling was subject to 10 CFR 50 Appendix B quality control requirements. Appendix B – Criterion III "Design Control" requires independent review of the adequacy of design, which was not performed. TS-MSBRs, as with all complex engineered systems, will be vulnerable to inadequate quality in their design, construction, operations, and/or maintenance. Development and validation of component, process, and system level modeling tools would be a useful governmental domain task in support of creating a TS-MSBR development roadmap.

As technology elements mature their development transitions from science to engineering, TS-MSBR development now has mostly transitioned from science to engineering, with a few notable exceptions. However, at the current state-of-the-art, some TS-MSBR functions currently involve sub-optimal, expensive engineering work-arounds that, while not infeasible, would significantly increase costs and/or decrease performance.

The technology assessment presented here draws heavily on the prior AEC TS-MSBR technology evaluation (WASH-1222) as well as the historic MSBR program documentation. Another, more recent, MSR technology maturity assessment was the Phenomenon Identification and Ranking Table (PIRT) exercise performed over 2020-21 that assessed the knowledgebase underlying the ability of MSRs to achieve their fundamental safety functions [49]. The focus of this assessment is on technology elements that are both distinctive to TS-MSBRs and are significant to supporting nuclear power production.

The evidentiary basis for TS-MSBRs is narrow and incomplete. The historic TS-MSBR program developed substantial evidence about the performance of graphite-moderated, uranium-fueled reactors that employ $2LiF\text{-}BeF_2$ (i.e., FLiBe) as the fuel salt carrier. However, going outside or beyond demonstrated technologies substantially increases risks. Notably, the historic TS-MSBR program never demonstrated integrated fuel salt processing. One example of the narrow range of applicability is that in some potential fuel salts, the temperature dependence of the solubility of structural alloy elements is sufficiently high to result in significant (i.e., blocking flow) deposits in cold regions. While this has been shown not be a significant concern for MSRE-type fuel salt, structural material deposits could be a substantial limitation for other salts [50]. Temperature-difference-driven corrosion/deposition can be minimized by operating with a smaller temperature difference across the core at the cost of increasing the flow rate, which may require significant structural changes as well as increased pumping power.

TS-MSBRs have multiple design options available. Technologies that are necessary for one option may be irrelevant for others. For example, the fission gases may either be kept within or removed from the reactor vessel with the first few hours of production. Removing the fission gases necessitates safety-grade cooling as the fission gases contain significant decay heat for the first few hours. The historic method for disengaging the fission gases from the fuel salt was sparging with a noble gas, which increases the off-gas volume sufficiently, so that it is impractical to be kept within the reactor vessel. On the other hand, disengaging the fission gases from the fuel salt (especially ^{135}Xe) improves the neutronic efficiency. Without removing most of the ^{135}Xe, TS-MSBRs will not achieve substantial breeding. Almost all the xenon poisoning in graphite-moderated MSRs would result from neutron absorptions in ^{135}Xe trapped within the graphite, giving a strong incentive to avoid graphite contact with the fuel salt [51]. The cost of additional safety-grade cooling of the off-gas stream must be balanced against the impact on reactor performance. Employing non-porous tubes or plates to contain the fuel salt may prevent ^{135}Xe from accumulating in the core. Alternatively, mechanical agitation may enable separating fission gases from the fuel salt without generating additional gas volume.

TS-MSBR design configurations are both diverse and evolving. For example, the MSRE employed a full flow path freeze valve to drain the salt from the reactor vessel. Freeze valves proved problematic in practice. Subsequently, the historic MSBR program developed a design for a frozen-seat-poppet-type valve [52]. Multiple versions of frozen seat valves are now available commercially. Not all modern MSR designs even include fuel salt draining as a safety response. Other recent MSR designs have either incorporated, valveless, gas-pressure-driven fuel salt position control or left the vessel drain open while simultaneously employing a transfer pump to refill the vessel from the drain tank. Pressure-driven liquid position control is a well-known technology and has been employed with aqueous homogeneous reactors, whereas continuously refilling the reactor vessel with fuel salt depends on the availability of reliable fuel salt transfer pumps.

TS-MSBRs have substantial changes in technology requirements with different design options. For example, radiation damage to graphite has substantial implications for reactor operations as both fission gas and fuel salt penetration can change significantly with radiation damage. However, while graphite is the only proven fuel salt compatible moderator, some designs employ fuel salt within tubes or plates preventing contact of the fuel salt and the moderator, making the fuel salt moderator interaction characteristics irrelevant. Then, non-graphite moderators with improved radiation damage characteristics become possible. For example, niobium carbide bonded beryllium carbide fuel salt tubes along with beryllium carbide moderator pieces present an alternative, high potential, low-maturity fuel-container-moderator configuration [53].

Supply chain technologies with substantial potential cost implications remain at laboratory levels of maturity. While not critical path technologies, their maturation could have a substantial positive impact on financial performance. For example, low-temperature, non-aqueous, organic synthesis of fuel salt could substantially decrease the cost of fuel salt [54][55]. Similarly, highly efficient lithium isotope separation technologies have been demonstrated at laboratory-level maturity [56] and are being commercialized [57]. While the early phase research in these technologies has been performed under direct government sponsorship, the government role in further maturation appears more likely to be in the form of incentives for private developers.

4.4.2.1 Significant Remaining Technology Maturation Areas

The major TS-MSBR areas that have been identified as having significant remaining technology development issues are listed and discussed next. The list aligns with prior TS-MSBR technology evaluations and derives from a functional decomposition of the plant. The list is limited to critical path technologies. Additional, non-critical path technology development areas also exist, such as thermochemical hydrogen production technology maturation [58] that could substantially enhance high temperature reactor usefulness. The list is as follows:

- Fuel salt separations technology development and demonstration
- Tritium management
- Graphite radiation damage
- Utility scale components
- Fission product and contaminant stripping from barren fuel salt
- Inspection and maintenance technology
- Xe-135 removal technology.

Fuel Salt Separations Technology

Development and demonstration of an integrated fuel salt processing system was the leading technical issue identified in the historic TS-MSBR review. Fuel salt processing remains the largest cost and schedule uncertainty today. The historic program fuel salt processing steps began by fluorinating the fuel salt to remove uranium followed by reductive extraction of protactinium into liquid bismuth, which would be allowed to decay into uranium prior to being reintroduced into fuel salt. Additional stages of reductive extraction into a thorium-loaded bismuth-lithium alloy were intended to be employed to remove fission products from barren fuel salt while maintaining stable thorium concentration in the salt phase [59]. The historically envisioned fuel salt processing steps are technically difficult both because fluorination is highly corrosive and because bismuth at applicable temperatures is not compatible with any reasonable, high-temperature engineering alloy. Only limited efforts to reevaluate the historic fuel salt processing steps have been performed [60]. However, several alternative separations technologies have been demonstrated over the intervening decades at laboratory levels of maturity. Notably, the co-separation of actinides from fluoride salts to an aluminum alloy [4] as well as separation of lanthanides from the resultant barren fluoride salts [61] were demonstrated nearly 2 decades ago.

The aluminum-alloy-based fuel-salt-processing technology needs to be matured from its current early phase laboratory status into an engineering development phase to be able to develop reasonable confidence in the cost and schedule for TS-MSBRs to enter the commercial marketplace. Many key processing parameters, such as the composition of the aluminum alloy (will need to be preloaded with beryllium to maintain stable beryllium content in the salt phase), remain to be investigated. Thorium has similar miscibility into molten bismuth as beryllium does into molten aluminum. Demonstrating the separations on minimally radioactive fuel salt surrogates (e.g., containing natural uranium, thorium, and non-radioactive isotopes of fission product elements) is likely an early phase in the development effort. However, detailed fuel-salt actinide, co-separation technology development, including the full set of actinides as well as fission, corrosion, and contamination products, will be a longer-duration, more costly activity dependent upon access to hot cell facilities. Development dependence on government-owned facilities necessitates support from both Congress and the Administration. Development and demonstration of the key technologies for actinide separation from fuel salt are recommended as the leading near-term government activity in support of TS-MSBRs.

The aluminum-beryllium alloy, co-separation process for actinide separation from fuel salt followed by fission product removal appears sufficiently promising that the processes could probably (based primarily on prior halide fuel salt processing costs) be matured, using pre-existing facilities, to an early phase engineering level of maturity in less than a decade at a cost on the order of 10 million dollars. Actinide separations would then require significant resources to mature into a commercial form. Also, lacking almost any current or recent evaluation efforts, it remains unknown whether the processes harbor substantial, unanticipated technical hurdles. Following the actinide separation, the resultant actinide aluminum alloy will need to be processed back into fluoride salt. While sets of processes have been proposed to first separate the actinides into chloride salts [62] and then substitute fluorides for chlorides [63,64], the technologies remain at laboratory levels of maturity and will require significant, sustained resources to adequately mature.

Tritium Management

Fuel salts that contain either lithium or beryllium will generate substantial quantities of tritium. Tritium is also a ternary fission product and can be generated by neutron interactions with fluorine. Tritium is especially problematic at high-temperature reactors because it diffuses through structural alloys at high temperatures (> 300°C). The primary heat exchanger for MSRs will be at a high temperature, have thin walls, and have a large surface area. Thus, the most problematic path for tritium escape at MSRs is via the primary heat transfer loop.

Multiple mechanisms have been proposed to prevent tritium from escaping the plant. The tritium can be chemically trapped, physically blocked, or stripped from the fuel salt. Tritium that escapes into the gaseous regions can be trapped as a metal hydride using the proven technology of flowing through a heated metal bed. Employing a nitrate salt coolant loop that will chemically trap the tritium is a mature technology but incurs cost and efficiency penalties. Nitrate salts are practically limited to ~550°C for long-term use and would react exothermically with hot graphite as well as precipitating out actinides from the fuel salt. In practice, this means that the nitrate loop will be implemented as a tertiary loop and will restrict the peak reactor temperature (thermal efficiency). Including a tertiary loop will also increase the reactor capital cost. A significant challenge for most tritium separation methods is that tritium has a low laminar diffusion coefficient in fluoride salts. Tritium will not separate from the salt if it does not reach an interface independent of whether the interface is with a gas (sparging or spray) or solid (window- or trap-type).

Other tritium management methods are at lower maturity levels. Evaluations done during the design of the MSBR indicated that an adequate sparging-based tritium stripping system "can be expected to increase significantly the cost and complexity of an MSBR" [65]. Similarly, "The spray disengager process to recover tritium from molten salt seems discouraging due to the large jet velocity, the number of nozzles, and the droplet size needed for mass transfer of tritium fluoride from salt" [66]. Ultrasonic or mechanical degassing technology has the potential, if sufficiently matured, to substantially mitigate the potential for tritium escape. Back diffusion of hydrogen introduced on the secondary side of the primary heat exchanger may also reduce the amount of tritium, which diffuses through the heat exchanger walls. One low-maturity, chemical tritium trapping mechanism that may be of particular interest is to exploit the sensitivity of the surface oxide on beryllium carbide (Be_2C) to hydrolysis to convert tritium dissolved within coolant salt into methane [67]. While Be_2C would not be compatible with uranium-bearing salt due to uranium chemically bonding with the carbon in Be_2C, MSRs that employ fuel salt within tubes may be able to both exploit the improved moderation of Be_2C and its tritium bonding capability.

Radiation Damage to Graphite

Radiation damage to graphite remains a potentially significant technical issue for TS-MSBRs. Displacement damage due to fast neutron exposure degrades multiple aspects of graphite including both its surface characteristics and its structural properties. Graphite radiation damage characteristics have substantial variation with dose, temperature, and grade. Graphite first shrinks and then swells under irradiation.

How significant the radiation damage susceptibility of graphite is to plant viability depends on the reactor design and the specific role envisioned for the graphite. Graphite is a brittle ceramic material prone to cracking. Thermal and/or radiation dose gradients promote crack growth due to generation of differential stresses, resulting from the dimensional change gradients, across the material. Flowing fluid-structure interactions also promote crack growth.

The understanding of the combination of radiation damage and fuel salt contact with graphite remains narrow [68]. MSRE fuel salts largely did not penetrate or wet its graphite. Much less information is available for other salt-graphite combinations. Once radiation damage to graphite progresses to the point where the graphite begins to swell, even MSRE-type fuel salt wets the graphite and penetrates its pores. Fission gases (notably including ^{135}Xe) also readily penetrate the damaged graphite.

Graphite radiation damage vulnerability was an element of the decision to transition from a two-fluid to one-fluid TS-MSBR design during the historic program in 1967. A major remaining concern for the two-fluid design was whether mechanical failure of the graphite tubes in the reactor core, resulting from the synergy of radiation damage and mechanical stresses, would cause the effective lifetime of the core to be significantly less than the overall graphite radiation lifetime necessitating frequent, expensive maintenance [69].

Graphite, nevertheless, remains the only proven fuel salt compatible moderator material. Developing alternate moderator materials and/or avoiding contact between the fuel salt and the moderator are two potential strategies to avoid graphite's radiation damage restrictions. The aircraft reactor experiment employed fuel salt within metallic tubes along with external moderation [70]. Metal fuel salt tubes are a possibility for TS-MSBRs. However, useful metals have sufficiently high neutron absorption to adversely impact the neutronic efficiency.

A number of different ceramic composite materials would be thermodynamically compatible with fluoride salts and exhibit good radiation damage characteristics, mechanical toughness, and acceptable neutron absorption (e.g., silicon carbide – silicon carbide composites). However, uranium has a strong affinity for carbon. The combination of high-temperature, high-radiation flux, and a uranium-bearing fluoride salt substantially restricts the potential set of compatible ceramics. Niobium has an even stronger affinity for carbon than uranium. However, niobium has a higher than desirable neutron absorption cross section. Consequently, the use of niobium carbide in-core needs to be minimized to maximize neutronic efficiency. One potential means to minimize the niobium content while benefiting from its chemical and physical properties is to employ niobium carbide as the binder phase for another carbide ceramic. The binder phase forms an enveloping layer around the otherwise non-fuel salt compatible carbide grains. Beryllium carbide powder has the potential to serve as the base material that would be joined together by a niobium carbide binder layer. Beryllium carbide and niobium carbide have closely matched coefficients of thermal expansion. While the combination of NbC and Be_2C appears thermodynamically favorable, and their cubic grain structure would promote radiation stability, the material remains at very early phase maturity. The impact of phenomena, such as energetic neutron-induced gas generation with beryllium, has not yet been experimentally evaluated.

Both powder metallurgy and structural ceramics have advanced dramatically over the half-century since the demise of the historic TS-MSBR program. The technology to consolidate high-density, high-purity Be_2C pieces was not available in the 1950s [71]. Microstructural engineering techniques, such as the inclusion of fibers or the use of nanoscale crystals to improve mechanical characteristics, were also not available historically. The radiation damage, formation technology, and structural characteristics of NbC-Be_2C-based ceramic composites need to be sufficiently matured to enable prediction of their cost and performance characteristics.

Other ceramic moderators are currently being developed, and an extensive graphite property development program has existed historically. Consequently, the cost and duration for an NbC-Be_2C maturation (to the point of engineering viability) program can be estimated by analogy as a roughly 10-million-dollar effort over 5–10 years. Further development would subsequently be required to raise NbC-Be_2C from engineering to commercial maturity. Much of the radiation damage evaluation will need to be performed using high-power test reactors (i.e., at government-controlled facilities). Evaluation of the potential for tritium capture using Be_2C would be a limited scope additional task in the structural ceramic development program.

Utility Scale Components

Hydraulic and heat transfer components need to transition from engineering and test scale to utility scale before TS-MSBRs can be deployed. To a large extent, molten-salt hydraulic components are already sufficiently mature to be suitable for private-sector-led scale-up and further maturation. However, first-of-a-kind technologies with a narrow customer base providing incentives for private industry could substantially accelerate development. Moreover, no large-scale molten-salt component test beds currently exist. Sponsoring a molten-salt component test bed (analogous to the historic liquid-metal engineering center [72]) that would be accessible by any prospective component developer could significantly reduce private sector risk.

Application of advanced manufacturing technologies to TS-MSBR components is a notable exception to the sufficiently mature assumption. For example, heat exchangers are expensive and complex to manufacture using conventional technologies. The financial performance of TS-MSBRs could be significantly improved by developing applicable advanced manufacturing technologies. Technologies, such as direct casting of large, complex structures, remain sufficiently high risk that the private sector is unlikely to adequately support their timely development without significant incentives.

Fission Product and Contaminant Stripping

Once the actinides have been removed from the fuel salt, the remainder of the fuel salt needs to be prepared for reuse. Most fission products exhibit high neutron absorption, so they need to be removed from the fuel salt. In sufficient quantities, other contaminants will adversely impact the fuel salt thermophysical properties, so they also need to be removed. Gaseous and insoluble fission products will partially separate inherently from the fuel salt. Xenon-135 has so high a neutron-capture cross section that its stripping is described in its own technology maturation section. The insoluble fission products will plate out relatively uniformly onto surfaces throughout the fuel salt circuit.

While multiple different separations processes are possible, none has been matured to commercial form. Moreover, overall process flowsheets for reconstituting the carrier and fuel salt have yet to be developed.

Different processes are likely to be preferred for removing different contaminants. Many rare earth fluorides contaminants can be converted to insoluble oxyfluorides or oxides from a fluoride salt melt [73]. The historic MSBR program studied both metal phase separation and high-temperature distillation to separate the rare earths from the carrier salt [74][75]. Some lanthanides can be removed from fluoride salt melts via electrodeposition. Indeed, one of the common industrial uses of fluoride salt melts is as a plating bath medium. However, several elements (e.g., Cs and Sr) cannot be easily separated from FLiBe electrically because beryllium plates out at a lower potential. Another separation technique, melt recrystallization, relies upon the differential solubility of impurity atoms in liquid versus solid phases, so it is widely applicable to separate small concentrations of almost any material from a melt. Some process steps may need to be applied each time the fuel salt is processed, others only periodically. Overall, the technical challenge is developing and maturing an efficient and effective set of process steps to recondition the carrier salt.

Most of the technology development and demonstration can be performed with non-radioactive isotopes (but would involve beryllium-bearing materials). Given the number of potential separation technique options and their relative maturity, carrier salt reconditioning is not viewed as an especially high-risk development step. However, it remains a critical path technology that needs to be adequately validated to minimize its risk to TS-MSBR investment.

Inspection and Maintenance Technology

To be economic, any TS-MSBR needs to operate reliably for decades. The historic MSBR program provides little information on long-term operation or maintenance of large-scale, highly contaminated equipment. Moreover, historically deployed advanced NPPs (non-MSRs) have not operated reliably. The potential that TS-MSBRs would not operate reliably is a significant technically based investment risk, which can be substantially mitigated by a combination of developing an understanding of the SSC degradation methods and means to detect degradation prior to failure. Maturing the system technology sufficiently to understand its degradation under representative conditions can be accomplished by a combination of separate and integral effects tests accompanied by theoretical and computational model development. Accelerated aging tests would be particularly useful to compress the time necessary to assess multi-decade performance.

Inspection provides information on the degradation of plant SSCs to enable timely maintenance. Performing inspections near the fuel salt will be much more difficult due to the high-radiation environment. Also, performing maintenance (especially ad hoc maintenance) on (repairing or replacing) fuel-salt-wetted components will be difficult due to the high level of contamination. Incorporating remote inspection and maintenance will be a major aspect of any TS-MSBR plant design. The technologies necessary for performing operations in highly radioactive, contaminated environments have already been developed in support of fuel cycle activities for other reactors. However, extensive planning and customized plant layout will be required for maintenance activities, so they do not significantly impact plant availability.

The specific instrumentation and methods for inspections at a given plant will be design dependent. However, developing a general toolset to enable the prediction of the remaining useful life of SSCs under representative conditions would be a useful support for any TS-MSBR developer. In some designs, the fuel-salt-wetted components near the core would be limited to tubes or plates. In others, everything within the reactor vessel would become highly contaminated. The entire fuel salt processing system, including the waste handling and off-gas systems, would also become highly contaminated. Heat exchanger tubing would also become highly contaminated on the fuel salt side.

Development of degradation-monitoring and remaining-useful-life prediction tools is a recommended early phase activity. While many aspects of the testing as well as numerical modeling and simulation could be performed by the private sector, development of common information on degradation processes would be both expensive to obtain and supportive of any developer. Minimizing the replication of tests and facilities would increase resource utilization efficiency. Governmental support for the development of common SSC degradation information and modeling tools would be a useful method to reduce investor risks for TS-MSBRs. Developing the type of material and component degradation information necessary to create adequate digital twins is likely to be integrated with development and validation of utility scale components and other fuel cycle plant elements with costs (based upon analogies with similar development activities) on the order of 10 million dollars and a duration of 5–10 years.

Xe-135 Removal

Maximizing the neutronic efficiency is a key design element of any TS-MSBR as it directly impacts the breeding ratio. Of the fission gases, only ^{135}Xe has a sufficiently high-parasitic neutron-absorption cross section to have a significant impact on neutronic efficiency. Stripping ^{135}Xe from fuel salt currently has an expensive, engineering work-around (sparging). Simplifying designs and minimizing the number of engineering work-arounds needed is an important element in developing confidence in adequate TS-MSBR financial performance.

The ^{135}Xe can be stripped from the fuel salt by sparging with an inert gas. Sparging is a physical process that strips the fission gases from the liquid fuel into a gas bubble stream. The fission gases, however, initially contain a significant fraction of the reactor decay heat and would require separate safety-grade cooling if separated from the reactor coolant. The necessary volume of sparging gas makes retaining the gas stream within the reactor vessel for a sufficient time for the decay heat to decrease impractical. Roughly 80% of the gaseous heat load will have decayed after 1 hour and less than 1% will remain after 2 days [76]. Hence, developing, a nonvolume increasing ^{135}Xe removal system would decrease plant capital and regulatory costs and increase neutronic efficiency while increasing the plant thermal efficiency (heat left in the reactor vessel and transferred to the coolant). Alternately, the sparging could be implemented in the form of a jet pump increasing the fuel salt flow velocity and balancing the cost of cooling against decreased fuel salt container material performance requirements.

Multiple different technologies are possible for removing dissolved gases from the fuel salt. However, none has been demonstrated to work in representative conditions (very high radiation with hot flowing fuel salt). Stripping fission gases from fuel salt is a sufficiently narrow market that governmental incentives will likely be necessary to develop and demonstrate adequate technology.

4.4.3 Financial Adequacy

The central conundrum to assessing the financial requirements for maturing TS-MSBRs sufficiently to attract substantial private-sector investment is understanding how much development will cost and how long it will take under realistic constraints. While technology development represents a major portion of the cost and schedule, because of the legal structures surrounding nuclear technology, TS-MSBR fuel cycle technology development is intertwined with national policy and regulatory processes. Moreover, the key remaining technology issue (fuel salt processing) for TS-MSBRs has sufficient uncertainties that substantial technical course changes may still be necessary.

TS-MSBRs have three primary remaining risks that require significant government support to resolve. The dominant remaining TS-MBSR technical risks are fuel salt processing and radiation-damage tolerant, high-temperature moderator development. These were both leading technical risks identified in the historic TS-MSBR technical evaluation. The other historically identified technical risks either have already been resolved, have acceptable engineering work-arounds, would be anticipated to be resolved in conjunction with the primary risks, or would be anticipated to be resolved by the private sector without substantial precursor governmental resources.

TS-MSBRs have one, largely non-technical, remaining governmental risk. TS-MSBRs need an efficient and effective regulatory process. The amount of time and effort that has been required to license recent water-cooled reactors (that the existing licensing process was designed for) results in significant investor hesitancy. Developing a regulatory process aligned with the technical characteristics of TS-MSBRs would be anticipated to substantially decrease the perceived risk for investors. While any stakeholder can submit topical reports to the NRC, which if applicable to multiple NPPs can resolve generic safety issues, tailoring the licensing process to the safety characteristics of TS-MSBRs appears likely to require regulatory development, which would involve government resources. Developing the technical and regulatory basis for applying containment-focused safety-adequacy evaluation is recommended as a near-term, government-supported task for reducing investment risk in TS-MSBRs.

Fuel salt separations (in particular, actinide separation from fuel salt) are the most significant TS-MSBR technology requiring maturation. Maturing this technology will require access to heavy actinides and hot cell infrastructure. This means that fuel salt processing technology development will have substantial government involvement. The separations technology, however, has sufficient technical overlap with the halide salt-based fuel component separations technology developed to support sodium fast reactors to be able to create a conceptual outline of the development and demonstration process. Moreover, early phases of the separations process development can be performed at a fundamental science level with low-radioactivity materials. Uranium and thorium are representative actinides, and the fission products have non-radioactive isotopes.

Electric power generation is performed by the private sector in the United States. Hence, electric power generation technology development needs to be led by the private sector. However, given that the leading technology development area for TS-MSBRs must be performed in hot cell facilities, requires access to transuranic materials, and that significant regulatory customization remains to support efficient TS-MSBR deployment, conventional financial adequacy assessment is not yet reasonable. For profit elements of the private sector appear unlikely to risk sufficient resources without strong signs of government support. Indeed, the lack of focused government support for TS-MSBR development for the past half-century remains a primary impediment to garnering private sector resources. More conventional financial adequacy assessment would become possible once the primary government-related risks have been retired.

An additional impediment to resolving the actinide separations from fuel salt technology risk is that while the fuel salt separations are necessary to achieve thermal-spectrum breeding and to avoid generating actinide-bearing wastes, they are not necessary for all potential MSRs. Private enterprises are strongly motivated to generate profit as early as possible. The initial focus of private enterprises has, thus, been on MSR variants that do not require higher-risk, longer-term development elements. While this indirect approach to TS-MSBR development does mature and validate component technologies and develop much of the supplier network, it does not resolve the central technology challenge with longest development timeline. Government resources, thus, appear especially necessary to perform the needed, fundamental fuel salt processing research and development.

4.4.4 Investor Exit Potential and Timeframe

To reiterate, this paper focuses on assessing which government sector actions would be useful to trigger large-scale private sector investment to commercialize TS-MSBRs. Initial TS-MSBR investments will be highly speculative. A key investor consideration is duration until the technology results in a company suitable to enter the public market. Government sector actions can primarily impact the investor exit timeframe by raising the technology readiness of the key technologies and developing a reasonable cost and duration regulatory pathway prior to needing to raise substantial capital. The government sector also has multiple potential financial methods to improve the investor exit potential (i.e., through the tax code and market guarantees) that are beyond the scope of the current evaluation.

Advanced reactor deployments have historically cost much more and taken much longer than initially anticipated. Moreover, commercial-scale advanced reactors have not performed well once constructed, leading to substantial investor skepticism. TS-MSBRs will be complex systems dependent on advanced materials and processes for proper operation. Developing adequate understanding of all the required systems and processes is central to achieving reliable performance on-time and within budget. Postmortem analysis of prior advanced-reactor-deployment failures shows multiple incidences of deploying inadequately understood technology, resulting in substantial cost escalations and delays. Government sector activities can minimize both advanced technology and regulatory risks. Improved modeling tools, such as digital twins, can significantly decrease the probability of design errors.

While the historic (25 year) TS-MSBR program provides a substantial technology base, a modern TS-MSBR will still need to progress through component and non-nuclear integrated system testing, small-scale nuclear testing, and test scale power production before being ready to enter the larger-scale power production market. The timeframe and development path currently underway for other advanced reactors, especially TS-MSRs, provides insight into the likely development duration (1–2 decades). TS-MSBRs do have the advantage of following the first wave of modern advanced reactor developers who have begun to reinvigorate supplier networks and both development staff and regulatory skills. Developing an optimized commercial licensing path is a long-duration activity that can continue in parallel with other early phase development activities. However, developing and validating the basic elements of the fuel salt processing technology need to occur prior to integrated system testing. Hence, beginning both regulatory and fuel salt processing development activities are recommended near-term government sector actions.

5 Summary and Conclusions

TS-MSBRs have a high potential for providing affordable, clean, safe, and abundant energy worldwide for the foreseeable future. The high potential of TS-MSBRs was recognized as early as the 1940s, resulting in a ~25-year development program. However, substantial hurdles remain. U.S. government support for TS-MSBR development stopped in the mid-1970s because of the combined belief that they were not a sufficiently high priority, and they still required substantial, expensive technology development.

Private sector investment in TS-MSBRs is currently stymied by multiple government-related issues. Detailed fuel salt processing technology maturation can only practically be performed at government facilities. Core materials testing will require access to high-power test reactors. Also, development of an efficient regulatory process aligned with TS-MSBR safety characteristics will primarily involve government sector activities.

The quantity of resources required to mature TS-MSBRs to the point where private sector investment becomes reasonable remains speculative. TS-MSBR technology readiness remains too low to enable a bottom-up cost estimate. The rest of this paragraph discusses a top-down resource estimate to mature TS-MSBR technologies sufficiently and demonstrate viability, derived primarily from analogy with prior nuclear power technology development efforts. Substantial amounts of work would remain following completion of the activities (listed in Table 1) to mature the technologies to commercial form. However, unlike the first nuclear era, significant experience with related technologies exists, enabling high-level scoping estimates of the resource requirements to mature technologies to sufficiently demonstrate feasibility. For example, fuel salt actinide separation is analogous to technology developed to reprocess LMFBR fuel. Given the differences between developed and required technologies, the estimates are likely only accurate to a factor of 2-3, and significant unanticipated issues may yet be discovered. The estimates also depend on access to existing facilities. Radiation damage studies require access to reactor irradiation facilities, and the fuel salt separation technology development requires access to hot cells and beryllium glove box trains. The resource estimate, also, does not include development issues anticipated to be addressed by private sector, likely with government incentives (e.g., production of commercial-scale quantities of fuel salt) or basic resource issues such as beryllium mining and processing.

Table 1 - Activities and Resource Estimates to Mature TS-MSBRs to Engineering Viability

Task	Duration (y)	Cost ($M)
Resource- and risk-loaded development roadmap	1	0.5
Actinide co-separation from fuel salt	5–10	10+
Fission product separation from barren fuel salt	3	3
Reconstitute fuel salt from aluminum alloy	3	3
Waste form development	5	5
Process instrumentation	4	5
Xe-135 separation	5	3
Tritium management	4	4
Maintenance technology	7	10
Prognostics and reliability (digital twin)	5	10
Licensing methodology – MSR tailored, containment-based	10	10
Beryllium carbide synthesis and properties	5–10	10+
Microstructure engineering	5	5
Niobium sintering	3	5
Refractory coatings of engineering alloys	4	4
Ceramic to metal joints	3	3

The worldwide need for large quantities of clean energy has changed dramatically since the 1970s. Moreover, half a century of technical progress has occurred. Limited-scale government sector investment in fuel salt processing technology, advanced materials, regulatory customization, and modeling tool development has the potential to trigger the substantial private sector investment needed to commercialize TS-MSBRs.

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