Preliminary Neutronic Analysis of Fission–Fusion Hybrid Systems for Minor Actinide Transmutation under the ARPA-E NEWTON Program

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1. Introduction

Repository loading in many used nuclear fuel (UNF) disposal concepts is driven primarily by long-term decay heat and radiotoxicity from actinides—especially transuranics such as plutonium and americium—once short-lived fission-product heat has been managed through an initial cooling period [1,2]. In the United States, where partitioning of uranium and plutonium from UNF is actively investigated, a strategy has emerged in which recovered uranium–plutonium streams are directed toward reuse in established reactor platforms, while the comparatively smaller minor actinide (MA) fraction is considered for dedicated transmutation pathways [1–3].

Systems fueled predominantly by minor actinides differ significantly from conventional uranium- or plutonium-based reactors, including relatively lower effective delayed neutron fractions and a near zero doppler coefficient under fast-spectrum conditions [3,4]. These characteristics motivate examination of externally driven configurations, in which a fast-spectrum blanket operates subcritically while an external neutron source sustains the required fission rate. Both accelerator-driven and fusion-based neutron drivers fall within this broader design space and are being explored in recent U.S. transmutation initiatives, including the ARPA-E NEWTON program [5].

In this work, we present the concept and preliminary modeling of fission–fusion hybrid (FFH) systems for MA transmutation. Emphasis is placed on the neutronic and burnup behavior of MA-bearing chloride salt configurations, including comparisons between idealized infinite-medium calculations and finite-length representations relevant to hybrid geometries [3,6].

2. Partitioning–Transmutation System Framework

Partitioning–transmutation framework is organized as a two-stream architecture in which UNF is separated into (1) a uranium–plutonium recycle stream and (2) a minor actinide (MA) transmutation stream. The uranium–plutonium fraction is routed to established power reactors, while the smaller MA fraction is directed to a dedicated fast-spectrum system for efficient destruction. This separation enables independent optimization of each stream according to its material properties, neutronic behavior, and system-level constraints.

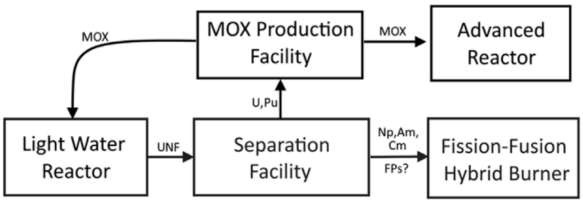


Figure 1. Simplified schematic of the partitioning and transmutation scheme. Reproduced from [3].

The MA stream, typically composed of neptunium, americium, and curium, represents a relatively small mass fraction yet accounts for a significant portion of long-term decay heat; small residual amounts of uranium or plutonium may also remain depending on separation efficiency. These isotopes exhibit higher fission-to-capture ratios in fast neutron spectra, motivating consideration of fast-spectrum systems for MA transmutation. However, MA-dominant fuel compositions have lower effective delayed neutron fractions and near zero doppler reactivity feedback compared to conventional uranium- or plutonium-based fuels, limiting the practicality of purely critical system implementations.

Within this framework, externally driven subcritical systems offer one approach to MA transmutation. In these configurations, a fast-spectrum blanket containing the MA-bearing medium is coupled to an external neutron source so that high neutron fluxes can be maintained without requiring the system to operate at criticality. Figure 1 schematically shows this two-stream arrangement, separating the uranium–plutonium recycle path from the dedicated MA transmutation path based on an externally driven fast-spectrum blanket.

3. Fission–Fusion Hybrid System Concept

Fission–fusion hybrid (FFH) systems have been considered for decades as externally driven configurations in which a fusion neutron source is coupled to a surrounding blanket to provide neutron multiplication and power generation [7]. More recently, studies relevant to the present UW effort have examined fast-spectrum blanket concepts for minor actinide (MA) applications, including solid MA-bearing fuel with liquid-metal cooling, demonstrating the feasibility of fusion-coupled blanket in a subcritical regime [4].

While solid MA fuel forms enable conventional reactor-style lattice configurations, fabrication and materials challenges associated with high concentrations of americium and curium motivate consideration of alternative fuel forms. Subsequent investigations therefore examined subcritical molten salt systems in which minor actinides are dissolved directly within a fast-spectrum salt medium [3,6]. Such dissolved-fuel configurations eliminate the need for fabrication of solid MA-dominant fuel assemblies and enable uniform distribution of transuranic isotopes within the neutron field.

Building upon this progression, the present FFH concept employs a chloride-based molten salt blanket containing separated minor actinides surrounding a central fusion neutron source. Fusion neutrons enter the blanket and induce fission reactions in the MA-bearing salt, while the system remains subcritical to avoid reliance on self-sustained criticality. The fusion device thus acts as an external neutron driver, and the blanket serves as a fast-spectrum transmutation region.

Figure 2 illustrates a representative mirror-based fission–fusion hybrid configuration reproduced from [8], highlighting the conceptual coupling between a fusion neutron source and a surrounding subcritical blanket. The schematic is intended to convey the general FFH framework, and detailed engineering aspects are beyond the scope of the present study. In this work, the blanket is specifically modeled as a molten salt configuration for minor actinide transmutation as aforementioned.

4. Neutronic Behavior of MA-Bearing Chloride Salt in FFH Configurations

The minor actinide (MA)-bearing chloride salt composition was adopted from [3], where the actinide vector was derived from spent nuclear fuel discharged from conventional PWRs. The salt was modeled as a LiCl–$AnCl_3$ mixture with a 70–30 mole fraction ratio, and chlorine was assumed to be enriched to 95 at % in Cl-35. The specific MA isotopic vector used in the present analysis is summarized in Table 1.

Depletion calculations were performed using OpenMC v0.15.3 with ENDF/B-VII.1 nuclear data [9]. A fast-spectrum depletion chain was employed, with additional (n,t) reaction channels for Li-6 and Li-7 incorporated into the chain file to account for tritium production pathways relevant to the present study. Figure 3 shows the modified depletion chain, with the added reactions highlighted.

To evaluate the neutronic evolution of the molten salt FFH blanket, depletion analyses were conducted under both idealized and geometry-dependent conditions. Particular attention was given to the sensitivity of system reactivity to fission product removal assumptions, including the treatment of hydrogen and noble gas species generated during burnup.

Two modeling approaches were considered. First, an infinite-medium representation of the MA-bearing chloride salt was analyzed to isolate intrinsic spectral and isotopic effects. Second, a finite-length (4 m) FFH configuration was modeled using ParaTAN [10], a wrapper built on OpenMC that enables efficient iteration of mirror blanket and shielding designs. Although the FFH concept is inherently an externally driven subcritical system and would be operated such that $k_{\text{eff}} < 1$ in practice, the present depletion study was conducted using an eigenvalue-based approach to enable consistent comparison between configurations. In addition, for systems operating near criticality, the fission neutron population dominates the neutronics characteristics of the system compared to the fusion source, such that the eigenvalue solution provides a reasonable approximation of the system behavior in both energy and space [3].

Depletion calculations were then performed for both the infinite-medium representation and a geometry-dependent configuration. For the infinite case, 50 inactive cycles and 100 active cycles were used with 50,000 particles per cycle, while the geometry-dependent model employed 100 inactive cycles and 100 active cycles. The salt temperature was fixed at 923.15 K for all cases, and depletion was carried out at a constant specific power density of 20 W/gHM.

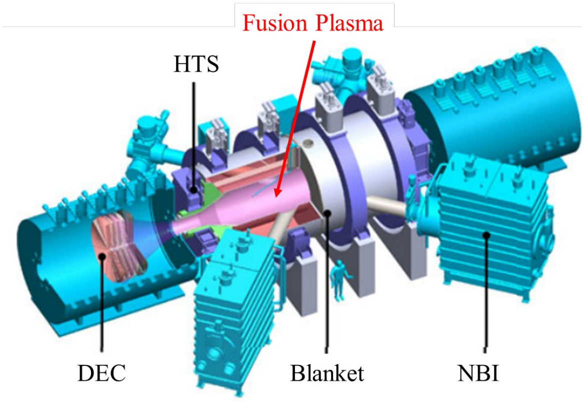
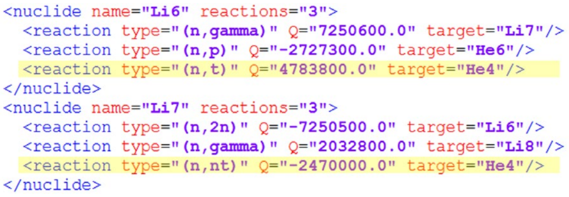


Figure 2. Conceptual mirror-based FFH configuration with a fusion neutron source and subcritical blanket. Reproduced from [8].



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  <reaction type="(n,t)" Q="4783800.0" target="He4"/>
</nuclide>
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  <reaction type="(n,2n)" Q="-7250500.0" target="Li6"/>
  <reaction type="(n,gamma)" Q="2032800.0" target="Li8"/>
  <reaction type="(n,nt)" Q="-2470000.0" target="He4"/>
</nuclide>
```

Figure 3. Modified OpenMC depletion chain, including Li-6 and Li-7 (n,t) reaction channels for fast-spectrum modeling. Added reactions are highlighted.

Table 1. MA isotopic vector

Isotopes	Fraction [-]
Np237	4.545E-1
Am241	4.545E-1
Am243	7.961E-2
Cm242	3.134E-6
Cm244	1.139E-2
Cm246	8.358E-5

For selected cases, gaseous and volatile species were removed during depletion, including hydrogen and helium isotopes and representative noble gas fission products. While the detailed removal behavior depends on system design, it is reasonable to assume that gaseous products would not remain fully retained in a molten salt blanket [11]. All simulations were performed on the UW–Madison Center for High Throughput Computing cluster using a hybrid MPI/OpenMP configuration with 256 total cores [12].

Figure 4 shows the burnup-dependent evolution of k_{eff} for both configurations, with and without gaseous species removal. The infinite-medium case exhibits higher multiplication due to the absence of neutron leakage and serves as a reference for intrinsic fuel behavior.

The geometry-dependent 4 m mirror configuration is shown in Figure 5, reproduced from [13]. This model is based on a simple mirror BEAM concept with an annular molten salt blanket surrounding the central plasma region [8]. In this configuration, neutron leakage and structural materials reduce overall multiplication relative to the infinite-medium case, as reflected in Figure 4. The influence of gaseous species removal follows similar qualitative trends but with reduced absolute reactivity.

The neutron energy spectra for the infinite-medium configuration are shown in Figures 6 and 7 for cases without and with gaseous species removal, respectively. In both cases, the system maintains a fast-spectrum character throughout burnup. Removal of gaseous and light species results in a modest hardening of the neutron spectrum.

In a fast-spectrum MA system, spectral hardening improves neutron economy by increasing the fission-to-capture ratio of transuranic isotopes. This behavior is consistent with the higher k_{eff} values observed in Figure 4 for cases with gaseous species removal.

For the geometry-dependent 4 m mirror configuration, the increase in multiplication due to gas removal is comparatively smaller because of neutron leakage and absorption in structural materials. Nevertheless, the effect remains noticeable and contributes positively to overall neutron economy, and should therefore be considered in the design and operational strategy of the proposed FFH system.

The evolution of the effective delayed neutron fraction, β_{eff}, with burnup is shown in Figure 8. For both the infinite-medium and 4 m mirror configurations, β_{eff} increases gradually over burnup. No significant differences are observed between cases with and without gas removal, nor between the infinite and geometry-dependent configurations.

Although MA-dominant systems are characterized by relatively low delayed neutron fractions compared to conventional uranium-based fuels, the subcritical nature of the FFH concept reduces reliance on delayed neutrons for stability, distinguishing its operational behavior from that of critical reactors [6].

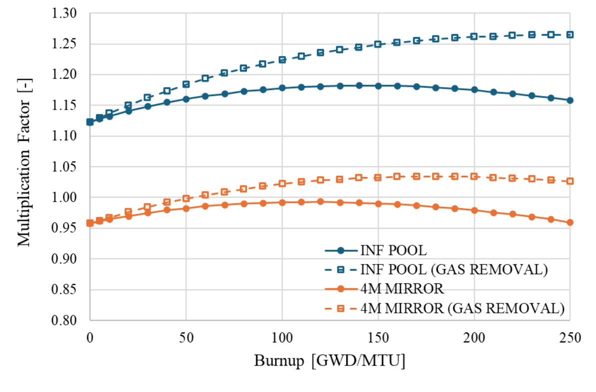
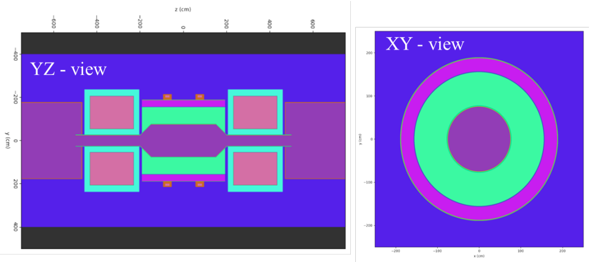


Figure 4. Burnup-dependent evolution of k_{eff} for the infinite-medium and 4 m mirror configurations, with and without gaseous species removal.



Cell Label	Cell Color	Material
Inner Vacuum	🟪	Vacuum
First Wall	🟨	Tungsten
Fuel Salt Blanket	🟩	Fuel Salt
Back Wall	🟦	Fuel Salt
Outer Shield/Reflector	🟪	Tungsten-Hastelloy
LTS Magnets	🟪	LTS Winding Pack
LTS Magnet Pack	🟧	Stainless Steel 304
HTS Magnets	🟥	Hastelloy-Copper-REBCO (0.55-0.43-0.02)
HTS Magnet Shields	🟦	Tungsten Boride-Water W2B5-H2O (80-20)

Figure 5. OpenMC geometry of the 4 m mirror-based FFH configuration generated using ParaTAN.

5. Conclusions

In this work, a preliminary neutronic assessment of a molten chloride minor actinide (MA) blanket coupled to a fusion neutron source was performed within a fission–fusion hybrid (FFH) framework relevant to the ARPA-E NEWTON program. Both an idealized infinite-medium representation and a finite-length mirror configuration were analyzed to examine fuel behavior and geometry-dependent effects.

The MA-bearing LiCl–AnCl$_3$ salt maintains a fast-spectrum character over the burnup range considered. As expected, the infinite-medium case exhibits higher multiplication due to the absence of neutron leakage, while the 4 m mirror configuration reflects reductions in reactivity associated with leakage and structural materials. Removal of gaseous and volatile species results in modest spectral hardening and corresponding increases in multiplication. Although the magnitude of this effect is smaller in the mirror configuration, it still results in a noticeable increase in k_{eff} value.

The effective delayed neutron fraction, β_{eff}, increases gradually with burnup and shows no significant sensitivity to gas removal assumptions or geometric representation. Although MA-dominant systems exhibit

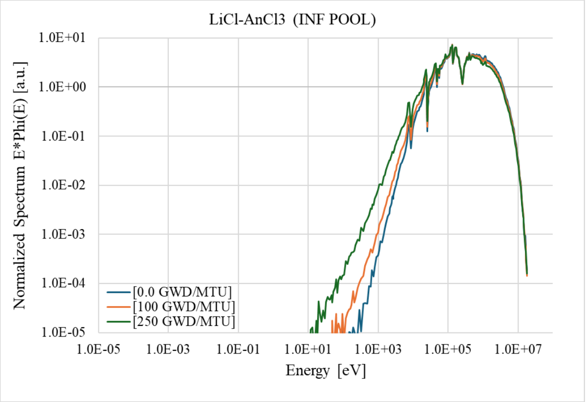


Figure 6. Neutron energy spectrum for the infinite-medium LiCl–AnCl$_3$ system at selected burnup steps.

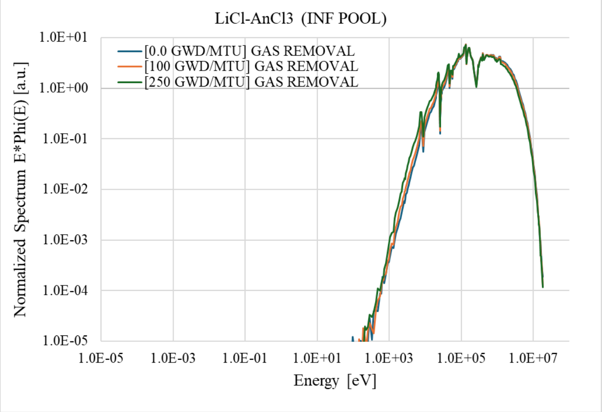


Figure 7. Neutron energy spectrum for the infinite-medium LiCl–AnCl$_3$ system at selected burnup steps with gaseous species removal.

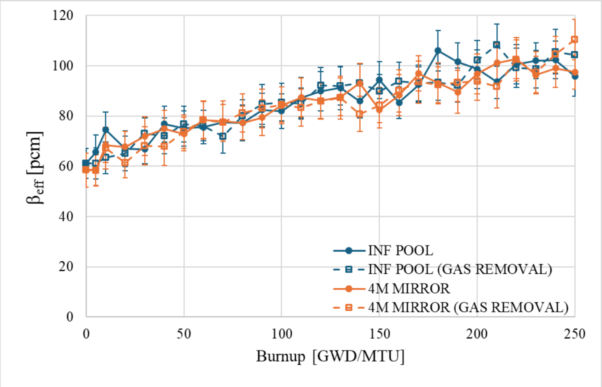


Figure 8. Burnup-dependent effective delayed neutron fraction β_{eff} for the infinite and 4 m mirror configurations.

relatively low delayed neutron fractions, the subcritical FFH configuration reduces reliance on delayed neutrons compared to critical reactors.

Overall, the present results clarify the neutronic behavior of an MA-bearing chloride salt under conditions representative of an externally driven FFH configuration. While the analysis is limited to eigenvalue-based depletion modeling, it identifies key trends associated with spectral characteristics, multiplication behavior, and gas removal effects. Although substantial work remains, including detailed engineering design, thermal-hydraulic coupling, tritium management, and coupled chemistry modeling of the molten salt system, the trends identified here provide practical insight for blanket design and operational strategy in FFH systems aimed at transmutation.

ACKNOWLEDGMENTS

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DECLARATION OF COMPETING INTEREST

Ben Lindley has an ownership interest in and is a technical advisor of Realta Fusion

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