Feasibility of a Breed-and-Burn Molten Salt Reactor

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INTRODUCTION

This work addresses the feasibility and characteristics of the breed and burn (B&B) cycle for Molten Salt Reactors. In the general B&B cycle, natural Uranium or Thorium is used as fuel for a reactor which breeds a sufficient amount to maintain criticality at equilibrium without reprocessing. Interest in applying this scheme to an MSR has developed recently [1] For the MSR B&B scheme considered here, fresh salt containing fertile material is continually fed into the core while salt with the composition of the homogeneous fuel is expelled without reprocessing. Through an analysis of the equilibrium conditions and startup requirements, the feasibility of such a cycle operating with various salts is assessed.

MSR B&B EQUILIBRIUM

For a given salt, fertile material, and power level, the equilibrium core composition will be determined by the salt feed/removal time constant. To find this equilibrium composition, long burnup calculations were run using a modified version of Serpent [2] that removes all isotopes from the fuel with a given time constant. These dumped elements were replaced with an adequate amount of fresh fertile salt. The total actinide molar share of the fuel was kept constant by altering the proportion of fertile heavy metal in the feed stream. Each fission product replaced one of the constituents of the original salt to keep a constant total atomic density. In all cases, noble metals and gasses were removed with a time constant corresponding to an in-core halflife of $30min$.

Infinite Geometry

To determine the feasibility of the MSR B&B cycle for various salts, the equilibrium burnup calculations were conducted using infinite media. The salts considered are listed in table I. The densities of the salts, from top to bottom, were taken from [3] [4] and [5]. For each salt, equilibrium calculations were run using both a natural Uranium feed and pure Thorium feed employing various time constants. The lithium in the lithium-fluoride salt was enriched to 99.99% ^{7}Li while the chlorine in the chloride salt was enriched to 99.99% ^{37}Cl. The power density of all salts was chosen to be $300W/cm^3$. The k_{inf} for each salt as a function of burnup is shown in figure 1. Neither of the cycles using fluoride salts were feasible breeders because at equilibrium they present a k_{inf} lower than unity for all time constants explored. However, the chloride salt showed breakeven potential employing the Uranium-Plutonium cycle which presented peak excess reactivity at equilibrium around a burnup of $0.39FIMA$. This burnup was achieved with a residence time (inverse of removal time constant) around $9year$. In terms of equilibrium k_{inf}, the Uranium-Plutonium cycle outperforms the Thorium-Uranium cycle in all cases.

TABLE I: Salts considered for analysis; x = 1 for all FP nuclides.

Salt	Molar Proportions	Density (g/cc)
(NaF+[FP]F$_x$) – KF – [*Actinides*]F$_4$	43-24-33	4.263
(LiF+[FP]F$_x$) – [*Actinides*]F$_4$	77.5-22.5	4.418
(NaCl+[FP]Cl$_x$) – [*Actinides*]Cl$_3$	67-33	3.107

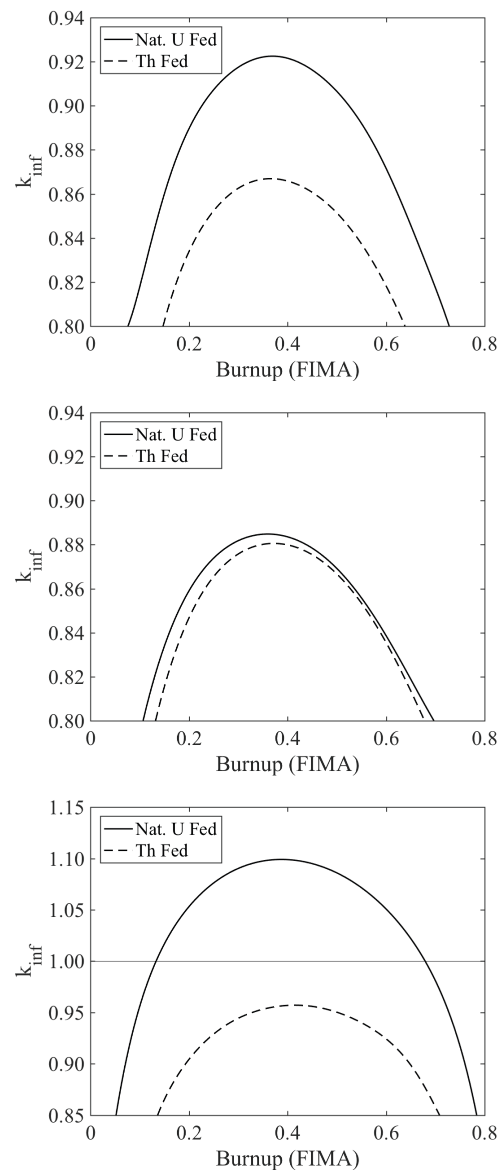

Fig. 1: Equilibrium k_{inf} as a function of burnup. From top to bottom: (NaF+[FP]F$_x$) – KF – [*Actinides*]F$_4$, (LiF+[FP]F$_x$) – [*Actinides*]F$_4$, (NaCl+[FP]Cl$_x$) – [*Actinides*]Cl$_3$.

Effect of Actinide Density

Several heavy metal chloride molar proportions were chosen to investigate the effect of actinide density on the chloride Uranium-Plutonium cycle equilibrium k_{inf}. The results are shown in figure 2. The increased actinide molar share increases the excess reactivity at equilibrium for a given time constant. The peaks of the curves shift to slightly higher residence times with increasing actinide density.

Effect of power level

The equilibrium k_{inf} curve for the chloride Uranium-Plutonium cycle at the arbitrarily chosen power density of $300W/cm^3$ is compared with the same salt/cycle at a power level of $100W/cm^3$ in figure 3. The peak of the $100W/cm^3$ curve occurs at a residence time approximately three times longer than the $300W/cm^3$ curve. The effect of changing the power level is thus essentially a shift in the residence time required to achieve the same k_{inf}. The peak of the $100W/cm^3$ curve is slightly higher than the $300W/cm^3$ curve (1.10240 vs. 1.09910) which suggests better breeding performance at lower power levels possibly due to lower insoluble and gaseous fission product absorption.

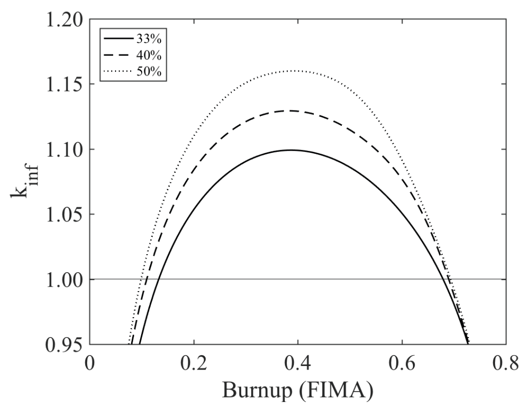

Fig. 2: Effect of $[Actinides]Cl_3$ molar proportion. The equilibrium k_{inf} curve stretches upward with increasing actinide density.

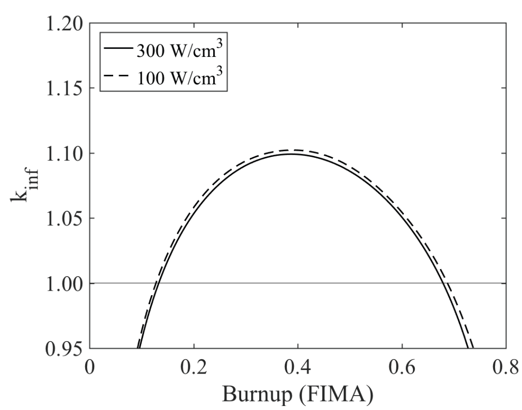

Fig. 3: Effect of power level. A decrease in power density slightly improves the equilibrium k_{inf} for a given burnup level.

Finite Geometry

Equilibrium calculations were also run using finite reflected cores for the chloride salt with the Uranium-Plutonium cycle at a power density of $300W/cm^3$ and various heavy metal densities. The core geometry was chosen to be a cylinder of equal height and diameter. Both lead and steel reflectors were employed. All reflectors were $1m$ thick on all sides, providing an upper bound estimate. Each equilibrium calculation was iteratively run with different core radii until a peak k_{eff} within 300pcm of unity was achieved. This was chosen here to be the minimum critical dimension. The minimum critical radii, initial Uranium content, initial Uranium enrichment, and burnup for the core at equilibrium for each reflector and heavy metal content combination is presented in table II.

TABLE II: Specifications for cores critical at equilibrium employing various reflectors and heavy metal densities. A 1:1 diameter to height ratio was used.

	[Actinide]Cl_3%	Radius (m)	Initial load (MTU)	Initial Enrichment (wt%)	Burnup (FIMA)
Lead	33	2.30	240	11.20	0.403
	40	1.95	157	11.20	0.397
	50	1.70	112	11.20	0.407
Steel	33	2.80	432	11.50	0.404
	40	2.45	312	11.58	0.409
	50	2.25	258	11.47	0.432

STARTUP FEASIBILITY

The start-up of a chloride salt B&B reactor employing the Uranium-Plutonium cycle as described here will require the initial feed salt to contain fissile material. Choosing enriched Uranium as the feed material keeps the MSR B&B cycle reprocessing-facility free. To investigate the feasibility of such a startup process, the same modified Serpent was employed as for the equilibrium calculations. The lower bound of the feed enrichment was chosen to be natural Uranium. The upper bound on the enrichment was chosen to be that of the initial core load.

The time constant and geometry for the minimum critical dimension core with 33% $[Actinide]Cl_3$ for both types of reflectors was used. The results are shown in figure 4. There is no reactivity drop in the cores fed with salt of the initial enrichment level. In the steel reflected core fed with natural Uranium, sufficient breeding has occurred at 2.08 years such that all reactivity has been recovered. The lead reflected core recovered from the initial reactivity drop in only 1.69 years. These results indicate that the enrichment levels required for the startup feed are manageable (no greater than the initial requirement) and not long lived.

ENRICHMENT SAVINGS

The lifetime enrichment requirements of the MSR B&B cycle were compared with those of an AP1000 [6]. The MSR case taken as reference was the 33% heavy metal content, steel reflected core operating at $300W/cm^3$. The power normalized SWU requirements as a function of lifetime length are shown in figure 5. The cumulative normalized separative work required for the operation of the AP1000 remains constant at 539

$SWU/GWt * yr$ while that for the MSR begins high around $9.01 * 10^5$ $SWU/GWt * yr$ and decrease rapidly. The MSR was assumed to have been fed using the initial enrichment level (11.5%) for the amount of time it took the natural Uranium fed core (figure 4) to recover its reactivity (2.08yrs). The intersection of the curves occurs at 5.91 years. This represents the minimum amount of time the MSR must be run before SWU savings occur.

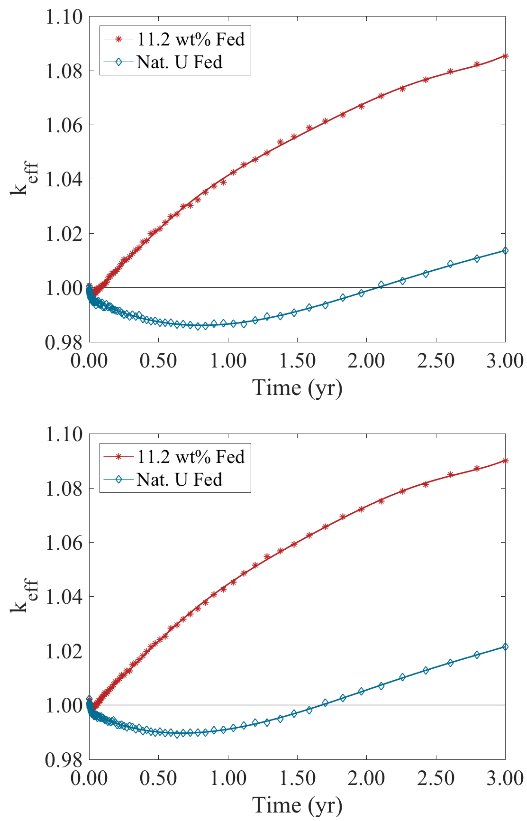

Fig. 4: Startup k_{eff} curves for steel (top) and lead (bottom) reflected cores with natural and initial enrichment Uranium feeds.

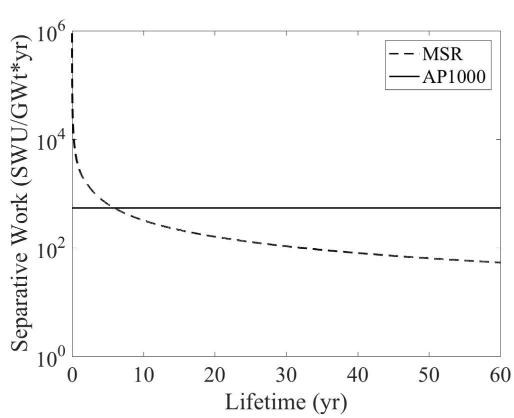

Fig. 5: Comparison of the cumulative separative work required per unit energy by the MSR B&B cycle and AP1000. The MSR presents SWU savings after 5.91 years.

CONCLUSIONS

The MSR B&B scheme studied here was shown to be feasible when chloride salts and natural Uranium fuel were employed. The equilibrium conditions showed adequate breeding performance that resulted in cores of reasonable critical dimensions with start-up feed requirements within practical bounds. Future studies will address the feasibility of attaining passive safety and of practically handling the radiation damage to structures adjacent to the core. The waste characteristics, proliferation resistance, and optimal method of approaching equilibrium for the MSR B&B cycle are also to be addressed.

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