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Characteristics of a Breed-and-Burn Molten Salt Reactor

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Abstract – *The feasibility of establishing a breed and burn mode of operation in several molten salt reactors is assessed and the resulting fuel cycle characteristics investigated. Only chloride salt with natural uranium feed fuel was found a feasible design; it offers a burnup of (10) e to 40% FIMA. Waste resulting from equilibrium operation of such a core are compared to that from a PWR.*

I. INTRODUCTION

This work addresses the feasibility and fuel-cycle 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 of fissile fuel to maintain criticality at equilibrium without reprocessing of fission products or actinides. Interest in applying this mode of operation 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 equilibrium fuel is expelled without reprocessing.

II. MSR B&B EQUILIBRIUM

For a given salt, fertile material, and power level, the equilibrium core composition is determined by the salt feed/removal time constant. To find this equilibrium composition, long burnup calculations are run using a modified version of SERPENT2 [2] that removes all isotopes from the core with a given time constant. These dumped elements are replaced with an adequate amount of fresh fertile salt. The total actinide molar share of the fuel is kept constant by altering the proportion of fertile heavy metal in the feed stream. Each fission product atom replaces one of the constituents of the original salt to keep a constant total atomic density. In all cases, noble metals and gasses are removed with a time constant corresponding to an in-core halflife of 30*min*.

II.A. Infinite Media

To determine the feasibility of the MSR B&B cycle for various salts, the equilibrium burnup calculations were first conducted using infinite media. The salts considered are listed in table I. The densities of the salts, from top to bottom, were taken from, respectively, [3] [4] and [5]. For each salt, equilibrium calculations were run using both a natural uranium feed and pure thorium feed

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

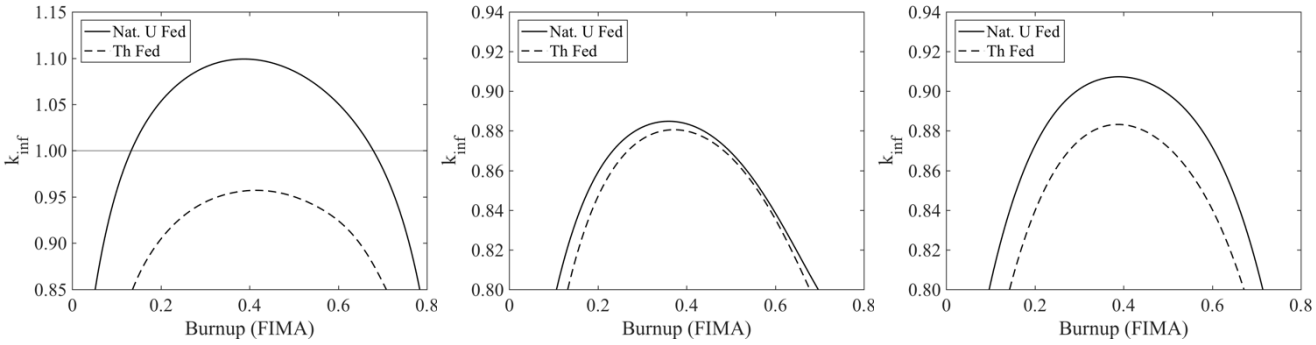

Fig. 1. Equilibrium *kinf* as a function of burnup. From left to right: (NaCl+[FP]Cl_x)−[*Actinides*]Cl_3 , (LF+[FP]F_x)−[*Actinides*]F_4 , (NaF+[FP]F_x)-KF−[*Actinides*]F_4.

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 $300 W/cm^3$. The k_{inf} for each salt as a function of burnup is shown in figure 1. Neither of the cycles using fluoride salts were found to be feasible breed and burners because at equilibrium their k_{inf} is lower than unity for all time constants explored. However, the chloride salt employing the uranium-plutonium cycle has a B&B potential; it offers a peak excess reactivity at equilibrium around a burnup of 0.39 *FIMA*. This burnup was achieved with a residence time (inverse of removal time constant) of around 9 years. The better breeding performance of the chloride salts can be explained by the harder spectrum shown in figure 2. No criticality could be established by the thorium-uranium fuel cycle in the breed-and-burn mode.

II.B. Finite Geometry

Equilibrium calculations were performed using finite reflected cores for the chloride salt with the uranium-plutonium cycle at a power density of $300 W/cm^3$ and various heavy metal fractions. The core geometry was chosen to be a cylinder of equal height and diameter. Both lead and steel reflectors were examined. All reflectors were $1m$ thick on all sides, providing an upper bound estimate. Each equilibrium calculation was iteratively run with different core radii until the peak k_{eff} was equal to one. The minimum critical radius, initial uranium content, and burnup for the core at equilibrium for each reflector and heavy metal molar fraction combination are presented in table II.

TABLE II
Specifications for critical equilibrium cores. A 1:1 diameter to height ratio was used. Radius excludes reflector.

Reflector	[Actinide]Cl3 %	Radius (m)	HM Load (t)	Burnup (FIMA)
Lead	33	2.30	240	0.403
	40	1.95	157	0.397
	50	1.70	112	0.407
Steel	33	2.80	432	0.404
	40	2.45	312	0.409
	50	2.25	258	0.432

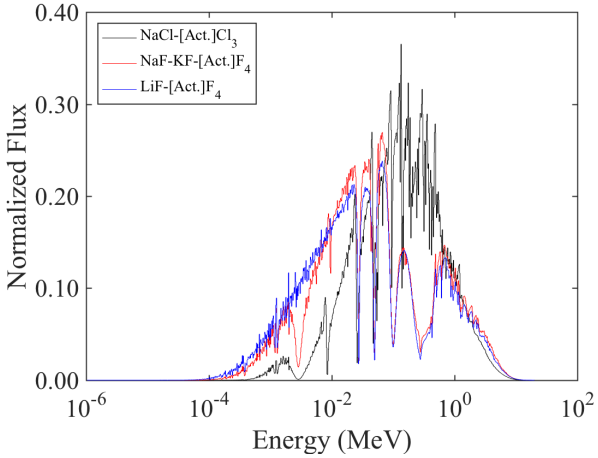

Fig. 2. Equilibrium spectrum for the three salts considered here.

III. Waste Characteristics

Because the homogenous B&B MSR core is continually fed and discharged, the composition of the waste at equilibrium is the same as the core salt. The standard version of SERPENT2 was used to follow the decay of this waste between discharge and 10^6 years. The resultant activity, decay heat, and ingestion radiotoxicity per unit of produced electricity as functions of time are shown in figure 3. A conservative 40% energy conversion efficiency was assumed for the MSR B&B. Efficiencies between 40% to above 50% can be expected for the B&B MSR system due to the high operational temperatures. These characteristics are compared with the waste from a simple PWR pin cell burned using SERPENT2 to a burnup of 50 MWd/kgU assuming a 33% efficiency. The activity and decay heat for both wastes are similar while the MSR B&B discharge has a slightly lower ingestion radiotoxicity. SERPENT2 uses radiotoxicity conversion factors taken from [6]. However, the ^{222}Rn ingestion radiotoxicity conversion factor reported in this source is 6.9E-04 Sv/Bq while in [7] the value appears a[illegible].5E–09 Sv/Bq. The authors have chosen to substitute the ^{222}Rn conversion factor in the standard SERPENT2 code with the value from [7]. The plutonium vectors and production rates for the MSR B&B and PWR pin cell are listed in table III and IV. The plutonium quality is similar for the two systems due to the nearly identical ^{240}Pu contents, although the PWR features higher decay heat and spontaneous fission neutrons emission rate per unit weight of discharged plutonium due to its higher ^{239}Pu and ^{242}Pu concentrations. However the MSR B&B produces less Pu waste per unit of energy due to the higher burnup and higher efficiency.

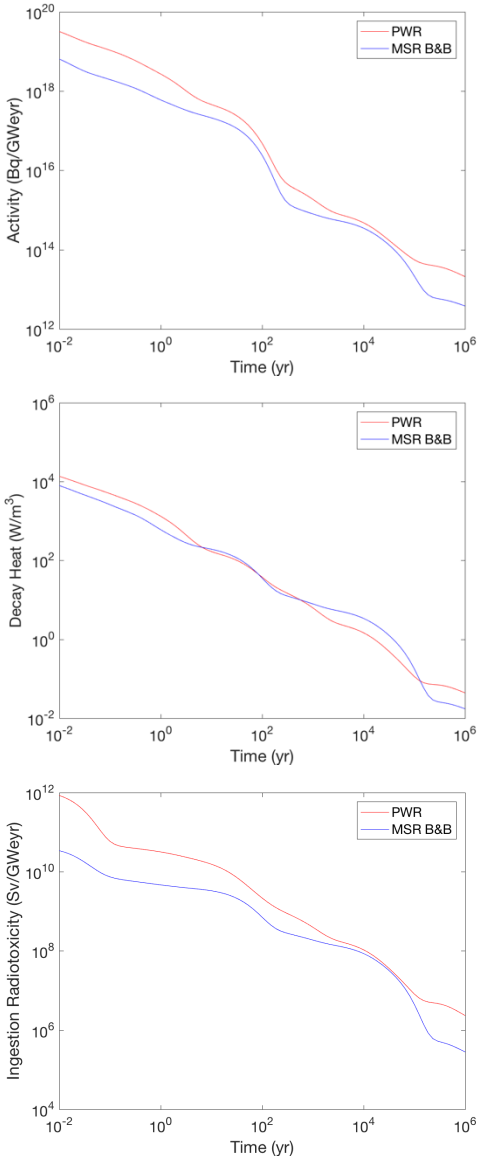

Fig. 3. Waste characteristics for the MSR B&B and PWR.

TABLE III
Plutonium vector for MSR B&B and PWR.

	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu
PWR	0.019	0.500	0.260	0.144	0.078
MSR B&B	0.004	0.693	0.252	0.035	0.015

TABLE IV
Plutonium production rate

System	Pu Production rate (kg/GWeYr)
PWR	275
MSR B&B	175

IV. CONCLUSIONS

The B&B mode of operation was found to be feasible in MSR when using chloride salt and the uranium-plutonium cycle. The minimum critical radii were found to be on the order of several meters and the attainable burnup is close to 40% FIMA. The MSR plutonium quality and waste characteristics are similar to PWR waste, however

a decreased level of radiotoxicity is observed for the MSR discharge. Future studies will focus on the optimal startup strategy and proliferation resistance.

REFERENCES

1. J. LATKOWSKI, "Emerging Commercial Design Concepts: TerraPower," in "Presented at the Workshop on Molten Salt Reactor Technologies Commemorating the 50th Anniversary of the Startup of the MSRE: From the MSRE to a New Emerging Class of Reactors 50 Years Later.", Oak Ridge, TN. (October 14-15 2015).
2. M. AUFIERO, A. CAMMI, C. FIORINA, J. LEPPÄNEN, L. LUZZI, and M. RICOTTI, "An extended version of the SERPENT-2 code to investigate fuel burn-up and core material evolution of the Molten Salt Fast Reactor," *Journal of Nuclear Materials*, 441, *1*, 473–486 (2013).
3. G. J. JANZ, *Molten salts handbook*, Elsevier (2013).
4. O. BENES and R. KONINGS, "Molten salt reactor fuel and coolant," *Comprehensive Nuclear Materials*, 3, 374 (2012).
5. V. DESYATNIK, S. KATYSHEV, S. RASPOPIN, and Y. F. CHERVINSKII, "Density, surface tension, and viscosity of uranium trichloride-sodium chloride melts," *Soviet Atomic Energy*, 39, *1*, 650 (1975).
6. E. D. SERIES, L. PACKER, and J.C. SUBLET, "The European Activation File: EAF-2010 biological, clearance and transport libraries,".
7. N. R. COUNCIL ET AL., *Risk assessment of radon in drinking water*, National Academies Press (1999).