Design of a Molten Chloride Fast Spectrum Reactor

Or: How I Learned To Stop Worrying And Love Sodium Chloride

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September 4, 2018

Background & Study Goals

Is the operation of an MCFR practical in the B&B mode?

Previous work has shown:

- Chloride salts fuel, of composition (NaCl + [FP]Cl_x) - [*Actinides*]Cl_3
- U-Pu cycle, fed with Natural Uranium (or DU) at equilibrium.

The minimum dimensions for a 1-to-1 height to diameter ratio, perfectly cylindrical core were determined, as below.

	[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

Figure 1: Cores critical at equilibrium from [Michael Martin, 2017]. The core specifications adopted in this study are highlighted in red.

- Na-K-F salts and Li-F salts have been excluded.
- Th-232/U-233 cycle excluded due to poor breeding characteristics in the fast spectrum.

Core Composition in B&B MSRs

$$FIMA = \frac{F\tau}{F\tau + N_{act}} \quad (1)$$

where

- F is the fission rate density of the equilibrium fuel composition in $cm^{-3}s^{-1}$.
- τ is the average residence time of fuel in the reactor in seconds. This can also be interpreted as the time required to completely re-fill the reactor with feed material.
- N_{act} is the number density of actinides in the equilibrium fuel composition.

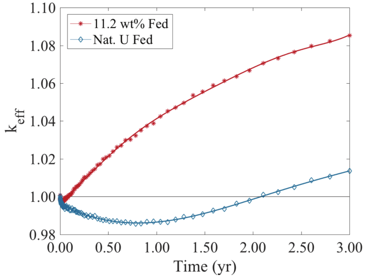


Figure 2: k_{eff} as a function of burnup-years for two enrichments of feed material for the steel-reflected MCFR simulated in Michael Martin [2017].

Burnup Code Strategy

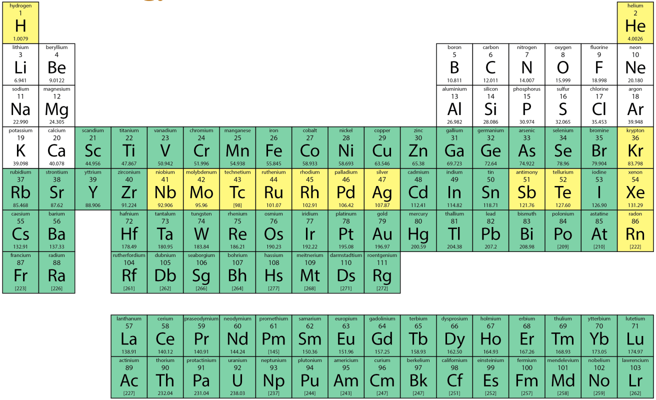


Figure 3: A periodic table in which the elements are grouped according to the rate at which they were removed from the fuel material [car].

In the modified Serpent code, the different color groups above were removed from the fuel with different time constants [Aufiero et al., 2013].

- Yellow elements (gases and heavy metals) were removed from the fuel and in-core half life of 30 minutes.
- Green elements (FPs and actinides) were removed with a variable time constant and replaced with natural Uranium - this determines the discharge burrnup in FIMA.
- White elements were not removed.

Reactor Geometry

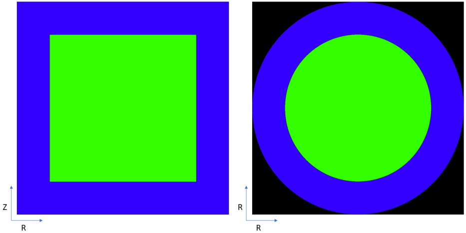


Figure 4: Radial (left) and axial (right) cross sections of Reactor Geometry A from [Michael Martin, 2017].

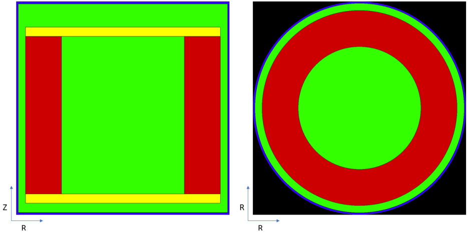


Figure 5: Radial (left) and axial (right) cross sections of Reactor Geometry B, conceived and simulated in this work.

Radial Reflector Study

The size and material composition of the reflector was varied and the change in leakage, k_{eff} and other parameters was observed.

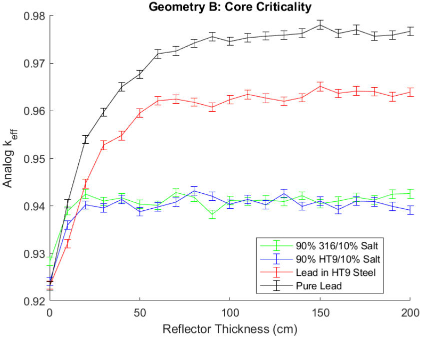
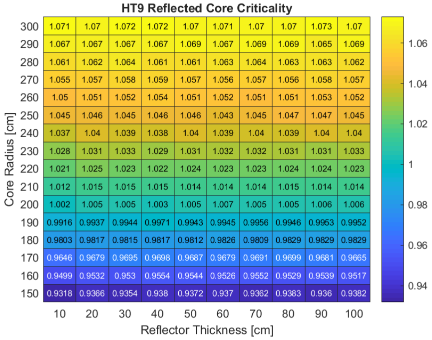


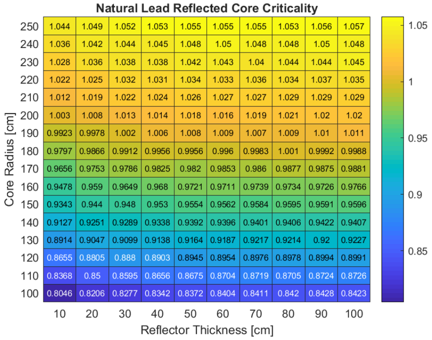
Figure 6: Criticality as a function of reflector thickness in geometry B.

A 20 cm steel reflector was chosen for further evaluation based on a 95%-of-$k_{eff,max}$ criterion. Pb-208 reflectors have shown optimal reflection characteristics in other studies, but lead was discarded due to potential operational issues.

Minimum Core Volume & Reflector Thickness

To observe the effect of reflector thickness, k_{eff} was plotted as a function of core radius and reflector thickness for the optimum feed/removal rate found in this study.





- A natural lead lead reflector allows for smaller core volumes of radius ∼ 180 cm.
- The reflection effect using natural lead saturates at ∼ 80 cm.
- The reflection effect using steel saturates at ∼ 20 cm.

Radiation Damage Calculation Method

A DPA estimation approach using 100-group displacement energy cross section data from the SPECTER code documentation (produced by the DISC code) was adopted. Displacement Energy (E_D) also obtained from the SPECTER documentation [Greenwood and Smither, 1985] [Qvist, 2014].

$$\text{DPA}\, s^{-1} = \sum_{j=1}^{N_{elements}} \left(\frac{0.8}{2E_{D,j}} * \frac{N_j}{N_{tot}} * \sum_{i=1}^{100} \sigma_{i,j}\phi_i \right) \tag{2}$$

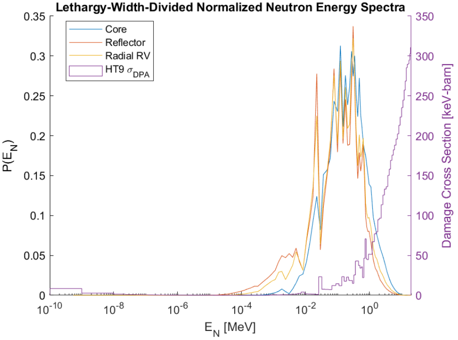


Figure 7: Neutron energy spectra and histogram of damage-cross section data for HT9.

DPA Model Validation

Table 1: Various DPA-per-fast-fluence results for validation of the DPA calculation method.

Source	$\phi_{>0.1\,\mathrm{MeV}}t$ [n cm^{-2}]	DPA	DPA/ϕt [DPA 10^{-22} n^{-1}]	Material	Method
This Study	5.39×10^{23}	200	3.71	HT9	SPECTER
Zhang et al. [2017]	10^{22}	4.0	4.0	HT9	SPECTER
Sencer et al. [2009]	3.89×10^{23}	$\sim$ 155	4.1 - 4.5	HT9	Experiment
Huang [1992]	$3.6\ \times10^{23}$	180	5	HT9	Experiment
Greenwood and Kellogg [1992]	1.00×10^{23}	43	4.30	Iron	Experiment

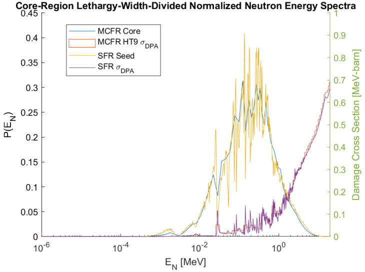


Figure 8: Neutron energy spectrum in the MCFR core. Histogram of damage-cross section data for HT9, produced using the SPECTER code documentation [Greenwood and Smither, 1985]. Seed-region SFR spectrum and SFR DPA cross section data provided by the authors of Zhang et al. [2017].

DPA-per-fluence ratios obtained in this study are in general agreement with those in the literature, although they may have been slightly underestimated in this study.

DPA Lifetime Estimation

And annular mesh was superimposed over reactor components in order to calculate the peak radiation damage rate in DPA / year using a grid-size of 1 cm. The minimum neutron mfp in the material was $\sim$ 2.44 cm.

Radiation damage would be most severe in the HAZ of welds in any component, so the lifetime estimates are very approximate.

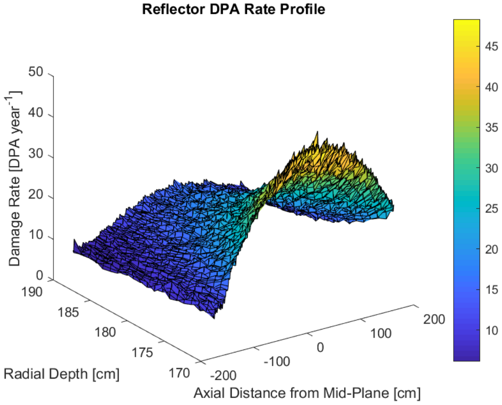


Figure 9: Radiation damage rate as a function of *r* and *z* position in the 20 cm HT9 reflector.

DPA Lifetime Results

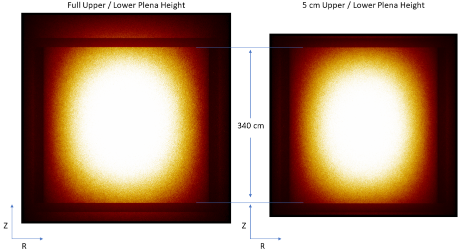


Figure 10: Radial cross sections of the power profile before and after the plena heights were reduced to 5 cm.

Component	Peak DPA/year	*z* [cm]	*r* [cm]	Lifetime [years]
Reflector	51	16.5	170.5	4
Upper Steel Internals	67	173.5	1.5	3
Lower Steel Internals	77	-179.5	0.5	3
Radial Reactor Vessel	9	13.5	210.5	24
Upper Reactor Vessel	18	196.5	6.5	11
Lower Reactor Vessel	24	-195.5	0.5	9

Table 2: Component lifetimes with plena heights reduced to 5 cm, using a 208 DPA limit.

Minimum Core Volume & Discharge Burnup

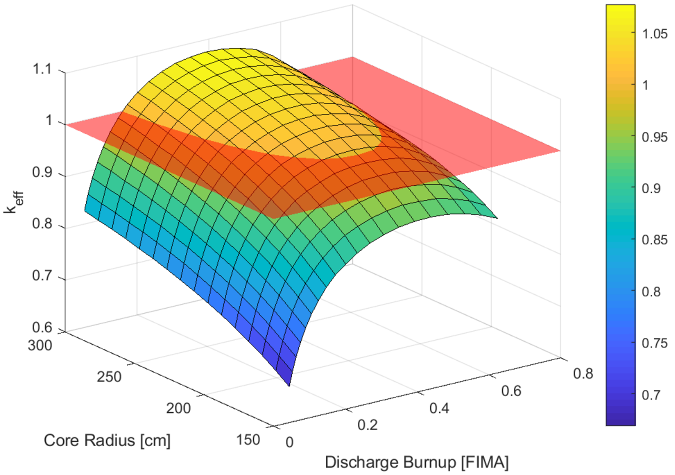


Figure 11: Equilibrium k_{eff} for Various Core Radii and Discharge Burnups. Criticality ($k_{eff} = 1$) indicated by the semi-transparent red plane.

Reactor Safety

$$\alpha_{Temp} = \alpha_{Doppler} + \alpha_{Dilation} = \left(\frac{dk}{dT}\right)_{Doppler} + \left(\frac{dk}{d\rho}\frac{d\rho}{dT}\right)_{Dilation} \tag{3}$$

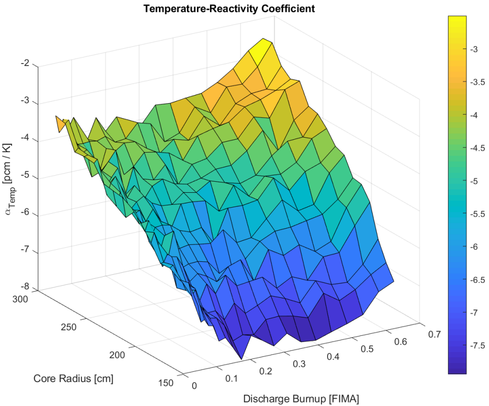


Figure 12: The temperature reactivity coefficient for the equilibrium fuel compositions.

Equilibrium Composition & Core Volume Results

	k_{eff}	**FIMA**	τ **[years]**	r_{core} **[cm]**	α_{temp} **[pcm/K]**	β_{eff} **[pcm]**
Max k_{eff}	1.0766 ± 0.0003	0.3914	13.6381	300	-3.7 ± 0.2	349.216 ± 1.30
Min FIMA (k_{eff} >1)	1.0000 ± 0.0003	0.1702	4.40	280	-4.3 ± 0.2	368.053 ± 1.51
Max FIMA (k_{eff} >1)	1.0124 ± 0.0003	0.6226	35.00	300	-2.8 ± 0.2	334.467 ± 1.37
Min Radius (k_{eff} >1, FIMA= min)	1.0032 ± 0.0003	0.3702	13.64	200	-5.9 ± 0.2	348.626 ± 1.35
Min Radius (k_{eff} >1, FIMA= max)	1.0027 ± 0.0003	0.4614	19.88	200	-5.7 ± 0.2	359.578 ± 1.33
Min α_{temp} (k_{eff} >1)	1.0121 ± 0.0003	0.2925	9.36	220	-6.1 ± 0.2	359.062 ± 1.41
Max α_{temp} (k_{eff} >1)	1.0124 ± 0.0003	0.6226	35.00	300	-2.8 ± 0.2	334.467 ± 1.37

Table 3: Extrema of the critical k_{eff} surface in figure 11 and the α_{temp} surface in figure 12.

- The minimum core radius was found to be 200 cm, corresponding to a total salt volume of 64.79 m^3. Burnups of between 37% and 46% were achievable for this volume of salt.
- α_{Temp} values ranged from -6.1 to -2.8 pcm/K for all critical & supercritical configurations.
- A general trend of increasing α_{Temp} with core radius and burnup was observed.

Results & Conclusions

Radiation Damage Constraints

- The upper and lower steel internals were found to have lifetimes of approximately 3 years. This represents the **greatest standing design challenge** identified in this study.
- Possible approaches to the radiation damage issue is the use of sacrificial material on the core-facing surface of components **OR** the qualification of better materials.
- TerraPower aims to qualify steels up to 500 DPA under heavy ion bombardment. However, neutron irradiation studies are still necessary [Hackett and Povirk, 2012] [Hejzlar et al., 2013].

Minimum Core Volume

- The minimum active core volume of $\sim$ 50.3 m^3 with a total salt volume of $\sim$64.79 m^3.
- Assuming a power density of 300 W cm^{-3}, the corresponding power of 15.08 GWth is probably **economically infeasible**.
- A lead reflector highly enriched in Pb-208 could allow this volume to be reduced while the delaying and minimizing power spike produced in reactor transient scenarios [Michael Martin, 2017] [Kulikov G.G. and E.G., 2018].

The large core volume and fast fluence are the largest outstanding design challenges. Pumps & heat exchangers should be placed in the downcomer regions (as in the MSFR) to shield these components from the core.

Bibliography I

A periodic table of the elements grouped by feed/removal rate in the modified version of serpent.

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