NSSC 8
NUCLEAR SCIENCE and SECURITY CONSORTIUM

Nuclear Science and Security Consortium

September Workshop and Advisory Board Meeting

Fuel inventory characterization for fast spectrum molten salt reactors

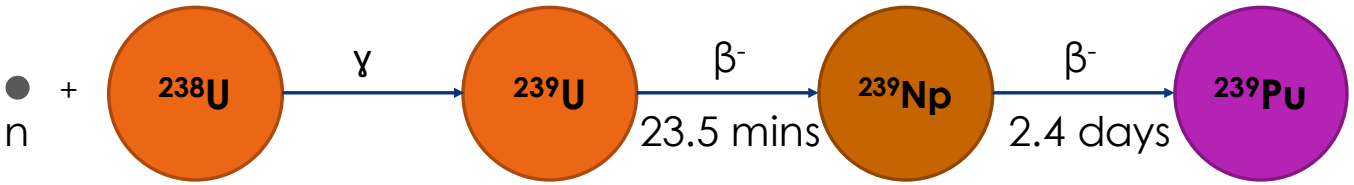
September 11 2017

Michael Martin
UC Berkeley
Nuclear Engineering

Outline

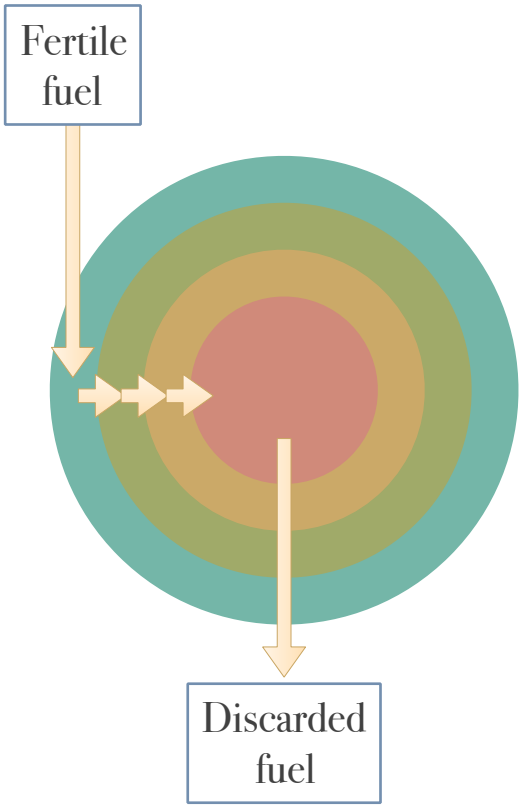
- A review of the Breed-and-Burn (B&B) concept in solid fuel
- The breed and burn (B&B) cycle in Molten Salt Reactors (MSRs)
- Methodology
- Parametric analysis on a single cell model
- Full core model

In the B&B cycle fissile material is bred and burned in situ



- No enrichment
  - at equilibrium the system is only fed with fertile material (natural, depleted, or recovered uranium).
- No reprocessing
  - this differs from breeder reactors in which bred fuel is removed and used to start/fuel a new reactor

The B&B cycle in solid fuel is limited by radiation damage on the cladding



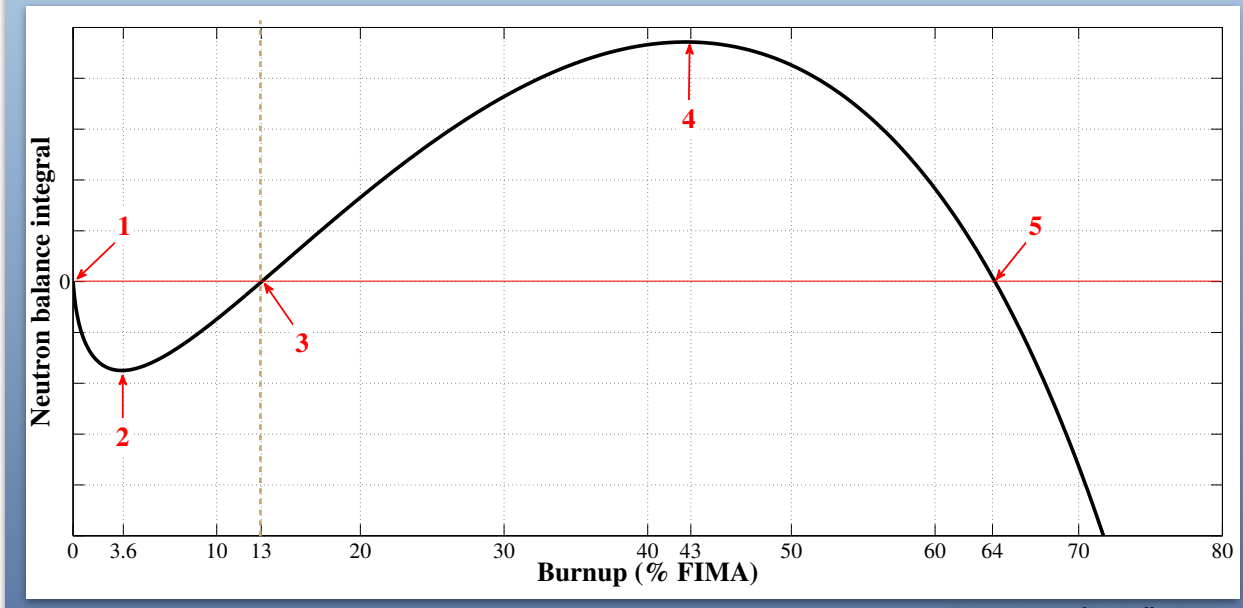
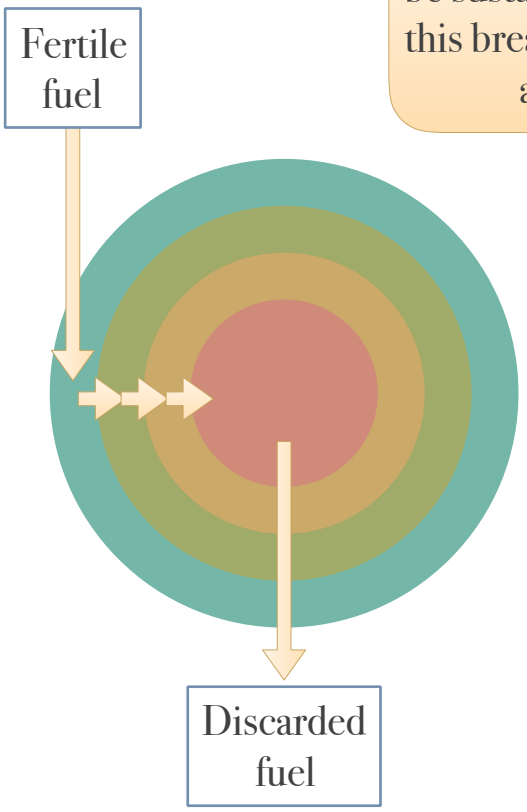


Figure courtesy of Dr. Staffan Qvist

Integral neutron balance in a B&B solid fuel fast reactor as function of fuel burnup starting from depleted uranium

The B&B cycle in solid fuel is limited by radiation damage on the cladding

B&B in solid fuel can be sustained only when this break even point is achieved



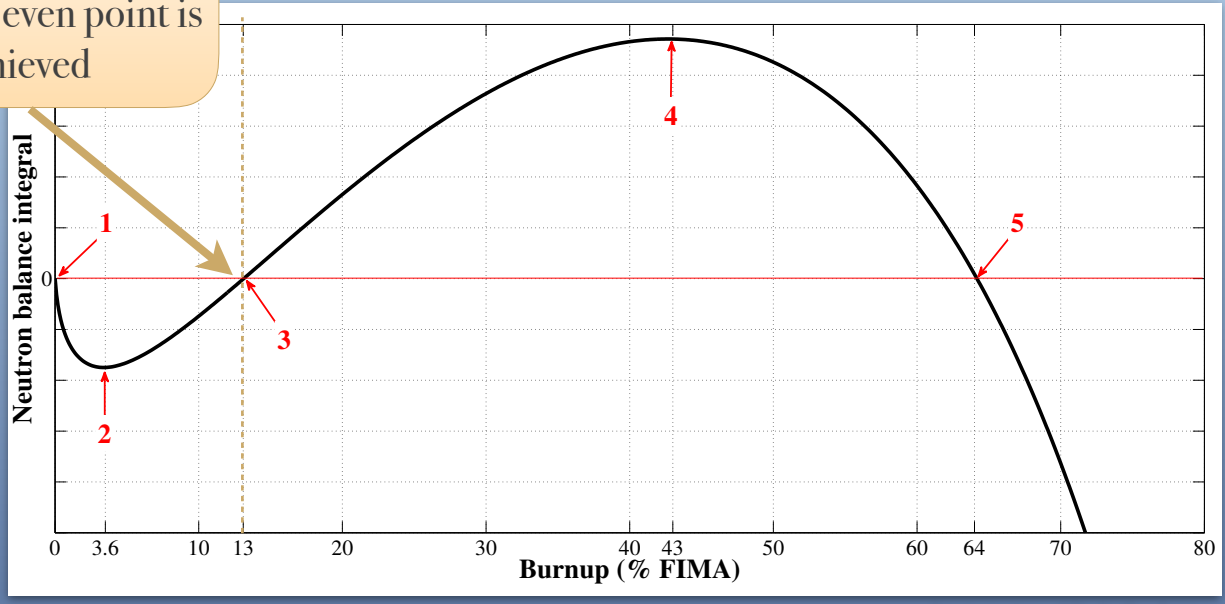
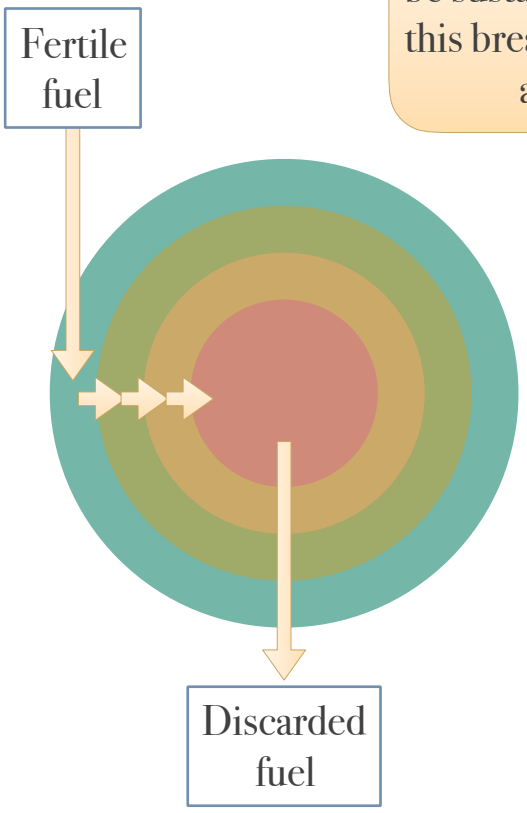


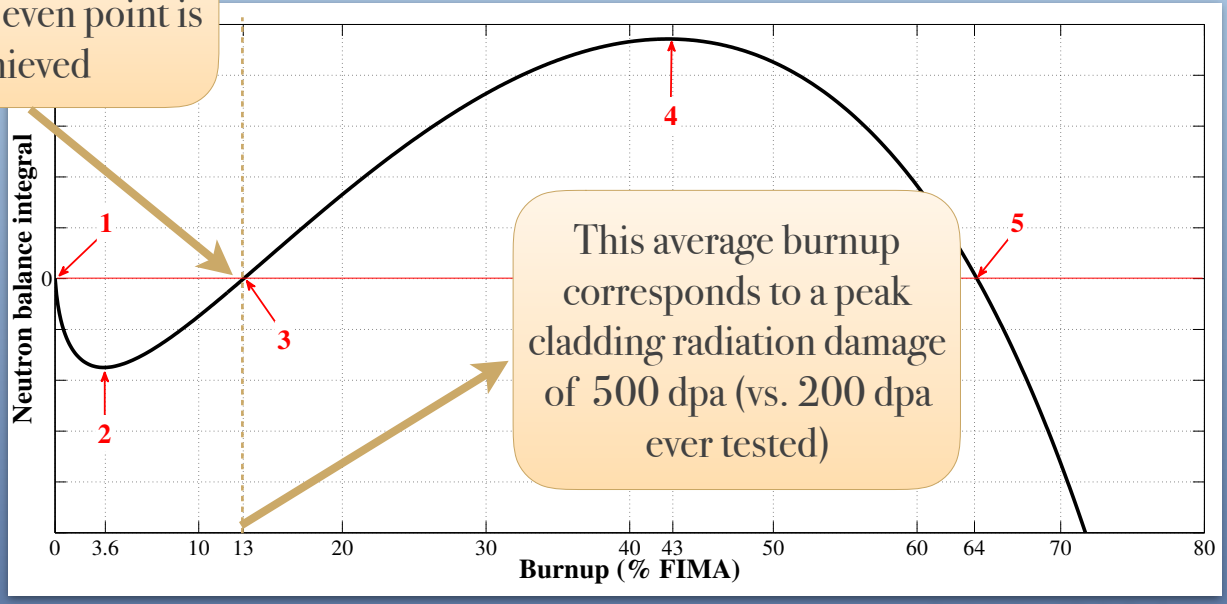
Figure courtesy of Dr. Staffan Qvist

Integral neutron balance in a B&B solid fuel fast reactor as function of fuel burnup starting from depleted uranium

The B&B cycle in solid fuel is limited by radiation damage on the cladding



B&B in solid fuel can be sustained only when this break even point is achieved



This average burnup corresponds to a peak cladding radiation damage of 500 dpa (vs. 200 dpa ever tested)

Figure courtesy of Dr. Staffan Qvist

Integral neutron balance in a B&B solid fuel fast reactor as function of fuel burnup starting from depleted uranium

The B&B cycle in liquid fuel is controlled by the rate at which salt is fed and removed

At equilibrium:

- Salt in the core (including fuel) is discarded at a constant rate
- Salt is replaced at the same rate with fertile salt (total volume is kept constant)
- Non-soluble fission products (gaseous and noble metals) are removed, typically at a much faster pace

There are two main differences in a B&B cycle employing solid and liquid fuel

Solid fuel

- Limited by radiation damage to cladding.
- Can select which fuel batch is discarded (i.e., the one with the highest burnup).

Liquid fuel

- Not limited by radiation damage.
- Fuel is mixed; when salt is discarded it contains infinitesimal salt “batches” at any burnup level.

A parametric analysis was carried out to determine B&B options in MSRs

Parameters

- Carrier salt
  - (NaF+[*FP*]F_x) − KF − [*Actinides*]F_4 (43/24/33)
  - (^{7}LiF+[*FP*]F_x) − [*Actinides*]F_4 (87.5/22.5/33)
  - (Na^{37}Cl+[*FP*]$^{37}Cl_x$) − [*Actinides*]$^{37}Cl_3$ (77/33)
- Fertile material
  - Uranium
  - Thorium
- Feed/removal rate (wide range)

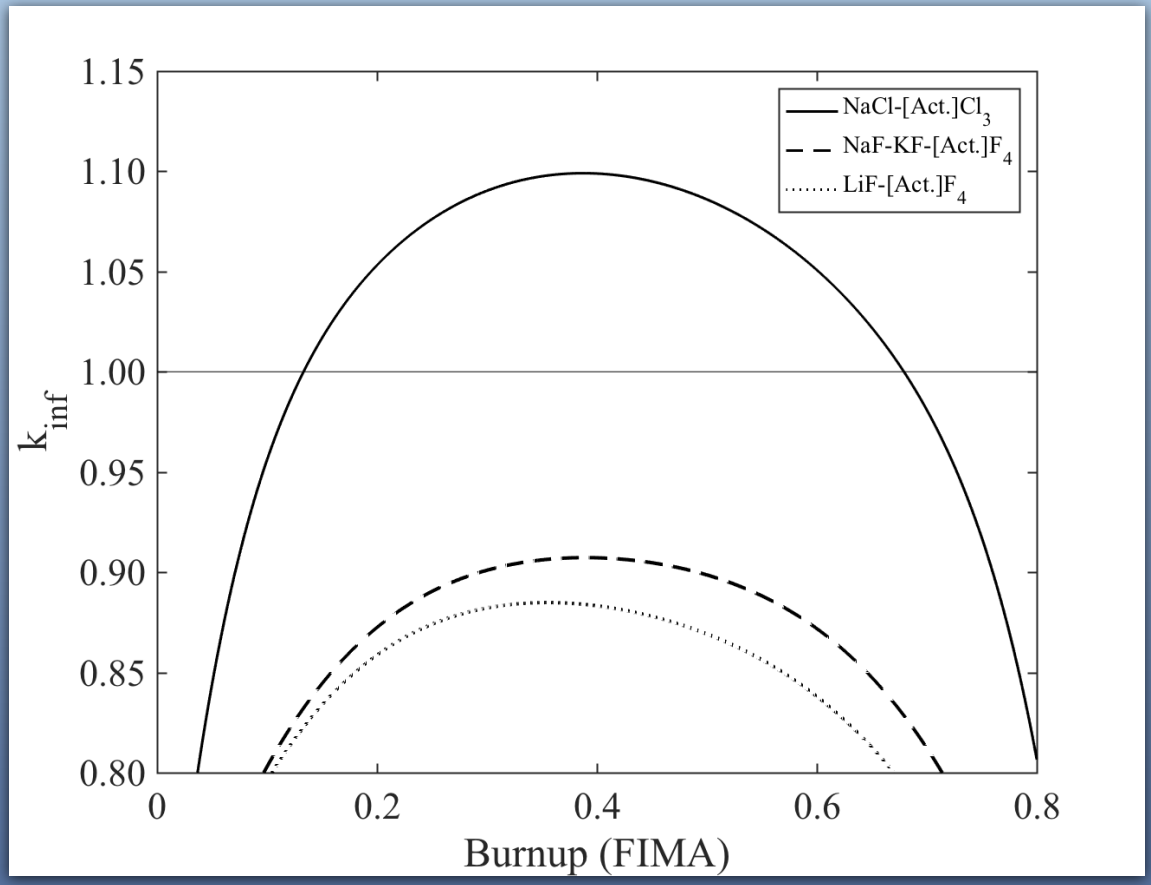
Viable combinations were down selected using a unit cell model

- The unit cell model consists of an infinite volume of salt.
- A salt, fertile material, and feed/ removal rate combination is considered viable if the equilibrium $k_{inf} > 1$.

A modified version of Serpent 2 was employed for equilibrium calculations

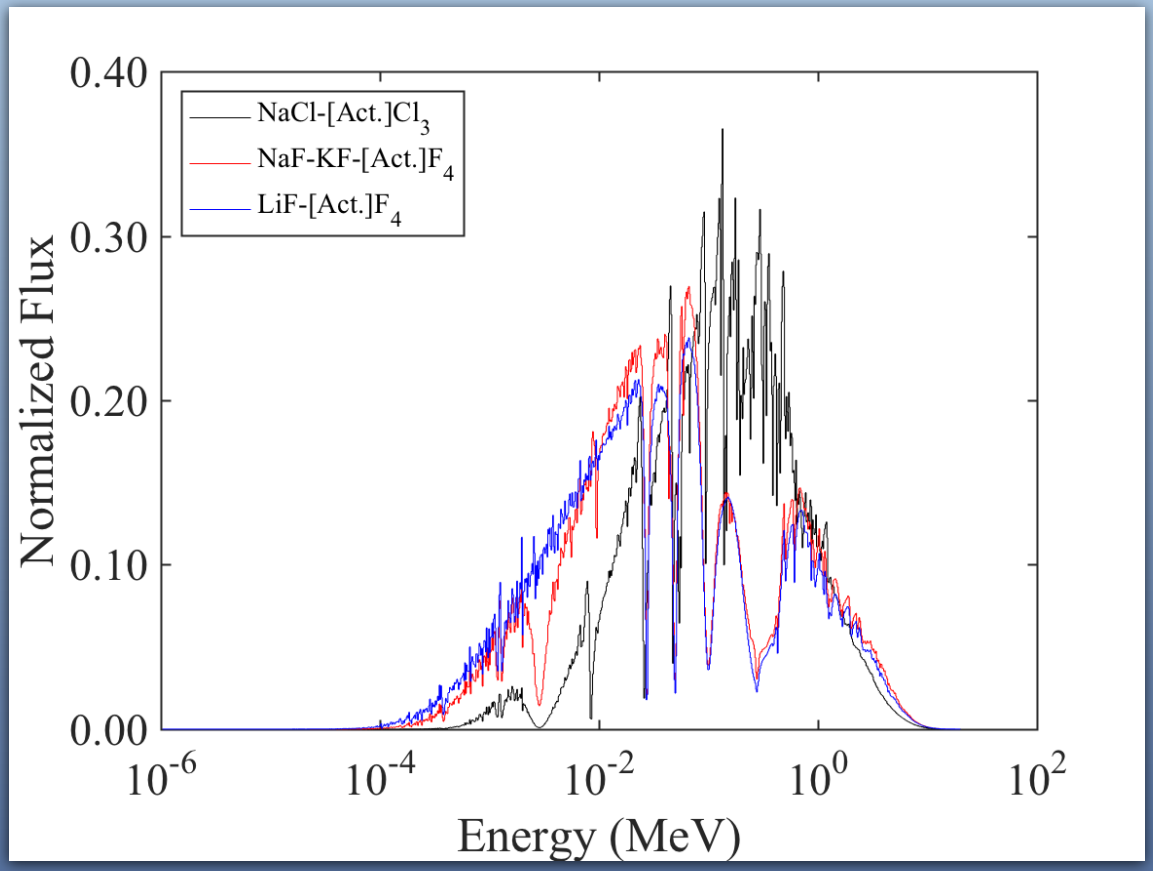
- Calculations were set to determine the equilibrium core composition (no transition).
- All isotopes were removed with a given time constant and replaced with an adequate amount of fertile fuel salt.
- Gasses and noble metals and were removed with an in-core half-life of 30 min.
- No additional reprocessing was assumed for other fission products.
- The nominal power level for depletion was fixed at 300 W/cm^3.

The B&B cycle fueled with natural uranium can only be sustained in a chloride salt



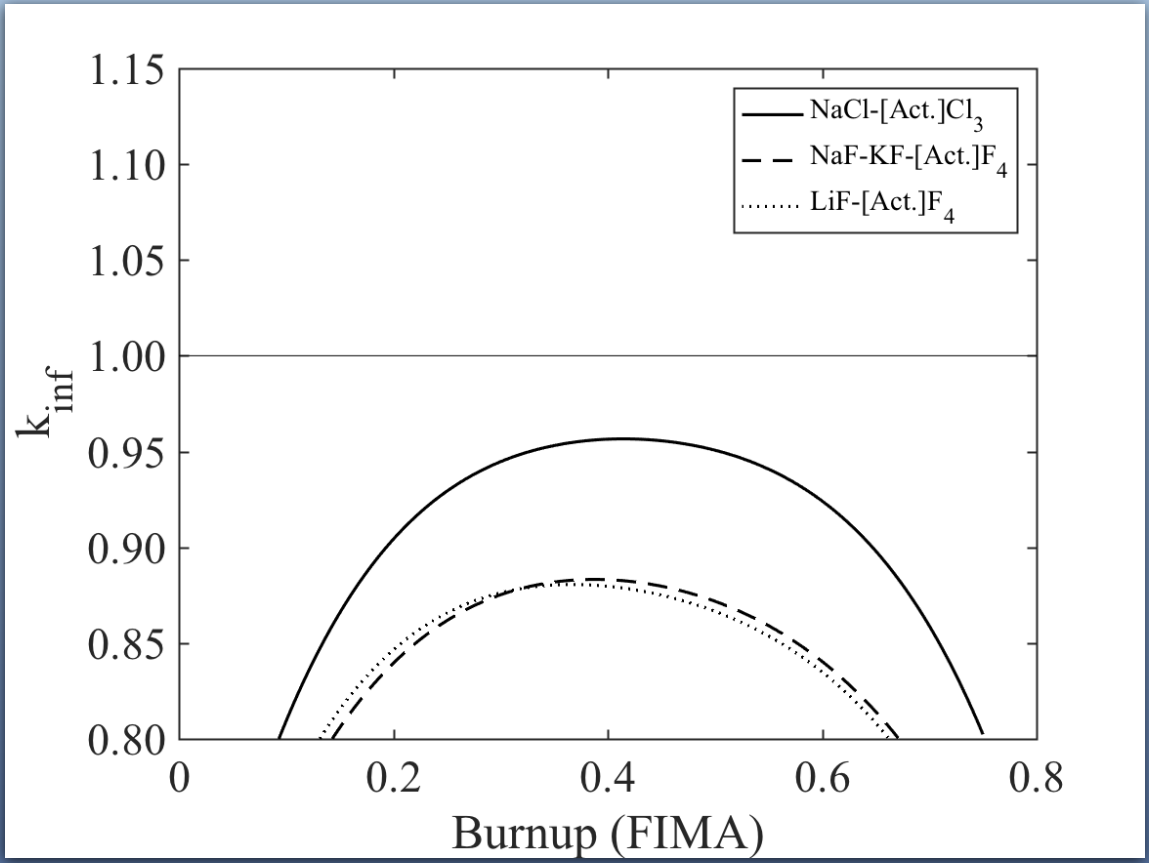
Equilibrium k_{inf} as a function of carrier salt and discharge burnup for natural uranium.

The chloride salt enables a faster neutron spectrum



Comparison of neutron spectrum in different carrier salts.

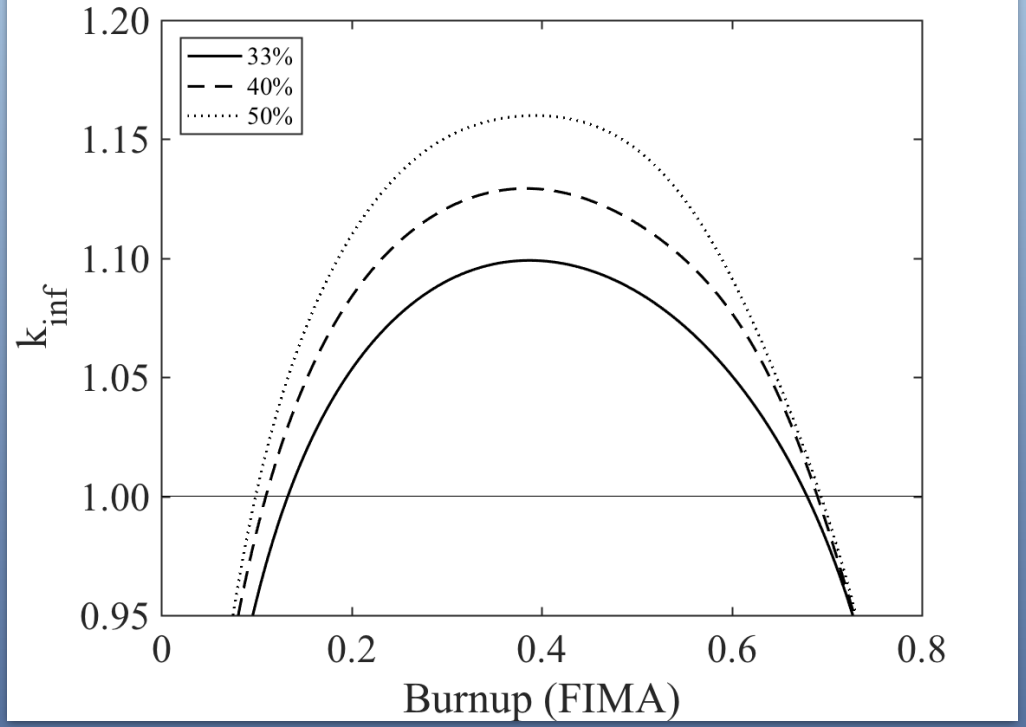
The B&B cycle fueled by thorium can not be sustained (as was expected)



Equilibrium k_{inf} as a function of carrier salt and discharge burnup for thorium-232 feed.

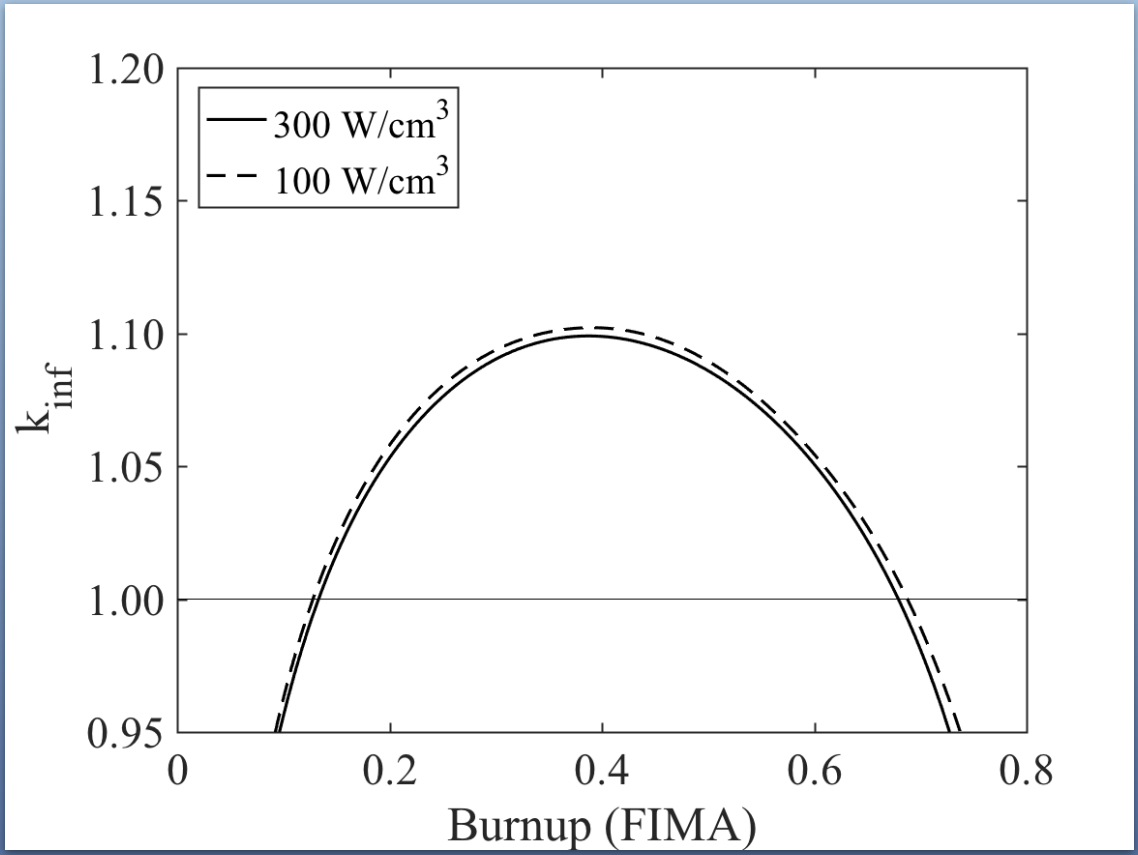
Increasing the actinides concentration provides larger margins for criticality

- Higher actinide concentrations are possible, but increase the melting temperature
- Trade-off between operational temperature and reactor size



Equilibrium k_{inf} for chloride salt as a function of discharge burnup and heavy metal densities.

Power density has virtually no impact on criticality range and margins



Equilibrium k_{inf} for the chloride salt as a function of discharge burnup with different power densities.

16

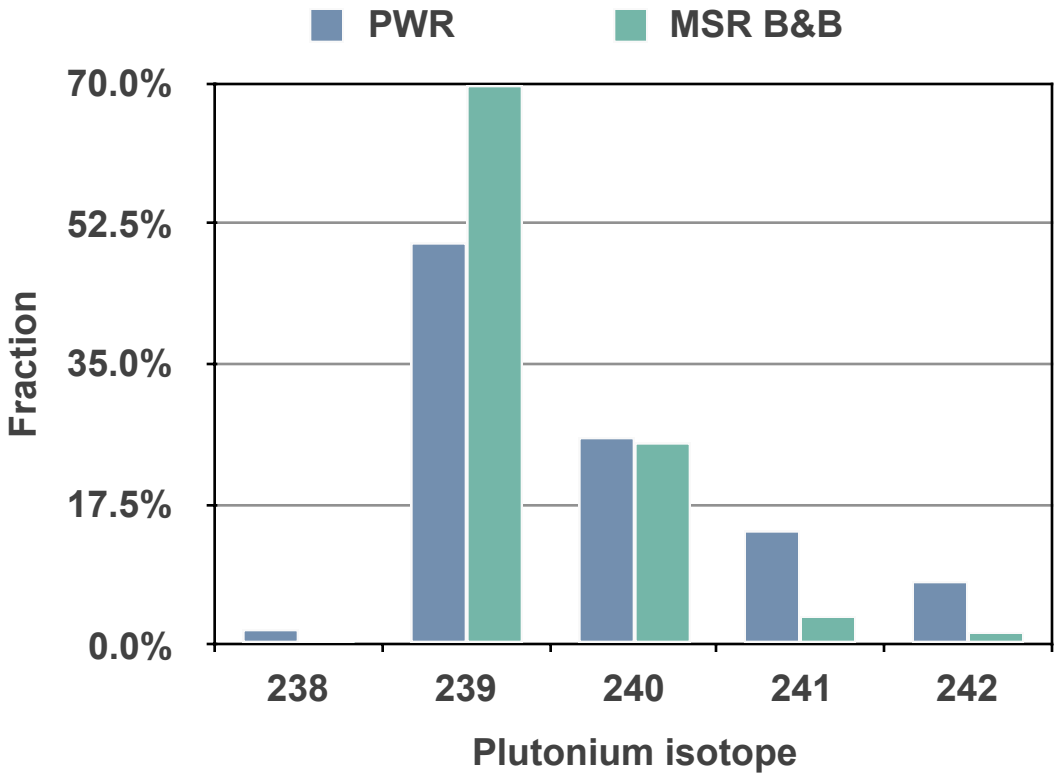
Full core equilibrium calculations were performed for chloride salt

- A right cylinder geometry with a 1:1 diameter to height ratio was employed.
- A 1 m reflector on all sides was used for each core.
- The volume of the core was varied searching for the minimum critical volume at equilibrium.

The minimum core volume is ~30 m^3
A burnup of ~40% can be achieved

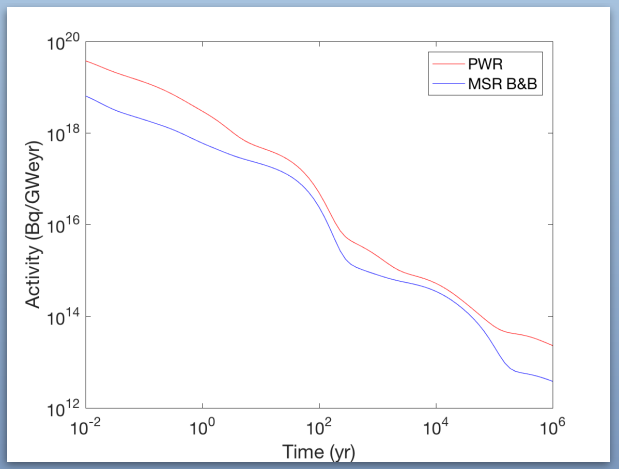
Reflector Material	[Act.]Cl_3 (molar %)	Radius (m) (Excluding ref.)	HM load (t)	Burnup (FIMA)
Lead	33	2.30	120	0.403
	40	1.95	78	0.397
	50	1.70	56	0.407
Steel	33	2.80	216	0.404
	40	2.45	156	0.409
	50	2.25	129	0.432

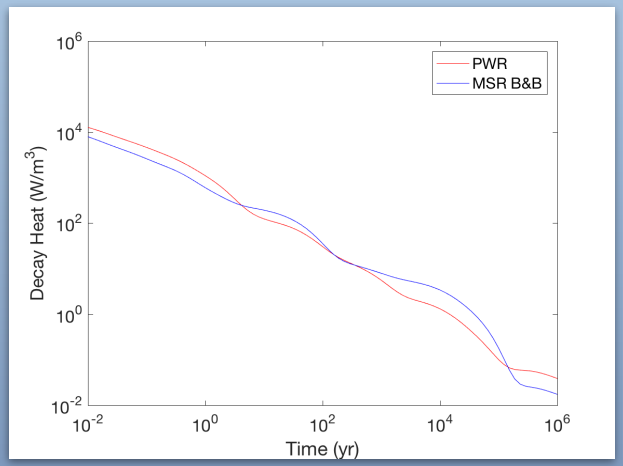
At equilibrium Pu-239 is less than 70% of the total plutonium

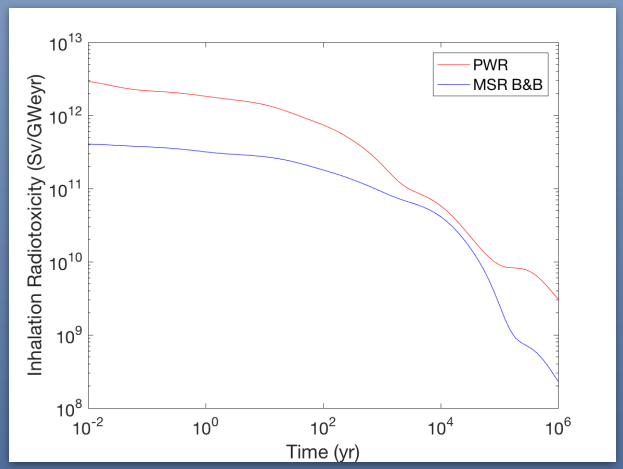


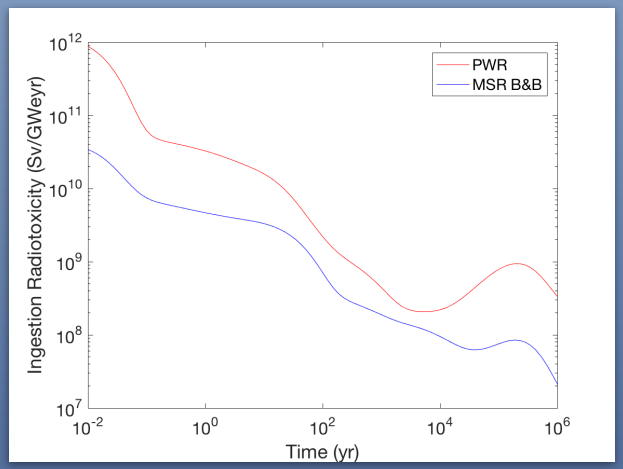
System	Discarded Pu (kg/GWeYr)
PWR	275
MSR	175

B&B MSR discharged fuel features reduced radiotoxicity





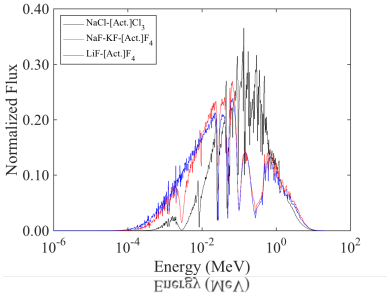


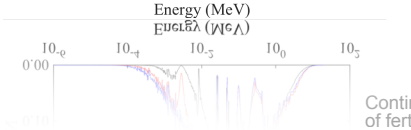


Comparison of properties of discharged fuel from a PWR and an B&B MSR at equilibrium per unit of energy generated.

Conclusions

- The feasibility of a breed and burn cycle in molten salt reactors was explored using multiple parameters.
- Chloride salt operating with the uranium-plutonium cycle was the only feasible combination.
- A full core model determined that a ~40% burnup can be achieved and a relatively large core would be required.
- Basic waste characteristics were established.
- Future work will use fuel cycle data to investigate safeguard strategies for molten salt reactors



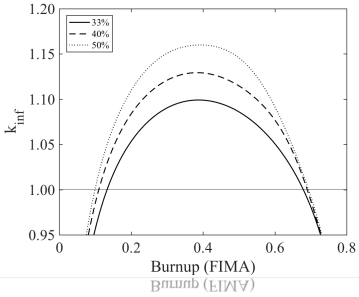


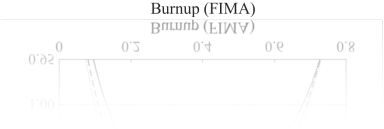
Continuous feed of fertile material

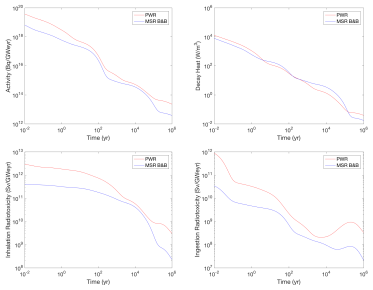
MSR core (at equilibrium)

Continuous removal of salt (whole

Continuous removal of gaseous fission products and noble metals







Thank you for your attention. Questions?

Disclaimer

This material is based upon work supported by the Department of Energy National Nuclear Security Administration under Award Number DE-NA0003180.