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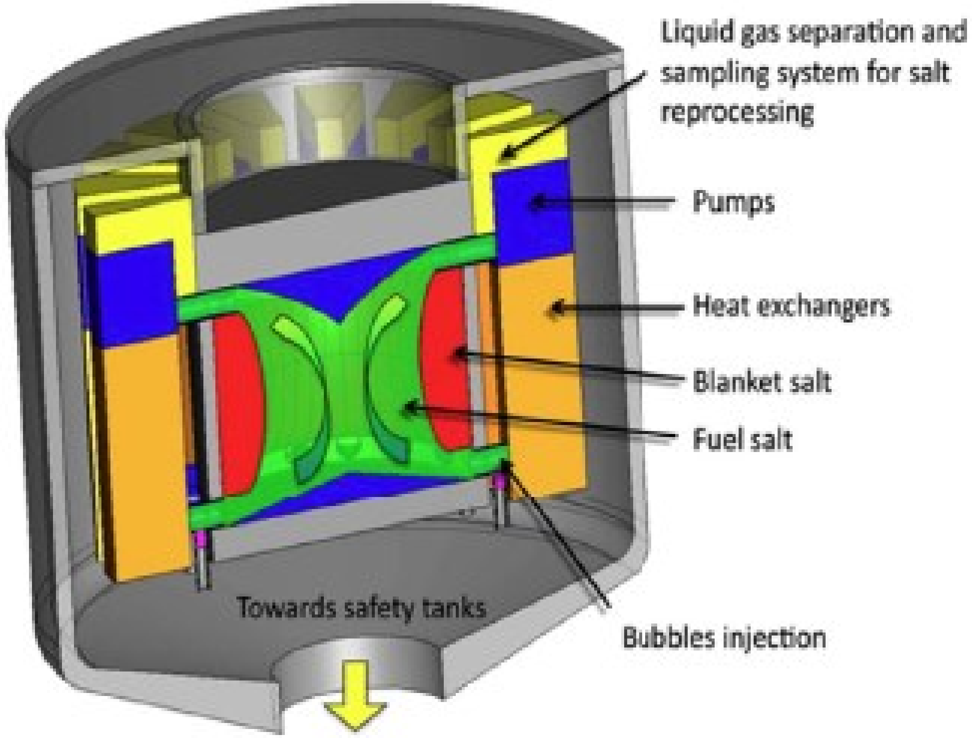
Parametric Study of Breed & Burn Molten Chloride Fast Reactor

Young Molten Salt Reactor Conference, Lecco, 2022

Overview

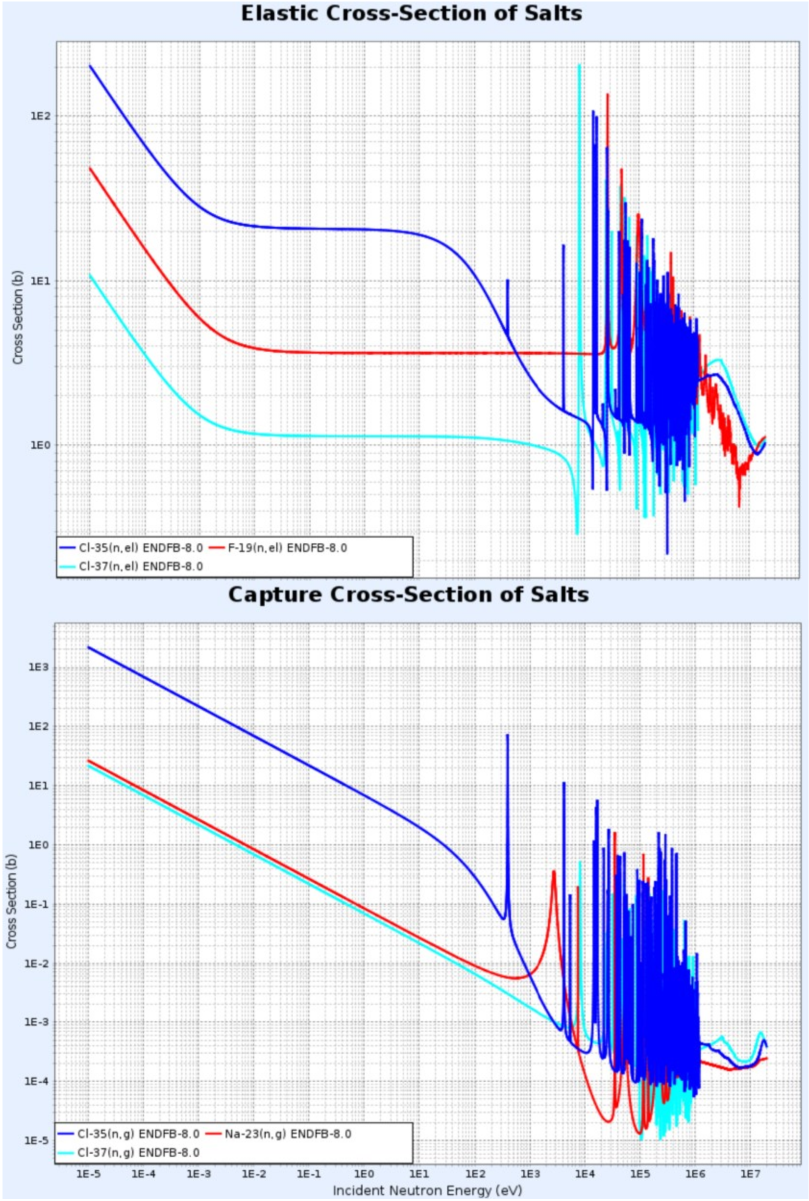
- Introduction to B&B MCFR
  - Salts
  - Processing
- Current research
  - Volatile removal
  - Material effects
  - Parametric study
- Conclusion & future work



Complex MSR Reactor Design

Introduction: Salts

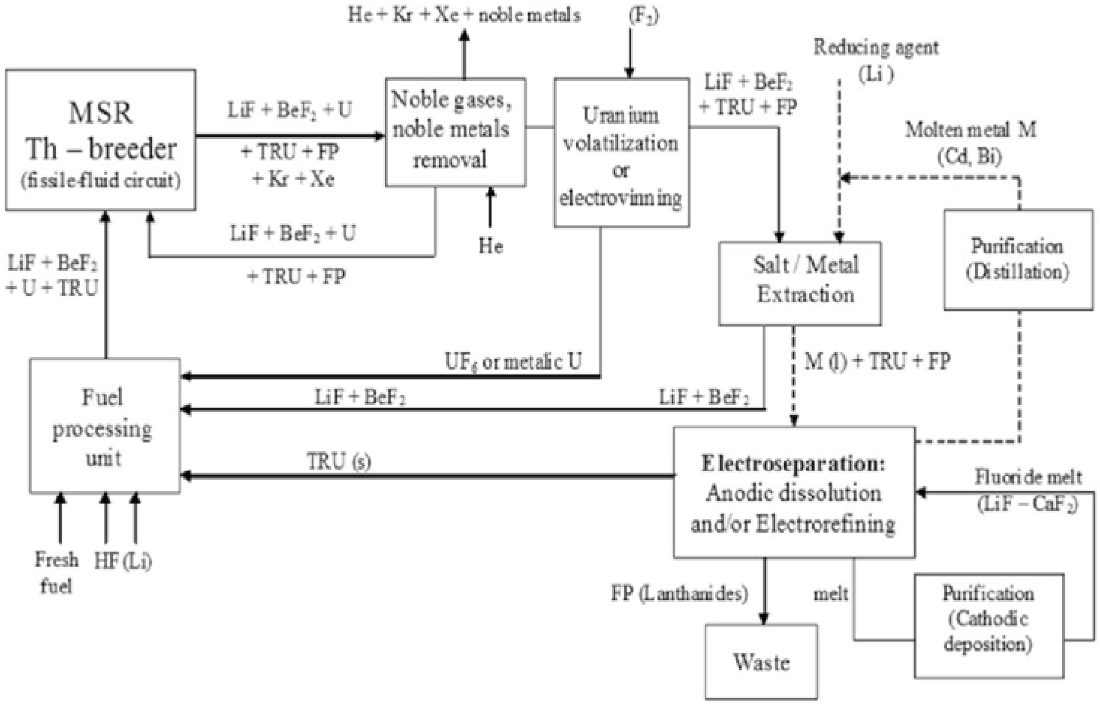
- Fluorine
  - Fast & thermal reactors
  - Main salt for past investigations
  - Low absorption XS
  - Higher scatter XS
- Chlorine
  - Breed & Burn reactors (U-Pu)
  - Breeder in closed loop fuel cycles (U-Pu, Th-U)
  - Minimal experimental data
  - Low absorption XS (Cl-37)
  - Low scatter XS (Cl-37)
    - Harder spectrum
    - Natural Chlorine – 76% Cl-35, 24% Cl-37
    - Must purify



Introduction: In-Situ Processing

- Nuclear reaction products and FP's not contained
  - Helium bubbling remove non-soluble FP's
  - Chemical treatment plant? It depends…

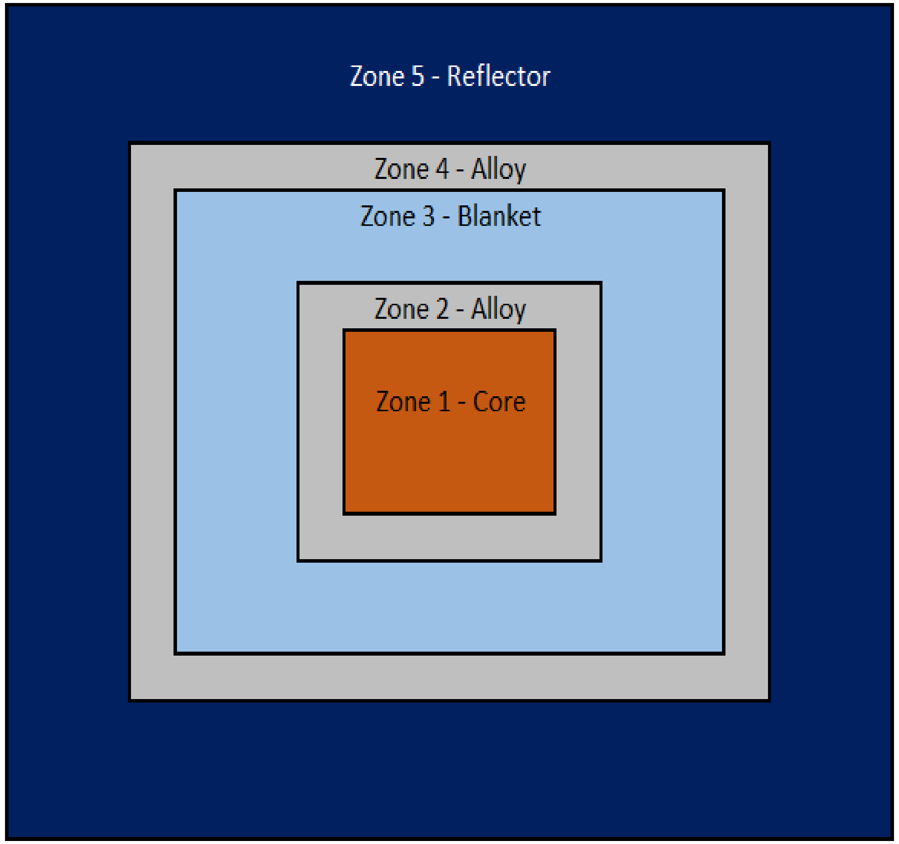
Complex Fuel Reprocessing Diagram



Breed & Burn MCFR

- Chlorine very transparent to neutrons
  - Large reactor – How to minimize
- Simplified geometry
  - Cylinders with D/H = 0.92
- Initial Fuel composition
  - $NaCl:UCl_3$ = 60:40
  - 11.5% U-235 enrichment
  - 100% Cl-37

Fuel Composition	
Isotope	Ratio
Na-23	21.4%
Cl-37	64.3%
U-235	1.6%
U-238	12.6%

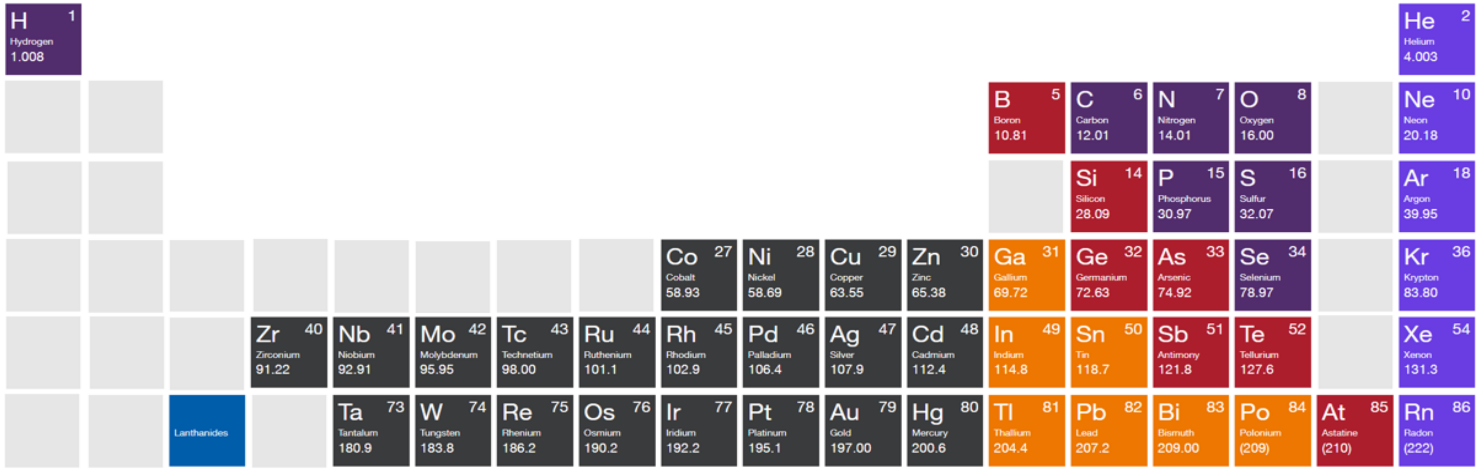


Cross section of MCFR (Not to Scale)

Salt Treatment

- Two removal systems
  - Transfer/Removal rate
    - Remove all elements
    - Vary 0.02-0.18 cm^3/s
    - Reservoir into blanket
    - Blanket into core
    - Core to waste
  - Off gas System
    - Remove Volatiles and non-soluble FPs
    - Cycle time: 30s
    - Efficiency = 100%
    - Needs validating

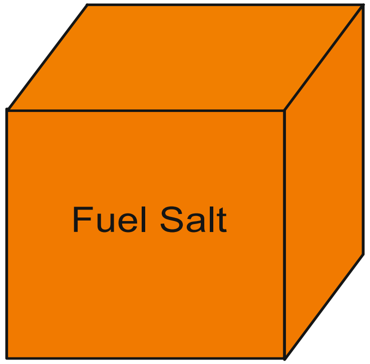
Elements removed by off gas system					
	1:2	5:8	10	14:16	18
	27:34	36	40:52	54	73:86



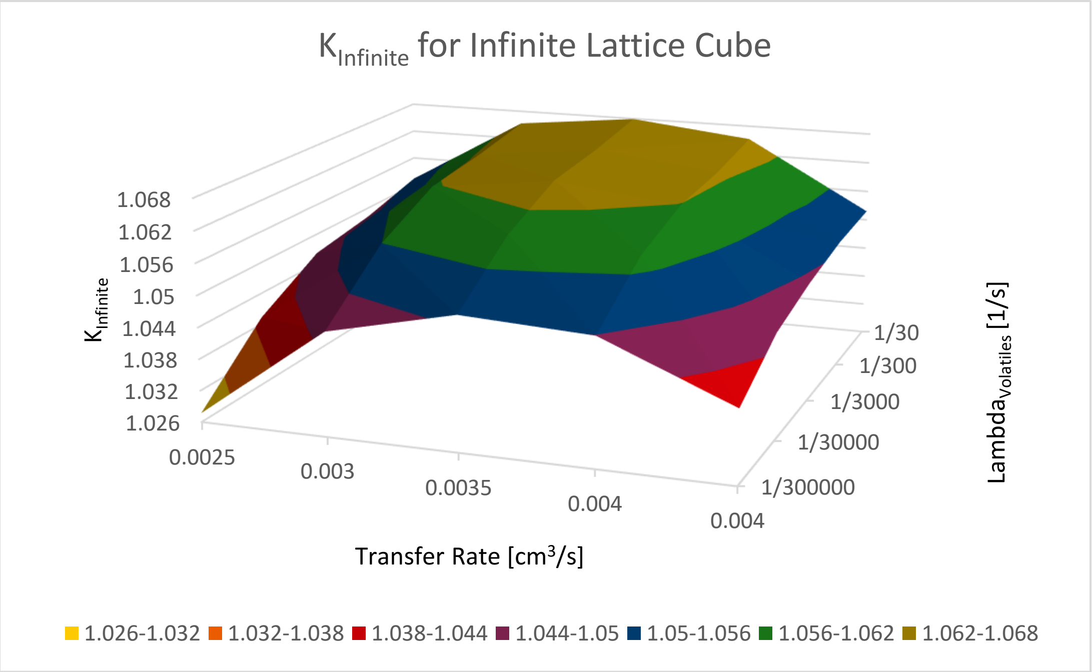
Simulation

- EQL0D fuel cycle procedure
  - MATLAB and Serpent based burnup calculation tool
  - Serpent Monte-Carlo code (Outer loop)
    - Obtain and update neutron reaction rates
      - Update cross-sections, flux data
  - MATLAB (Inner loop)
    - Compute fuel evolution using CRAM (Chebyshev Rational Approximation Method)
      - Solve Bateman equation
    - Criticality calculation
    - Remove waste from reactor and replace with fresh salt
  - Continual fuel treatment

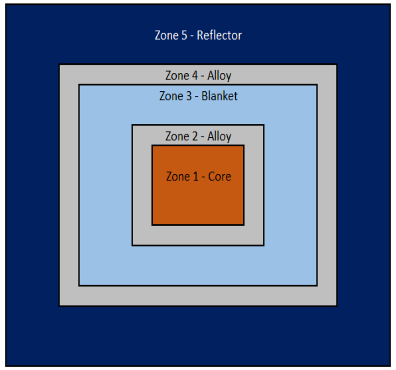
Research: Removal of Volatiles & Transfer Rate



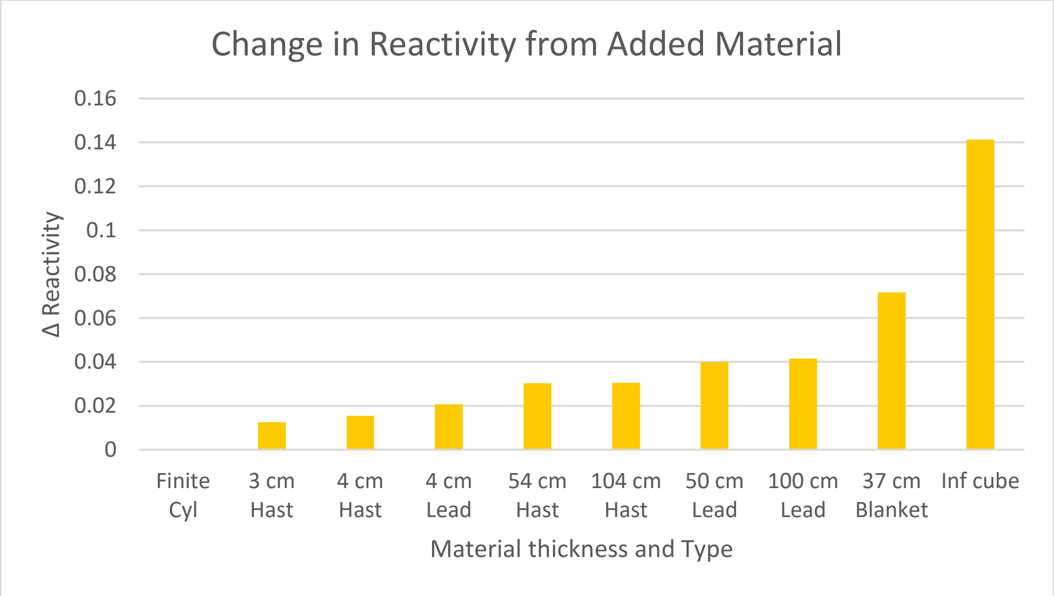
- 1 m^3 infinite lattice cube
- Variables
  - Fuel tapping speed
  - Volatile removal speed
- Outcome
  - Fast volatile removal important
  - Exists ideal transfer rate

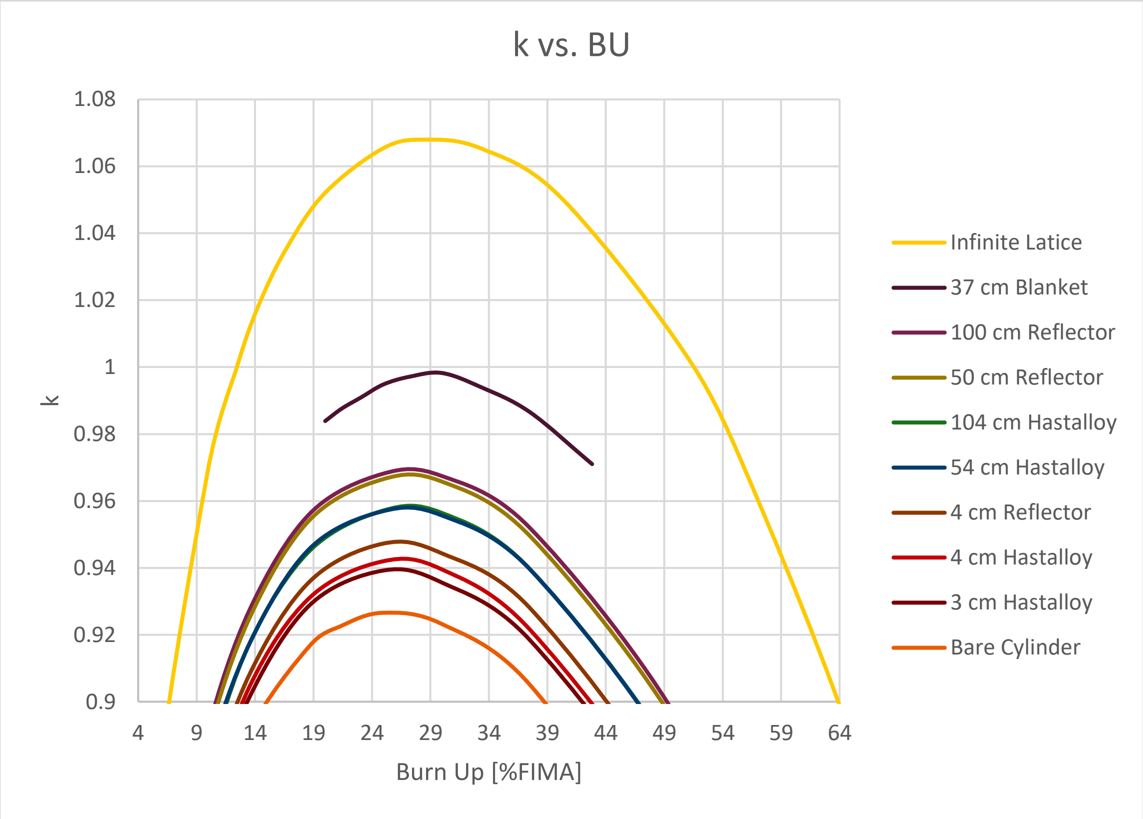


Research: Material Effect

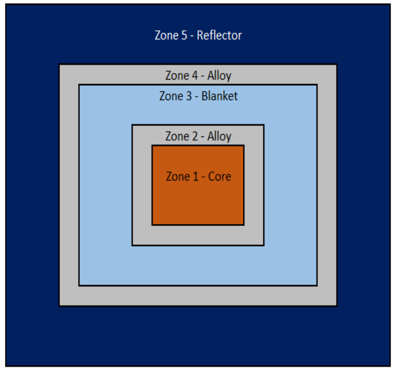


- 150 m^3 core
- Variables
  - Fuel tapping rate
- Add to simulation layer by layer
  - Material effects leakage and absorption
- Identify ideal design material and geometries
  - Best use of money

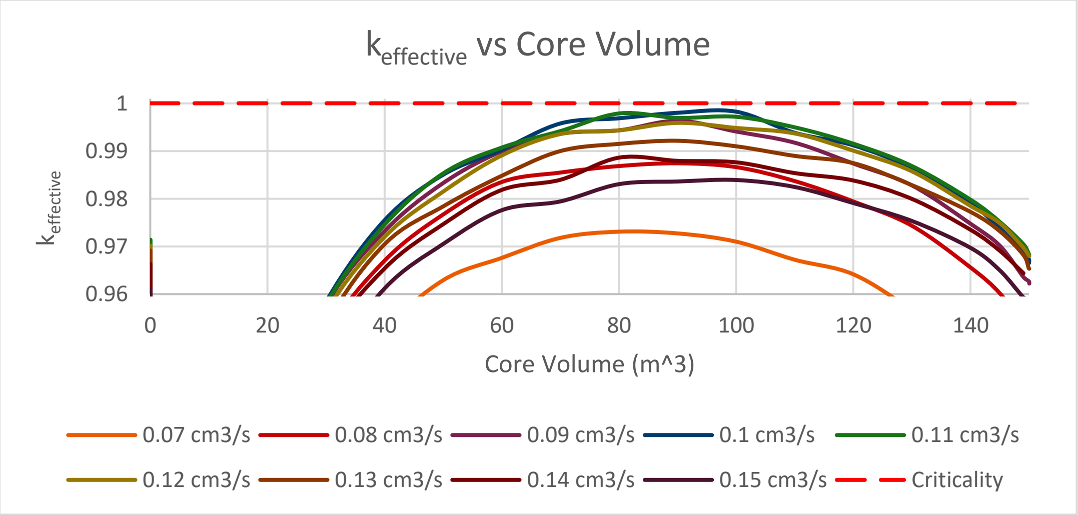


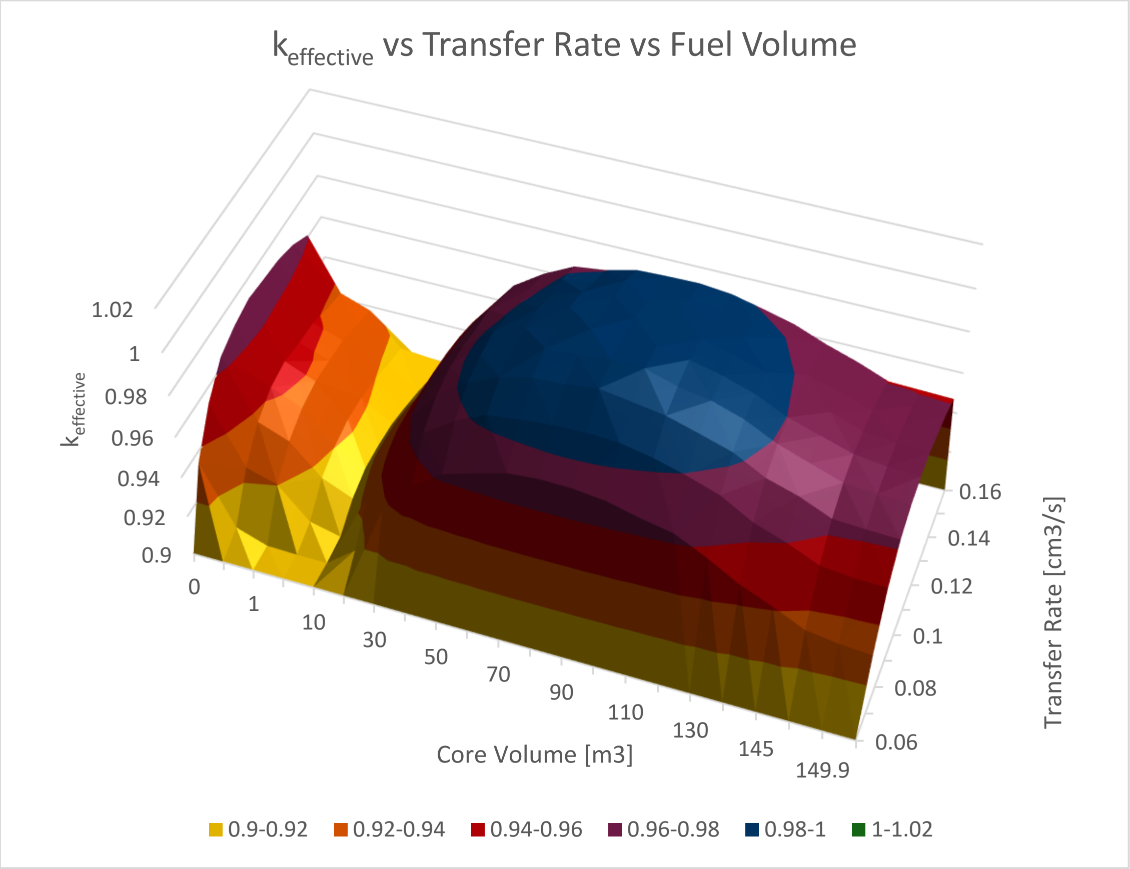


Research: Geometric Study



- Sum of blanket and fuel salt – 150 m^3
- Variables
  - Core/blanket volume
  - Fuel tapping speed (transfer rate)
- Thickness of separating walls constant
- 30s cycle time for gas/non-soluble FPs
- Results
  - Ideal rate of transfer – 0.1 cm^3/s
  - Ideal core & blanket size – 100 m^3 / 50 m^3





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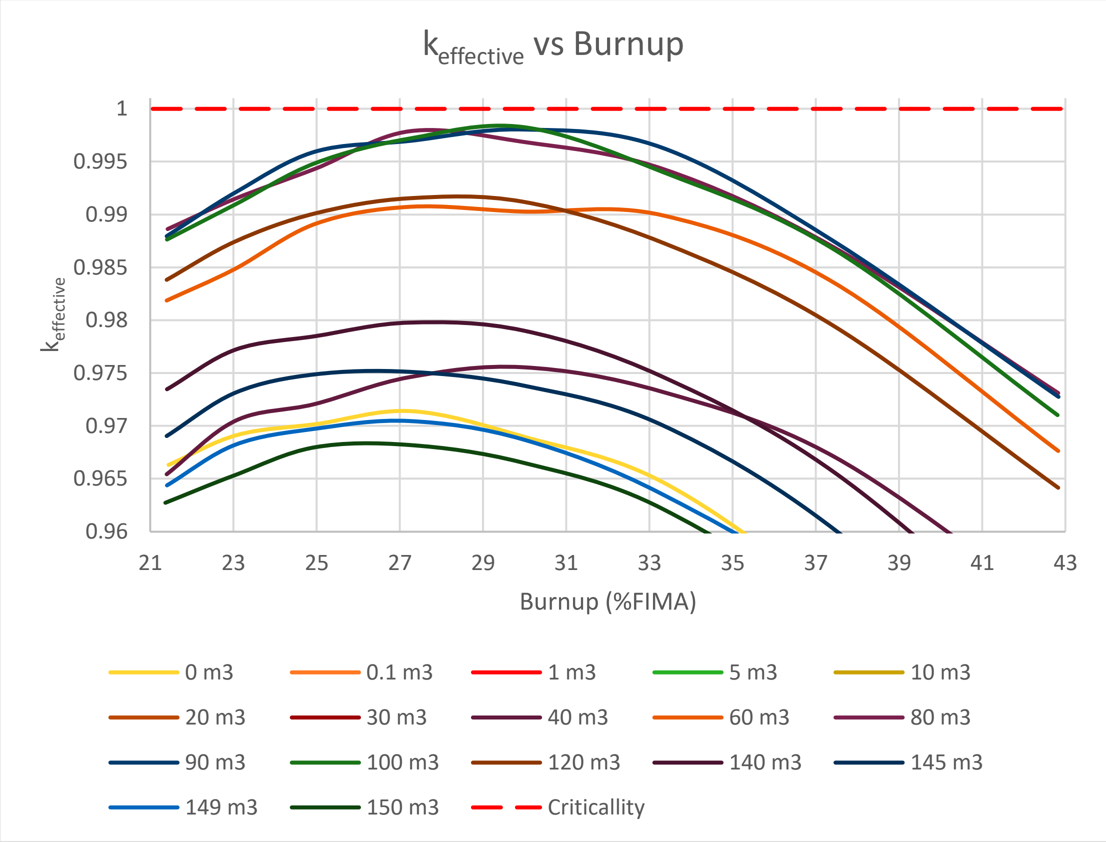
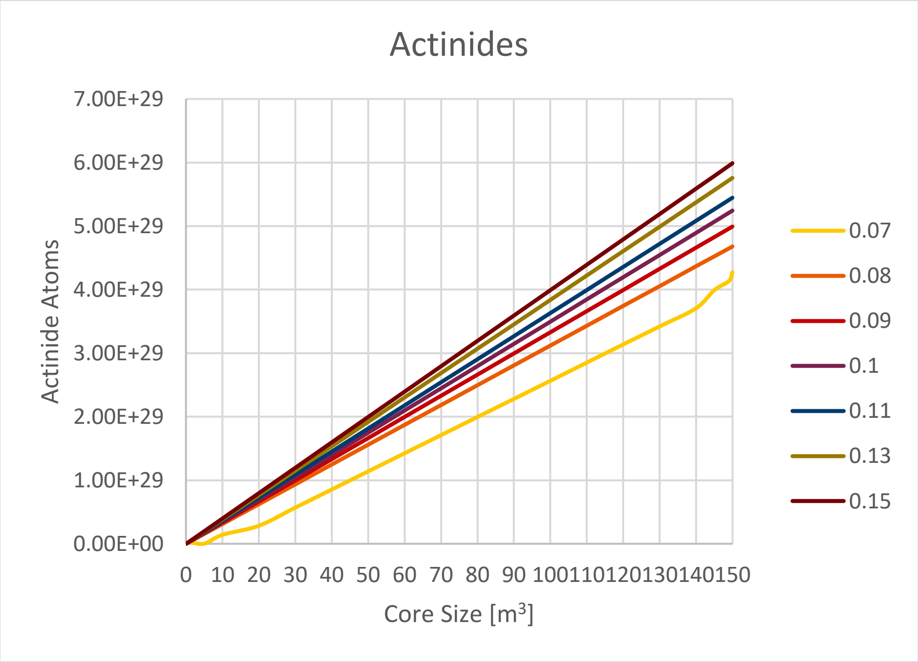
Research: Burnup

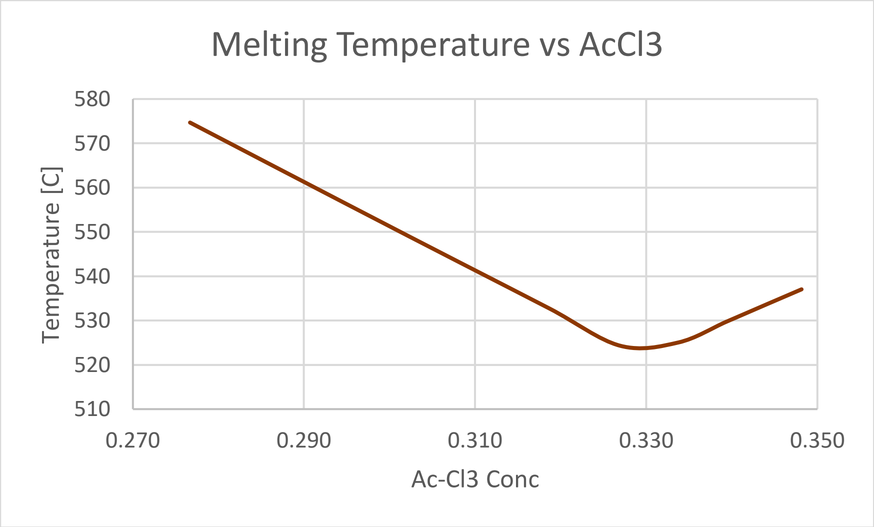
- New definition of burnup
- Transfer rate effects burnup
  - Fast flow = low residence time = low burnup
- Concentration fed into core effects burnup
  - %FIMA vs FP/(FP+Ac)
  - Ideal Burnup = 29-31 %FIMA

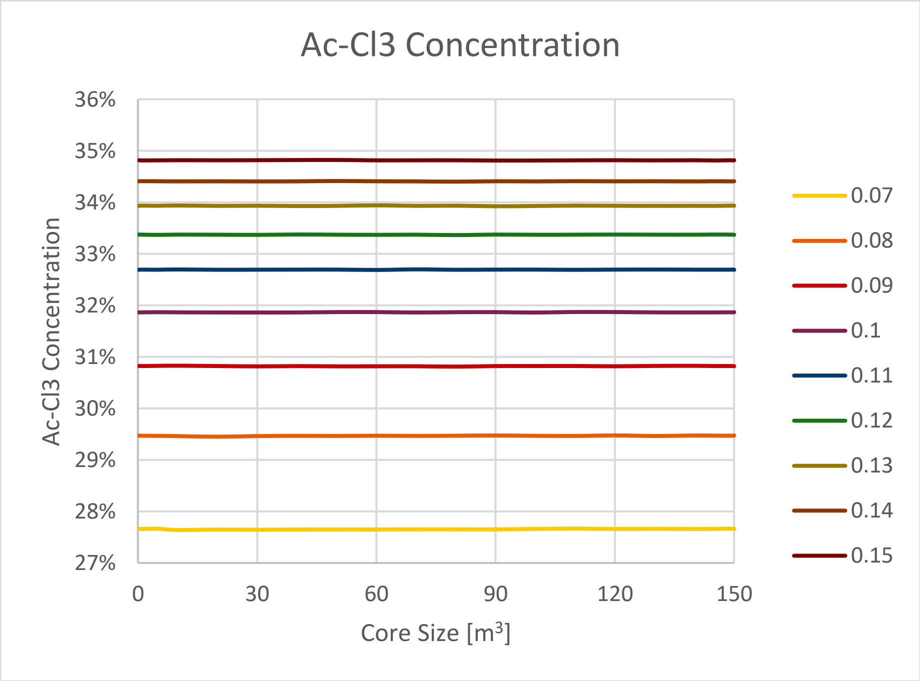




Research: Melting Temperature

- Burnup effects actinide concentration
  - Actinide concentration effects melting point
- Ideal
  - Minimize melting temperature
  - Maximize $k_{effective}$





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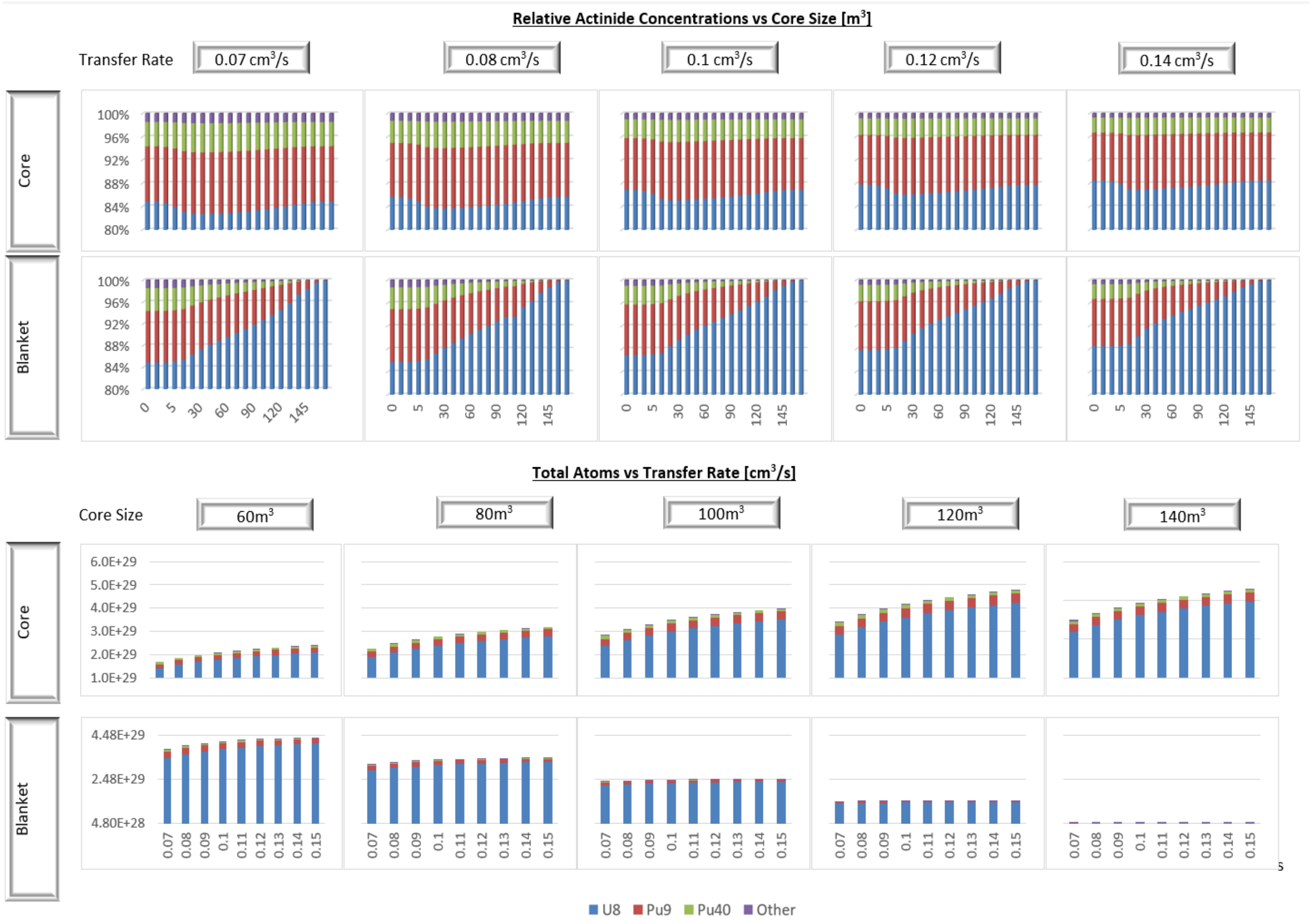
Research: Salt Evolution

- Small fluctuations of ratios in core at equilibrium
  - Highly effected by what is fed into core
- Area of interest – $100m^3$ & $0.1\ cm^3/s$
  - Not max Pu-239 in blanket
    - Continue breeding when in core
  - Low amount Pu-240 in blanket



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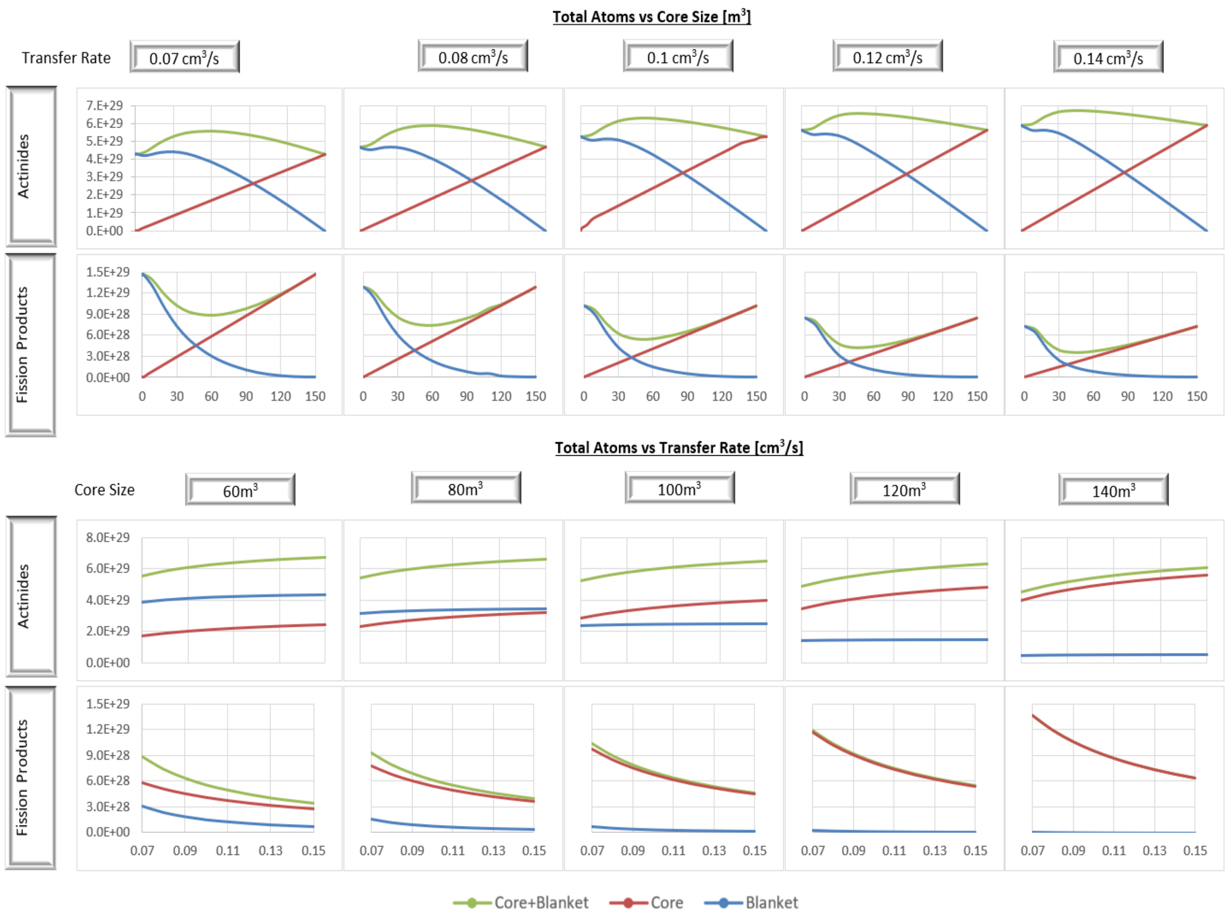
Research: Salt Evolution

- Ideal system
  - Size of blanket and transfer rate effect residence time
    - Want minimum amount FPs in blanket
  - Want nearly all FPs in core
    - Flow more fissile material canceled by mor FP poisons



Conclusion & Future Work

- Conclusion
  - Fast removal of non-soluble and volatile FPs critical
  - Blanket greatly improves reactivity of system
  - Exists ideal size and transfer rate for core/blanket system
    - Effect of Actinide concentration and melting temperature

- Future Work
  - Investigate simulations with constant actinide concentration
  - Investigate simulations controlling ratio of U, Pu to minimize T_{melt}
  - Continue research into MCFR reactor designs to minimize size of critical reactor
    - Different material types and thickness
    - Adding reflectors/moderators in various positions
    - Different fuel compositions

Thank you for your attention.

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Reference

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Introduction

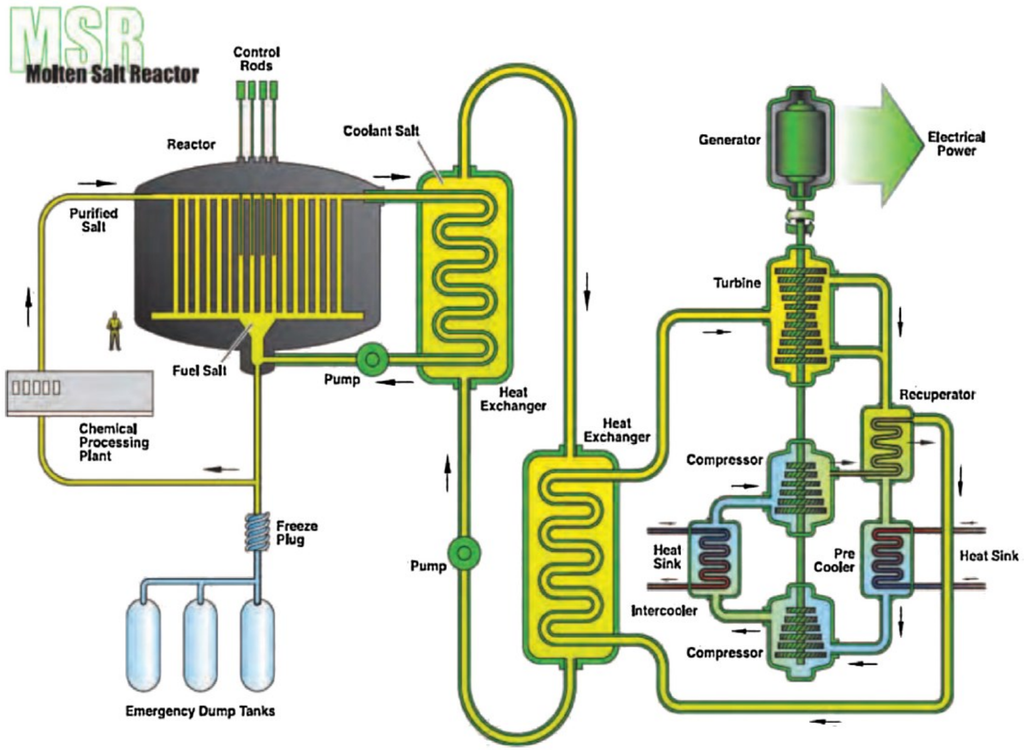
- Benefits
  - Coolant with large heat capacity
    - High operating temp. (700 C)
    - Passive Decay heat removal
  - Low vapor pressure
    - Atmospheric operation
  - In-situ fuel processing
  - No fuel fabrication
- Drawbacks
  - Lack of experimental data
  - Circulating fuel
    - Complex chemistry
  - Corrosion risks
  - On-site chemical plant
  - Breeder reactor
    - Proliferation risk

Salt Compositions, Densities and Melting Temperatures

Composition	[mol%]	Density [g cm^{-3}]		Melting
		Total	Act.	Temp.
$LiF-ThF_4$	72–28	4.59	2.84	565 °C
$LiF-UF_4$	73–27	4.67	2.89	500 °C
$NaCl-UCl_3$	68–32	3.32	1.66	520 °C
$NaCl-UCl_3$	60–40	3.64	1.97	590 °C
$NaCl-UCl_3-UCl_4$	15–15–70	3.64	2.22	500 °C
UCl_4-UCl_3	80–20	3.79	2.38	545 °C
UCl_4	100	3.56	2.20	590 °C
$NaCl-ThCl_4$	50-50	3.15	1.61	375 °C
$NaCl-ThCl_4-UCl_3$	50–25–25	3.16	1.67	500 °C
$ThCl_4$	100	3.82	2.33	770 °C

Safety

- Negative temperature coefficient
- High heat capacity
  - 50 vs. 4.2 J/g· °C for water
- High boiling temperature of salts
  - 1,465 °C - Large safety margin
- No solid fuel or cladding
- Freeze plug



Thermal Salt Reactor with Power Production Systems