Neutronic Feasibility of a Breed & Burn Molten Salt Reactor

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Serpent User Group Meeting 2016 - Milan

26-29 September, 2016

University of Cambridge
Department of Engineering

Objectives

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1. Demonstrate possibility of breed & burn operation in a system with separate molten salt fuel and coolant
2. Compare performance with benchmark system: TWR
3. Thermal-hydraulic analysis in OpenFOAM

System Description

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- “BBMSR”: Breed & burn molten salt reactor
- Separate fuel & coolant salts (based on Moltex SSR)
- Fast breeding of fissile Pu from natural U
  - › Partially burned regions contribute neutrons to fresh fuel

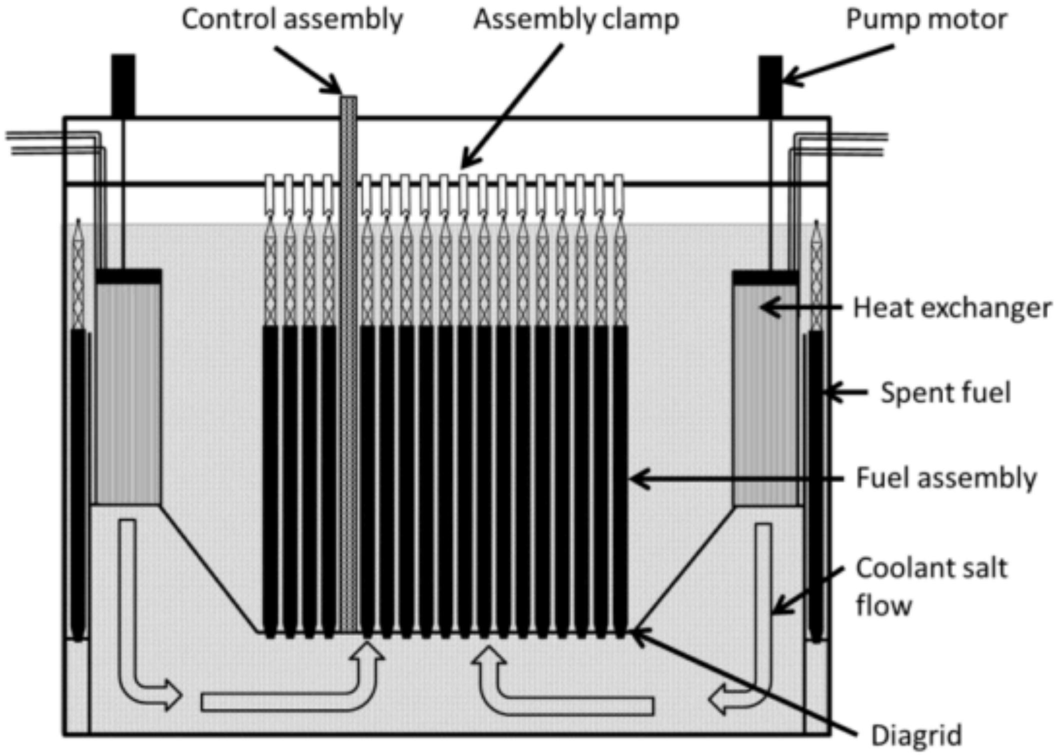

Image: I. Scott, T. Abram, and O. Negri, “Stable Salt Reactor Design Concept,” in Proceedings of the Thorium Energy Conference, (Mumbai, India), 2015.

Overview of Analysis

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Homogeneous 2-D unit cell in SERPENT

- Benchmark vs. initial BBMSR configuration
- Increase HM loading
- Absorption balance→ low-capture version
- Reduce scattering

Benchmark: Traveling Wave Reactor

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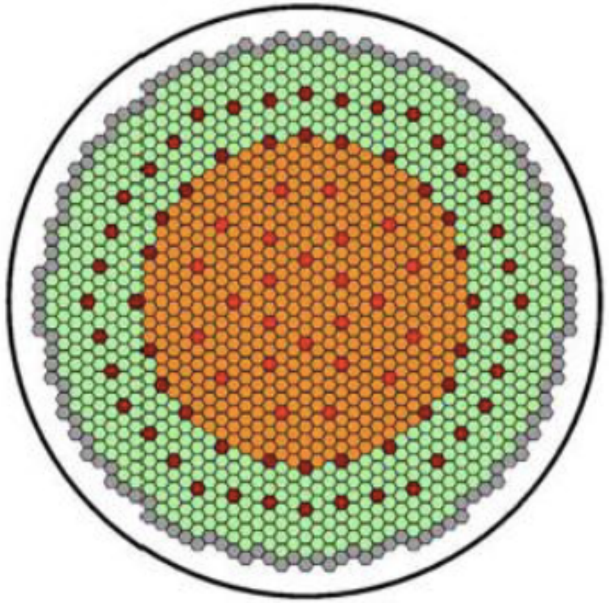
- 35 vol% U2Zr metal fuel
- 50 vol% sodium coolant
- 15 vol% T91 cladding



Pin cell burnup in Serpent:

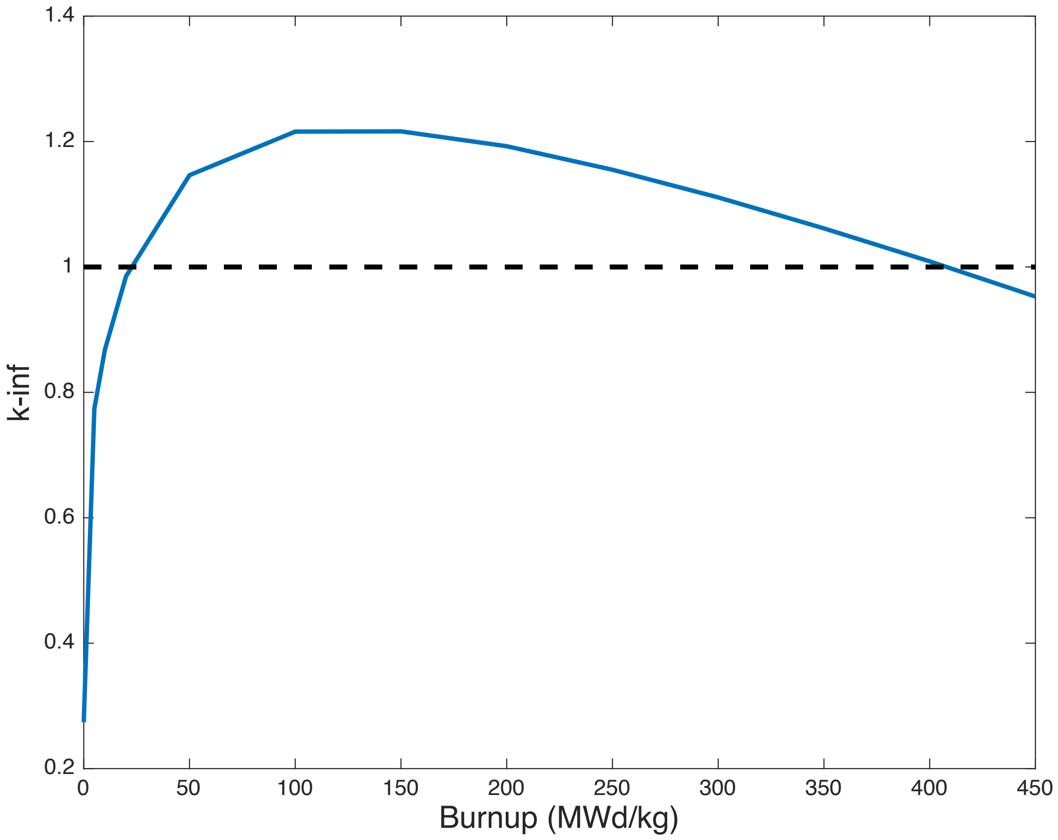
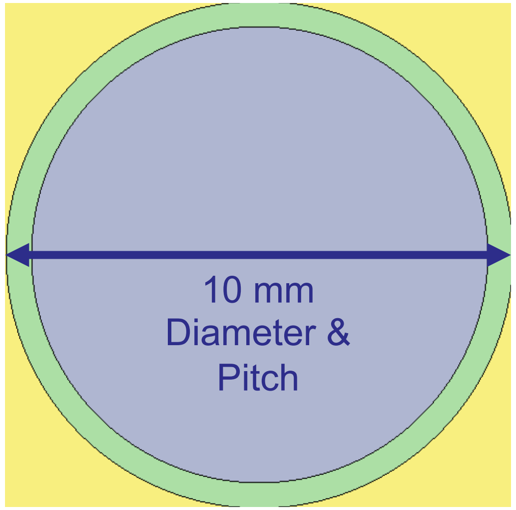


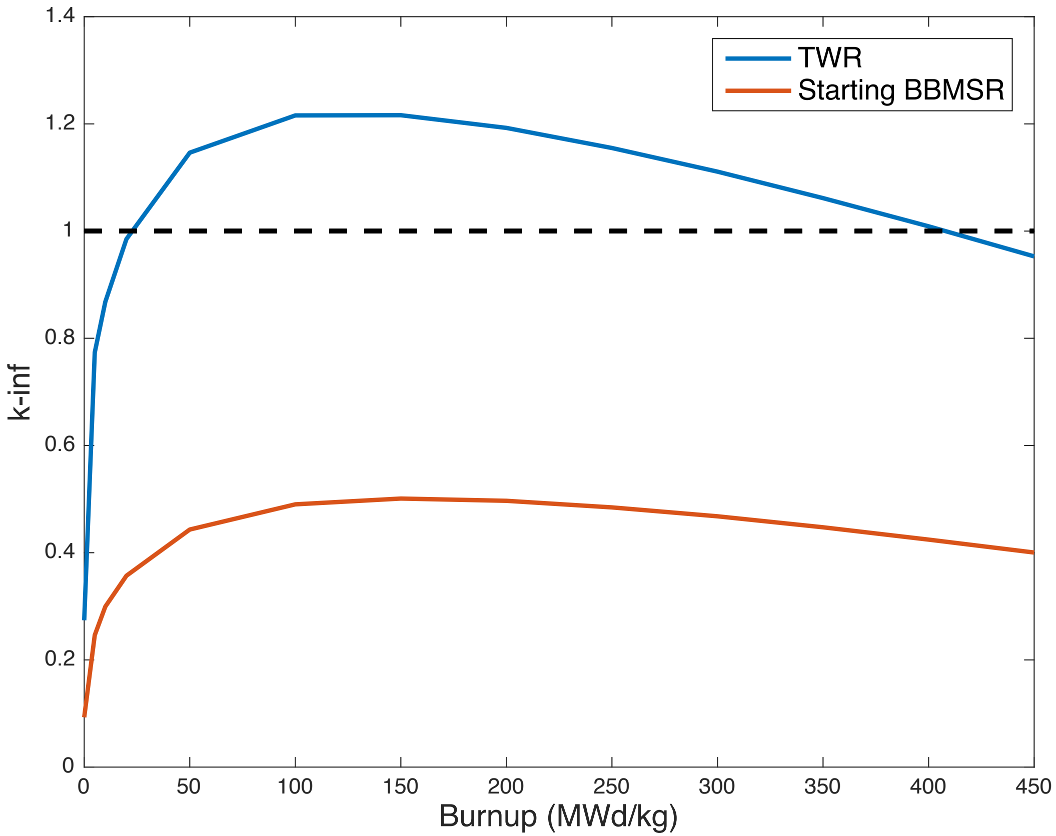
Image: T. Ellis, et. al, “Traveling-Wave Reactors: A Truly Sustainable and Full-Scale Resource for Global Energy Needs,” International Congress on Advances in Nuclear Power Plants, 2010.

Starting BBMSR configuration

- 64 vol% fuel:
  - 40 mole % UCl_3 (natural U)
  - 60 mole % NaCl
- 21 vol% KF-ZrF_4-NaF coolant
- 15 vol% molybdenum cladding



Pin cell burnup in Serpent:



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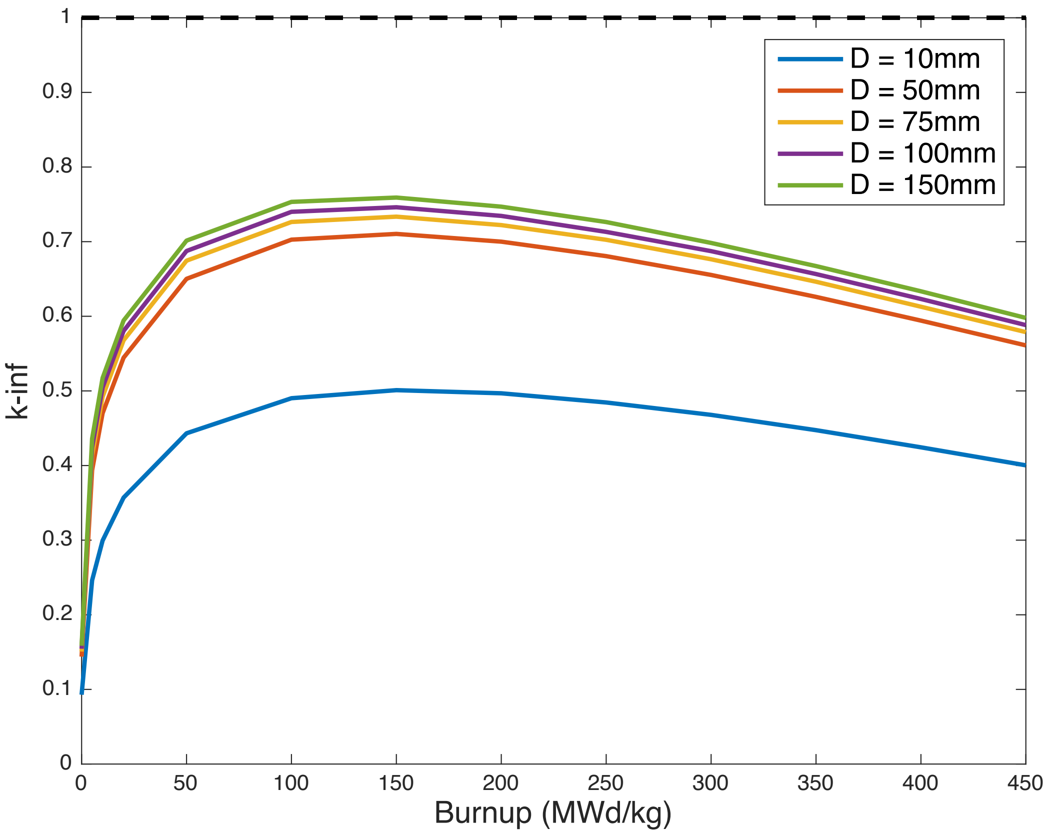
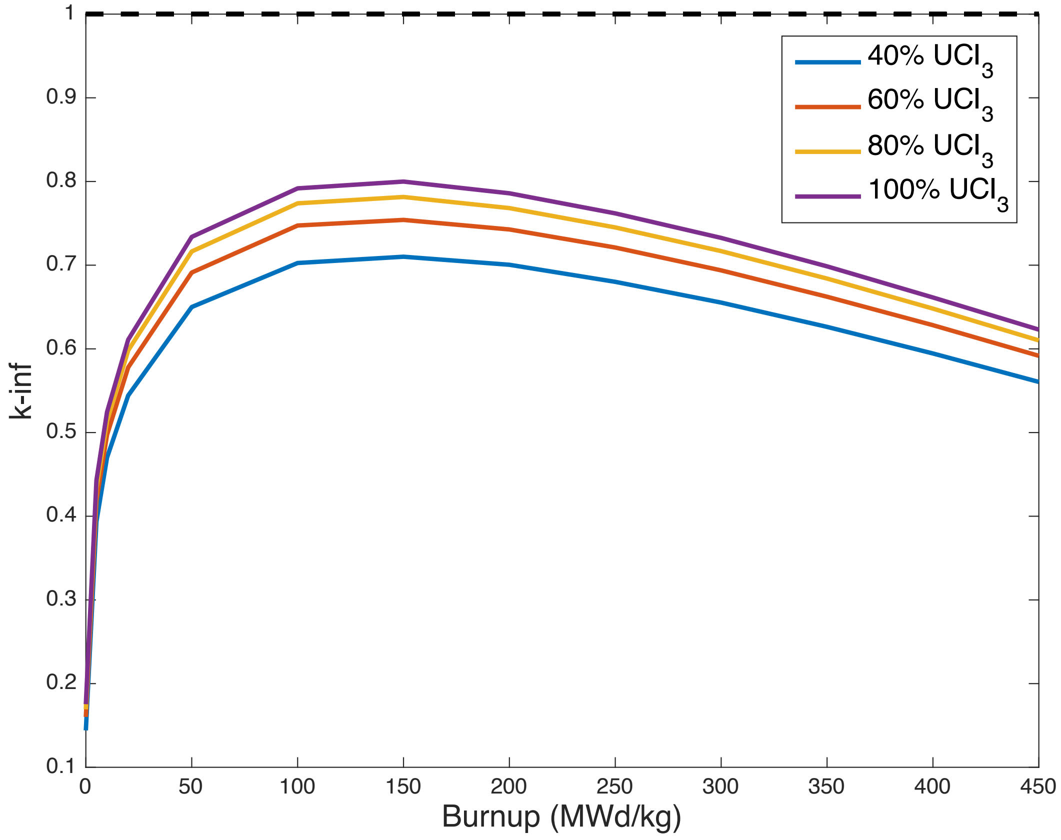
Increase relative HM loading

Increase tube diameter



Increase UCl_3 concentration



Neutron Absorption Balance

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	TWR	"Natural" BBMSR	Enriched BBMSR
Fission: Σ_f	2.77E-03	1.18E-03	1.14E-03
Pu239	78.70%	77.52%	77.74%
U238	15.19%	10.42%	10.00%
Pu240	3.51%	5.23%	5.35%
Pu241	1.79%	5.86%	5.99%
Capture: Σ_c	3.91E-03	3.14E-03	2.56E-03
U238	63.52%	39.18%	46.62%
Pu239	9.58%	11.12%	12.64%
Pu240	2.50%	3.96%	4.63%
Nat-Mo	-	12.73%	(^{94}Mo) 0.17%
Nat-Zr	0.41%	2.58%	(^{90}Zr) 0.00%
Cl35	-	2.15%	(^{37}Cl) 0.54%

- Natural materials:
  - 40% capture in ^{238}U
  - 17.5% capture in natural Mo, Zr, Cl
  - Relatively low capture in fission products
- Enriched BBMSR:
  - 47% capture in ^{238}U
  - 0.7% capture in ^{94}Mo, ^{90}Zr, ^{37}Cl

“Low-capture” BBMSR

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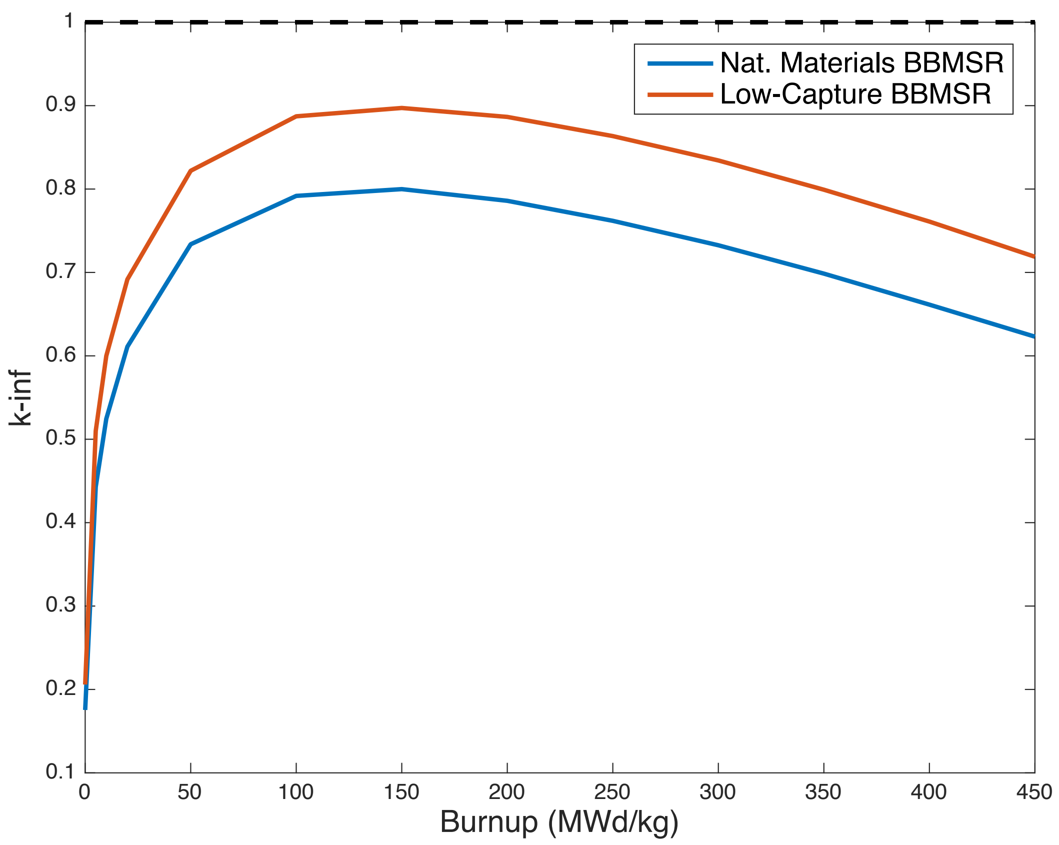
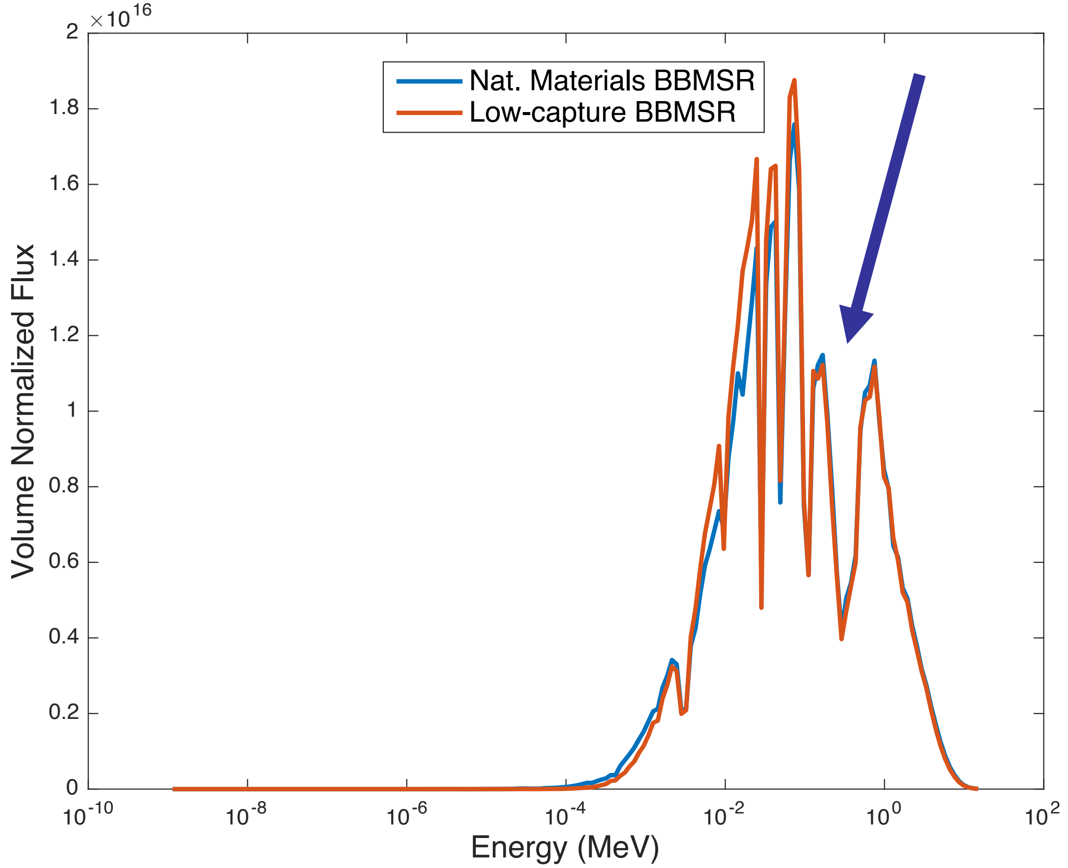
k still < 1…

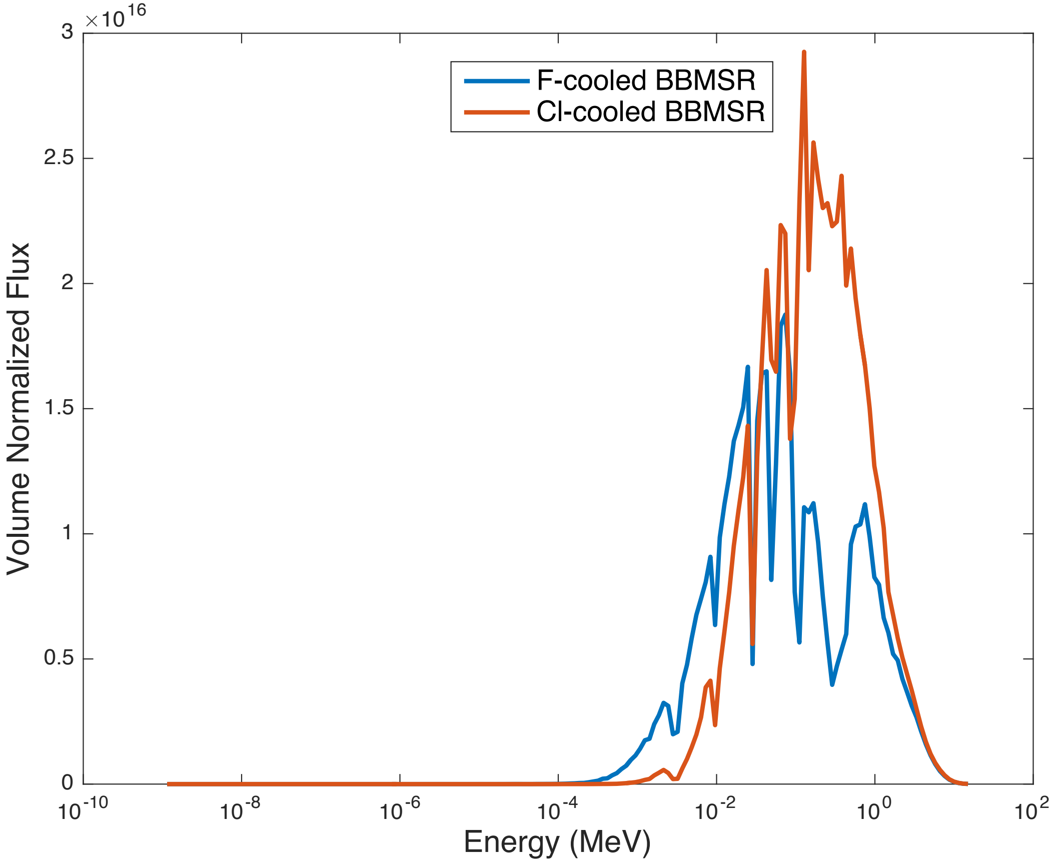


Many holes remain in spectrum

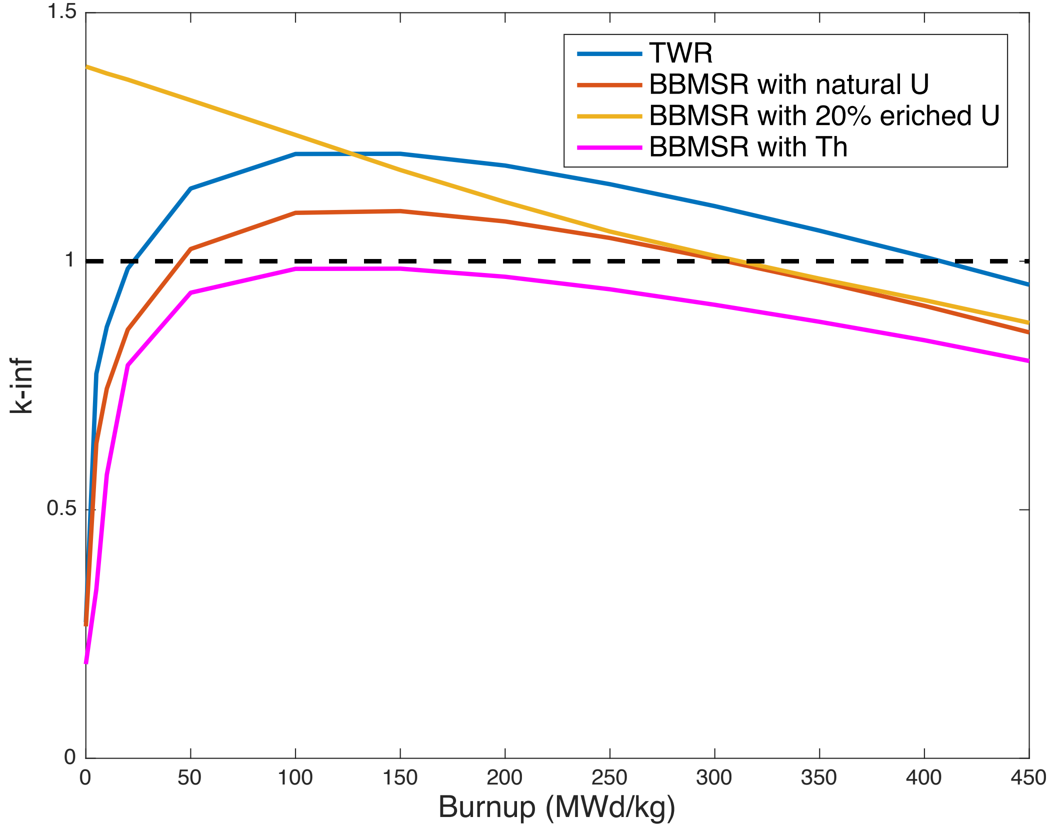


Chloride coolant: $MgCl_2$-NaCl-KCl

Cl coolant hardens spectrum



BBMSR *k* > 1! Potential for LEU version



Neutronics Summary

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- Neutronically feasible BBMSR identified using Serpent burnup calculations and detectors
  - 50 mm tube
  - 100% UCl_3
  - Enriched Mo & Cl
  - Chloride coolant

May not need all! TBD

- Ongoing: Trade-off study with low-enriched U in fuel salt → may allow operation with natural Cl, smaller diameter, etc.

Thermal-hydraulic modelling

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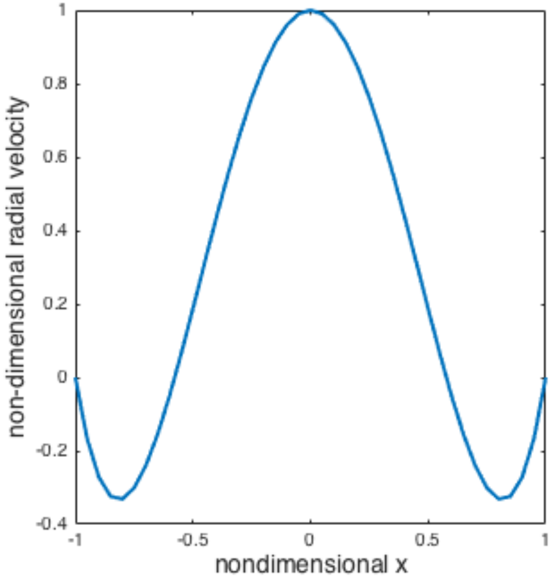
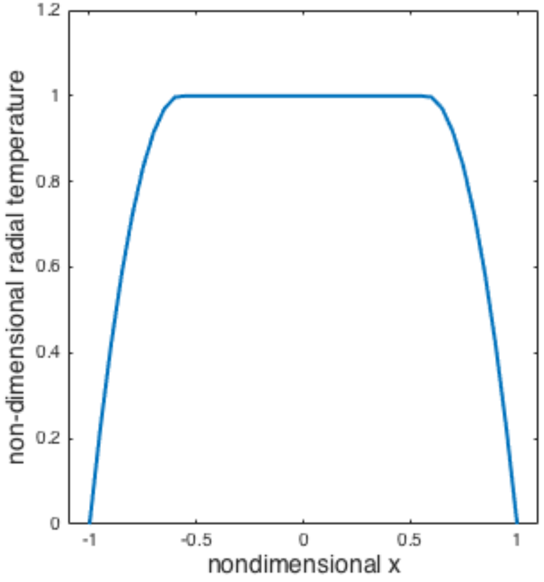
- Natural convection of heat-generating fluid – a tricky problem!





- Momentum (Boussinesq approximation)

$$u\frac{\partial \upsilon}{\partial x}+\upsilon\frac{\partial \upsilon}{\partial y}=\nu\frac{\partial^2 \upsilon}{\partial x^2}+g\beta(T-T_0)$$

- Energy

$$u\frac{\partial T}{\partial x}+\upsilon\frac{\partial T}{\partial y}=\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)+q'''$$

TH result in OpenFOAM

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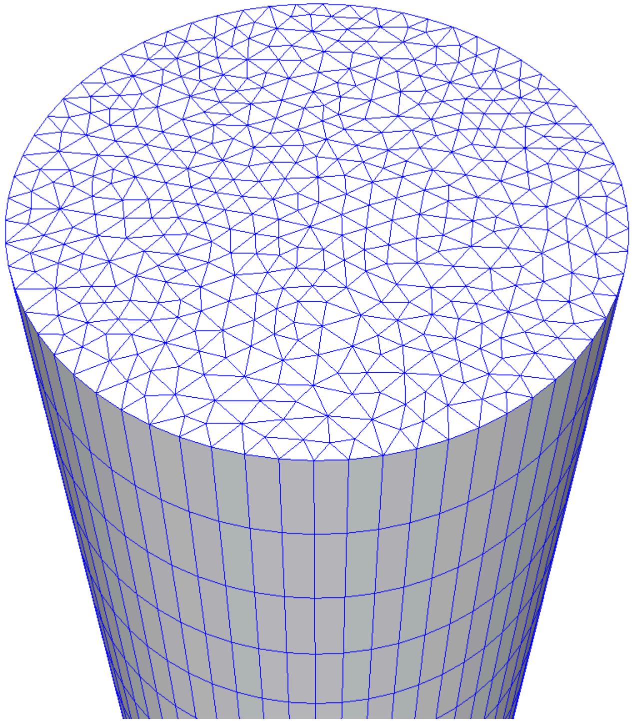
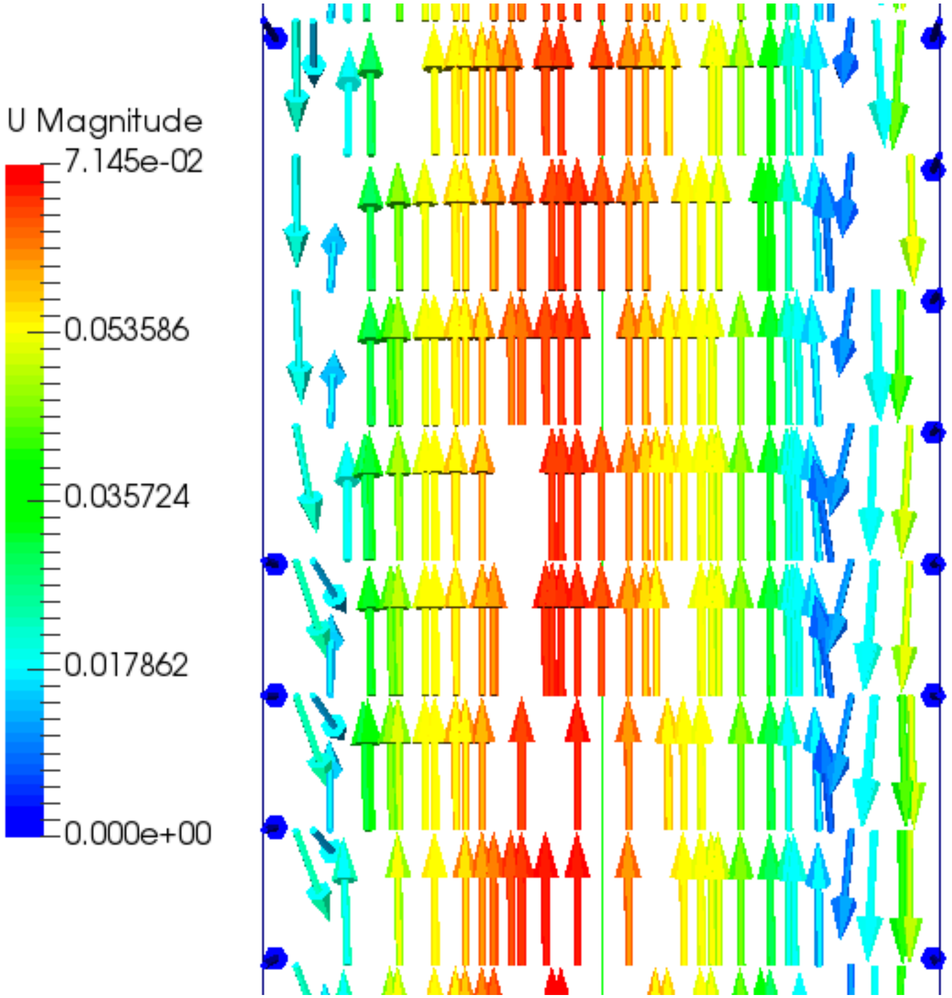
* To be coupled to Serpent model – diameter, power density?





Thanks!

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- To you, for listening!
- To the Cambridge Trust and Winston Churchill Foundation of the United States, for funding

- Questions?

Backup

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NaCl-UCl_3 Melting point

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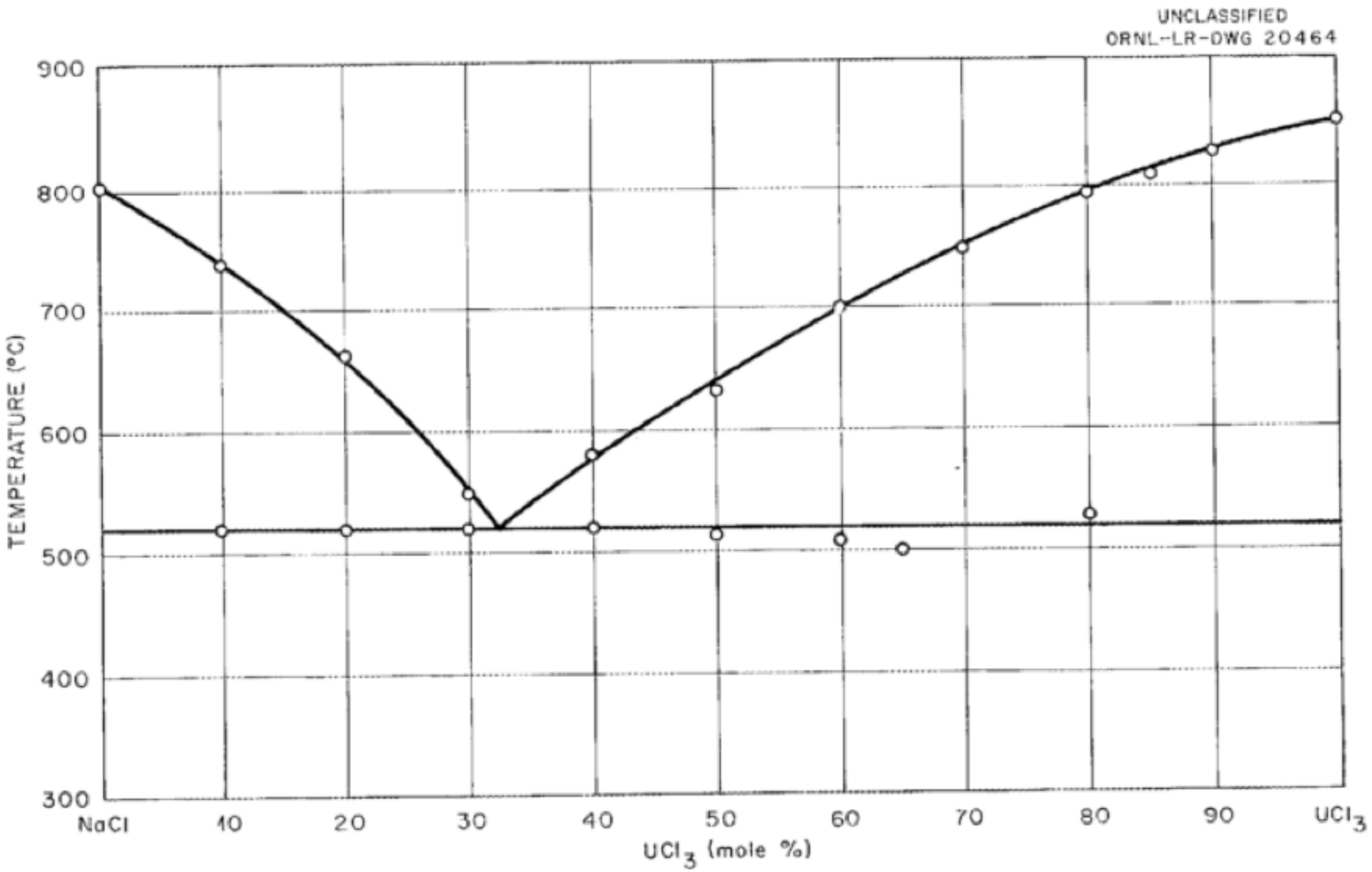

Image: R. E. Thoma, “Phase diagrams of nuclear reactor materials,” tech. rep., Oak Ridge National Laboratory, 1959.

Homogeneous vs Heterogeneous

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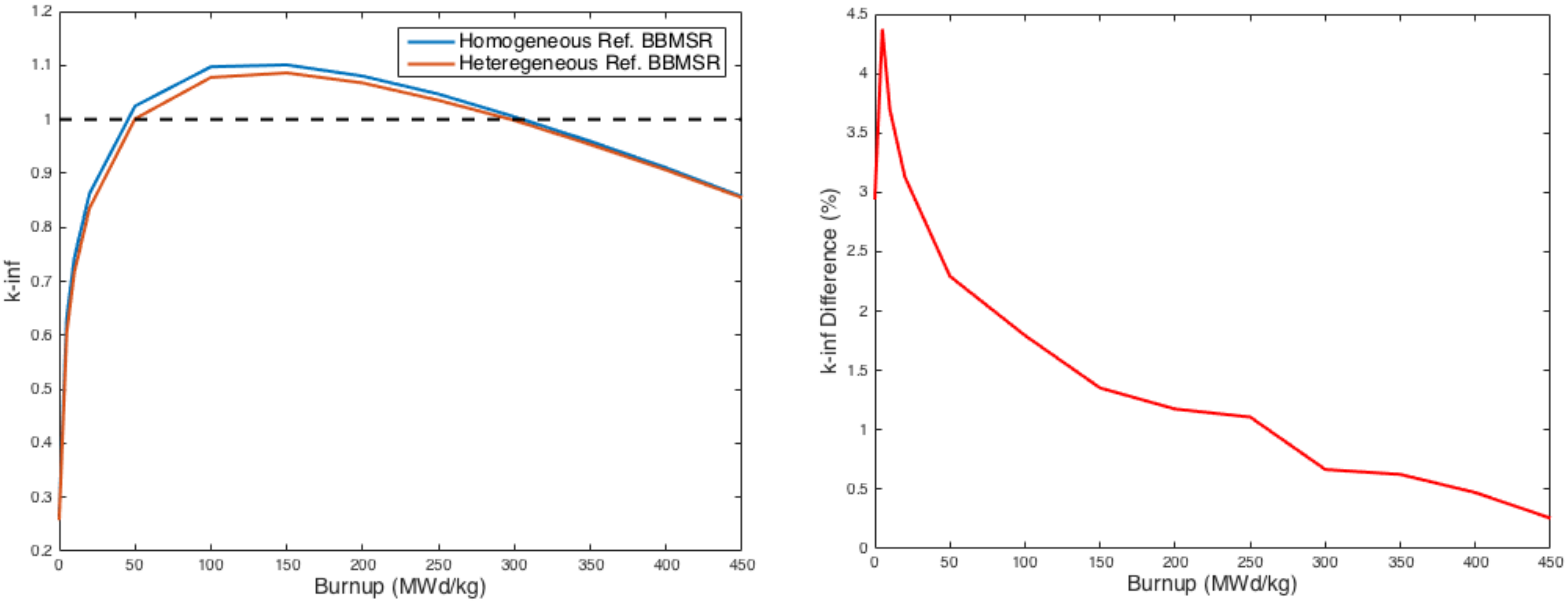

BBMSR versus BBSFR

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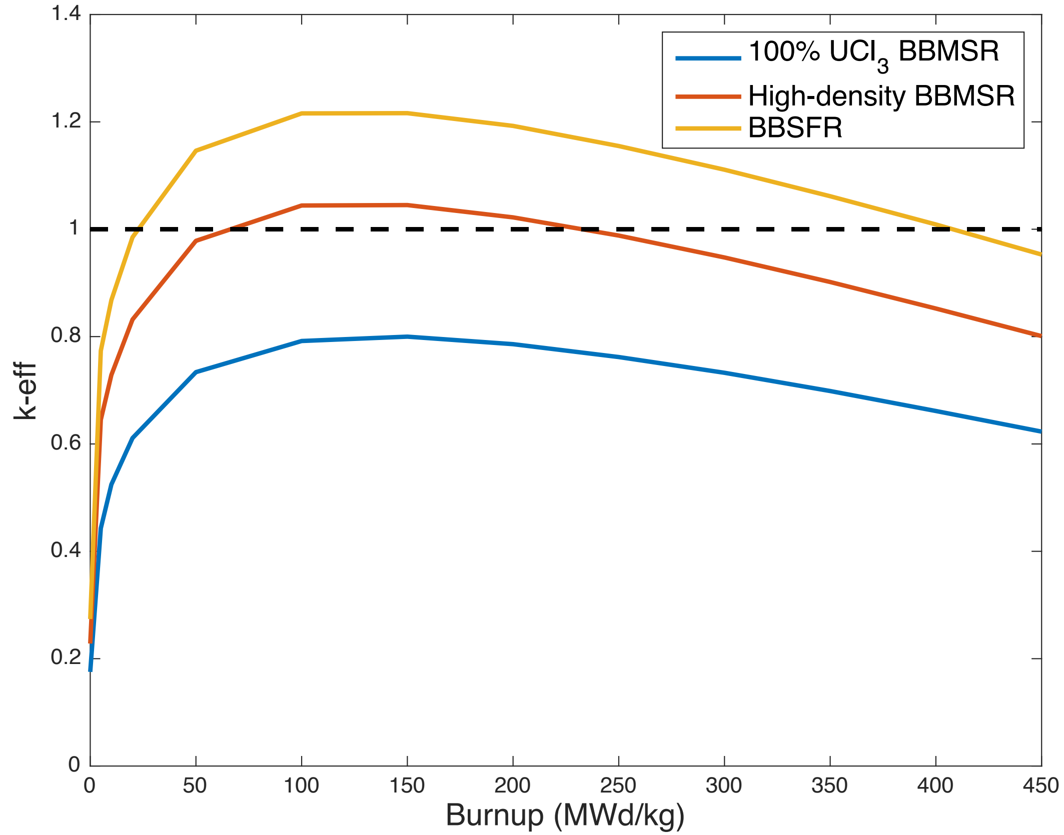
- TWR - example
  - 35 vol% U2Zr fuel
  - 15 vol% T91 cladding
  - 50 vol% Na coolant

- "High density" BBMSR
  - ^{238}U and ^{235}U nuclide densities from BBSFR
  - Conclusion: fuel density is not the only weakness!



Fuel: 100% $ThCl_4$

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