

# The U-Battery, a Conceptual Design of a Natural Circulation Cooled Nuclear Battery for Process Heat Applications

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# Introduction

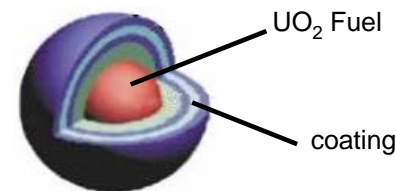
The U-Battery is a very small reactor (20 MWt) for process heat applications with the following features:

- Inherently safe
- Self regulating (minimal control and maintenance)
- Natural Circulation Cooling
- High reliability and availability
- Burnup of at least 10% FIMA

# Design boundary conditions

## U-Battery

- To comply with non-proliferation treaties
  - Use of max. 20% enriched TRISO coated particle fuel
- To make road transport possible
  - A combined core and reflector diameter of less than 3.5 m
- To reduce neutron leakage
  - $H_{\text{core}} = 0.924 D_{\text{core}}$  (minimal buckling)
  - Prismatic core geometry
- To improve economics
  - Fuel cycle length of 5-10 yrs
  - Burnup of at least 10% FIMA



# Parameter Study

Other U–Battery Parameters:

- Core Volume & Reflector Thickness
- Fuel enrichment (<20%)
- Coolant (liquid metal, liquid fluoride salt)
- Volume fractions

To assess the feasibility of the U-Battery, a parameter study was performed on:

1. Neutronics (burnup calculations and reactivity coefficients)
2. Natural circulation and heat transfer

# Neutronic Feasibility

Burnup calculations were performed (using SCALE codes) for different cases during a desired fuel cycle length followed by a  $k_{\text{eff}}$  calculation at the end of the cycle (EOC).

If  $k_{\text{eff}} < 1$  the design is not feasible.

Calculation methods:

	Basic calc.	Heterogeneous calc.
Nr of fuel zones	1	9 (cylindrical symmetric)
Neutron flux & Power profile	Normalized uniform	zone and time dependent
Nr of time steps in burnup calc.	1	11

# Input parameters and Coolants

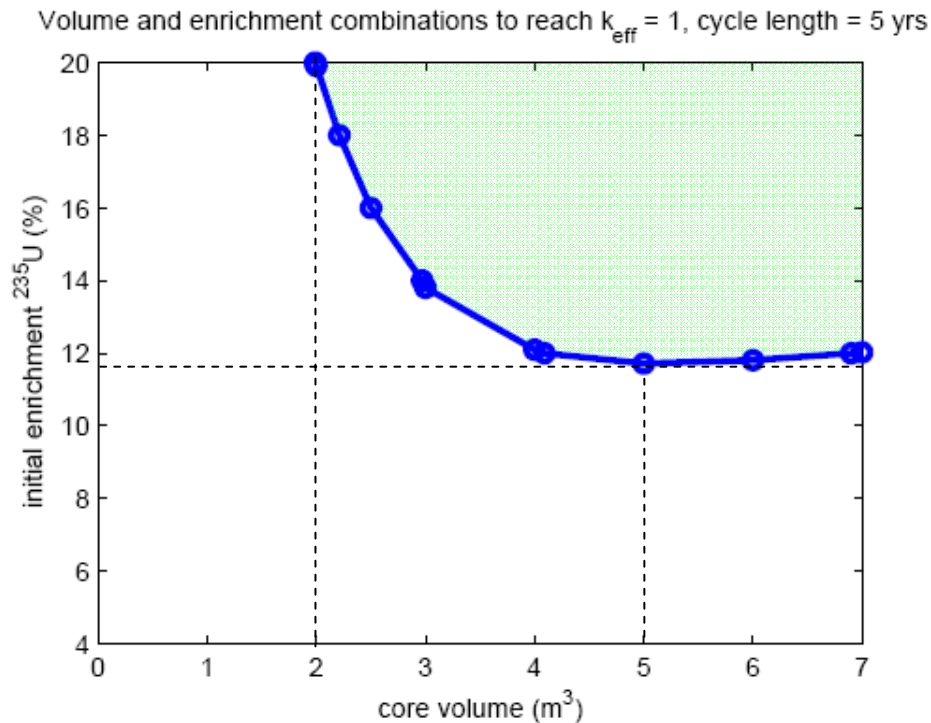
Input parameters for burn up and eigenvalue calculations

parameter	value
Core power	20 MWth
Fuel cycle length	5 & 10 yrs
FIMA	10, 12.5, 15 & 17.5 %
Fuel enrichment	12 – 20 %
Core volume	1-14 m <sup>3</sup>
Reflector thickness	0 – 1.6 m
Uniform core temperature	1073 K
Coolant volume fractions	10 % (salts), 3.5 % (tin)

Liquid fluoride salts	Liquid metal
Na-Be, Na-Zr, <sup>7</sup> Li-Na-Zr, <sup>7</sup> Li-Na-K, <sup>7</sup> Li-Be	tin

# Results burnup and $k_{\text{eff}}$ calculations

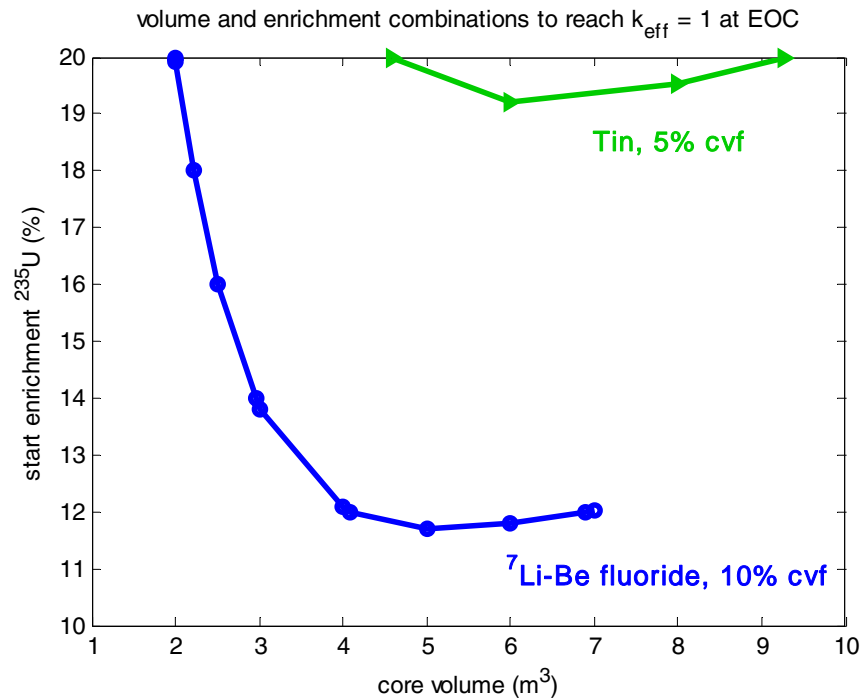
Core volume vs enrichment,  ${}^7\text{Li}$ -Be fluoride 5 yrs, refl = 1.2 m, cvf = 0.1



- On blue line  $k_{\text{eff}}$  at EOC = 1
- Larger core volume allows lower initial enrichment
- Area on upper right side provides  $k_{\text{eff}} > 1$  at EOC
- Upper right side is feasible, lower left side not
- Minimal volume = 2 m<sup>3</sup> (20 % enr)  
Minimal enrichment = 11.7 % (5 m<sup>3</sup>)
- For volumes larger than 5 m<sup>3</sup> enrichment needs to increase
  - over moderation (C/U relation)
  - reduced effect of reflector

# Results burnup and $k_{\text{eff}}$ calculations

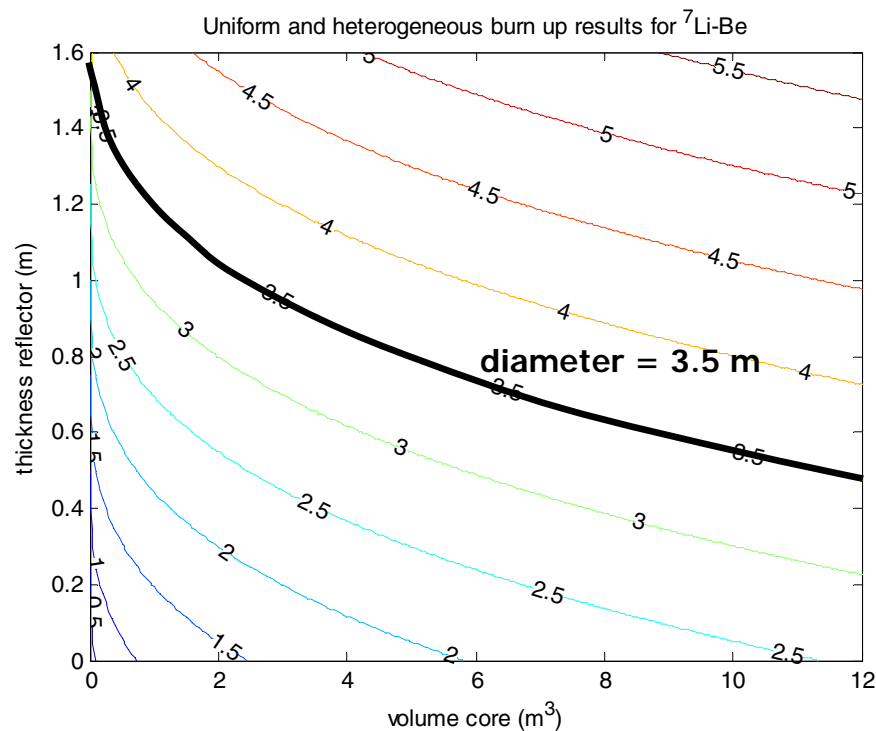
Core volume vs. fuel enrichment,  ${}^7\text{Li}$ -Be fluoride and tin



- Tin coolant volume fraction 5% because with larger coolant fractions no feasible solutions were found
- Minimum fuel enrichment is much larger for tin than for  ${}^7\text{Li}$ -Be fluoride due to absorption

# Core volume and reflector thickness

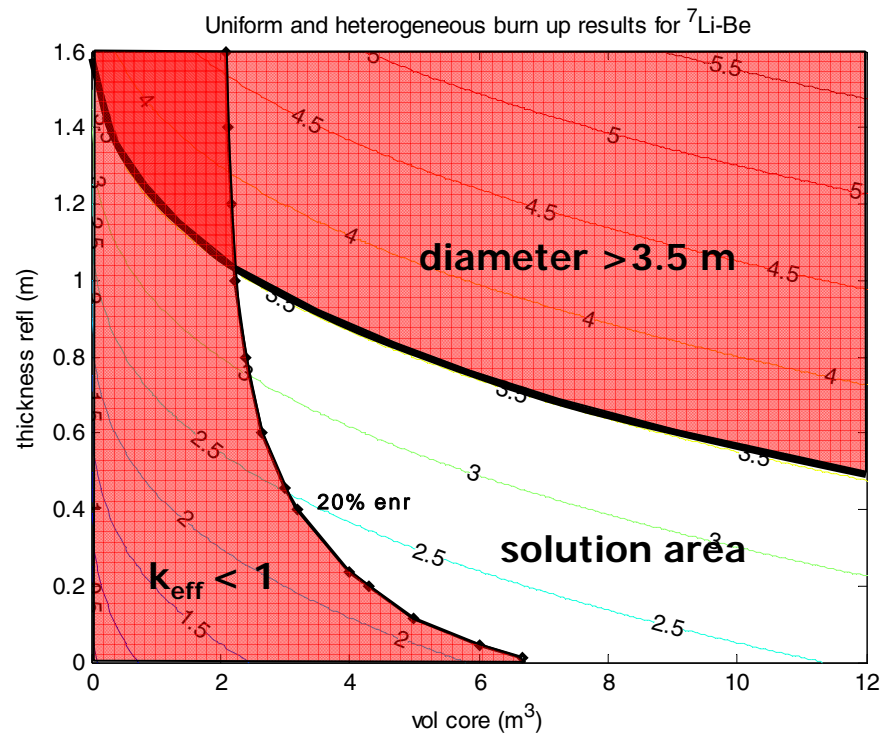
Contour plot of diameter core and reflector combined



- When using slimmer reflectors, core volumes can be larger while the total diameter  $< 3.5$  m
- Core and reflector combination should be below 3.5 m

# Results ${}^7\text{Li}\text{-Be}$ fluoride, 20% enr, 5yrs

Core volume and reflector thickness combinations to achieve  $k_{\text{eff}} = 1$  at EOC



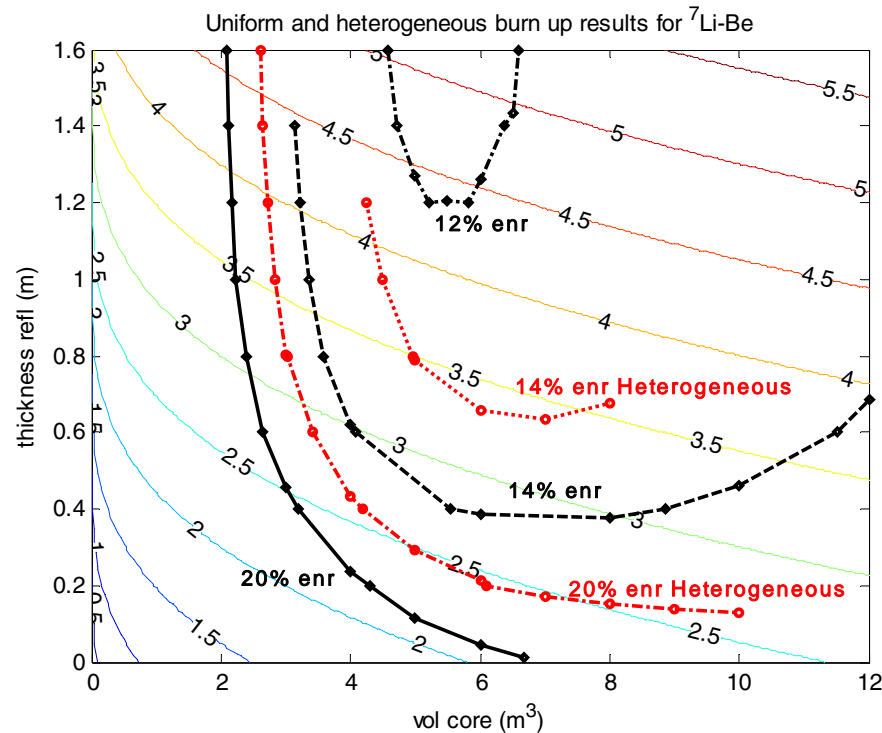
- When using larger core volumes, smaller reflectors are needed to give same  $k_{\text{eff}}$  with smaller total diameter

The solution must be found:

- Below the 3.5 diameter constraint
- Above the  $k_{\text{eff}} = 1$  at EOC curve

# Results $^7\text{Li-Be}$ fluoride , 5yrs

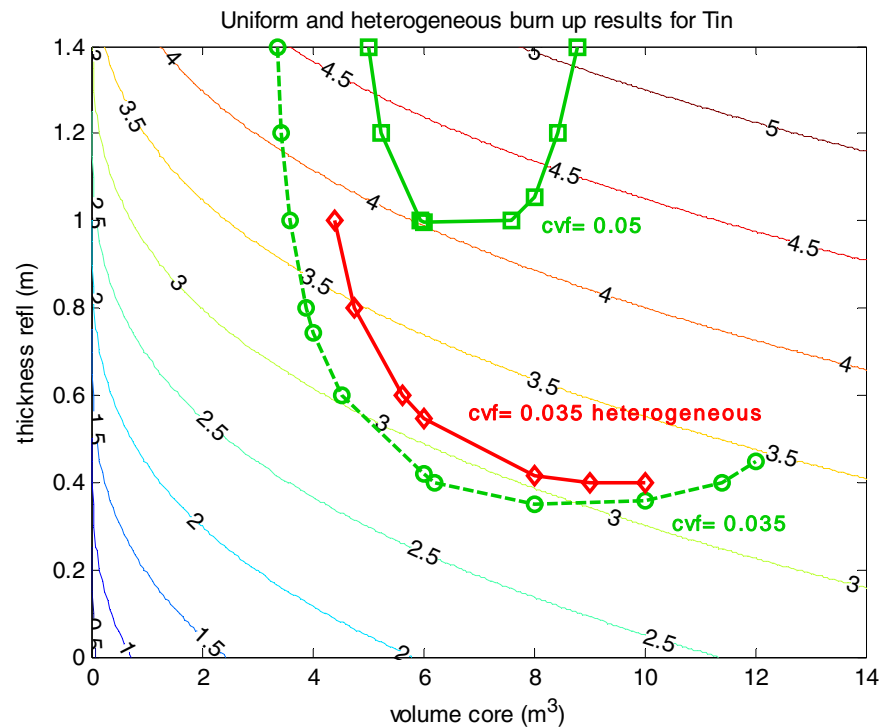
Core volume and reflector thickness combinations to achieve  $k_{\text{eff}} = 1$  at EOC



- Results of initial enrichments 20, 14 and 12 % are shown
- Effects C/U relation visible
- Calculations performed with basis method (black) and with heterogeneous method (red)
- Results heterogeneous method are less optimistic, because no effort was made to flatten the flux. The true curves will lay in between both methods
- The minimum applicable initial enrichment when using  $^7\text{Li-Be}$  as coolant is 14 %  $^{235}\text{U}$

# Results tin, 5yrs

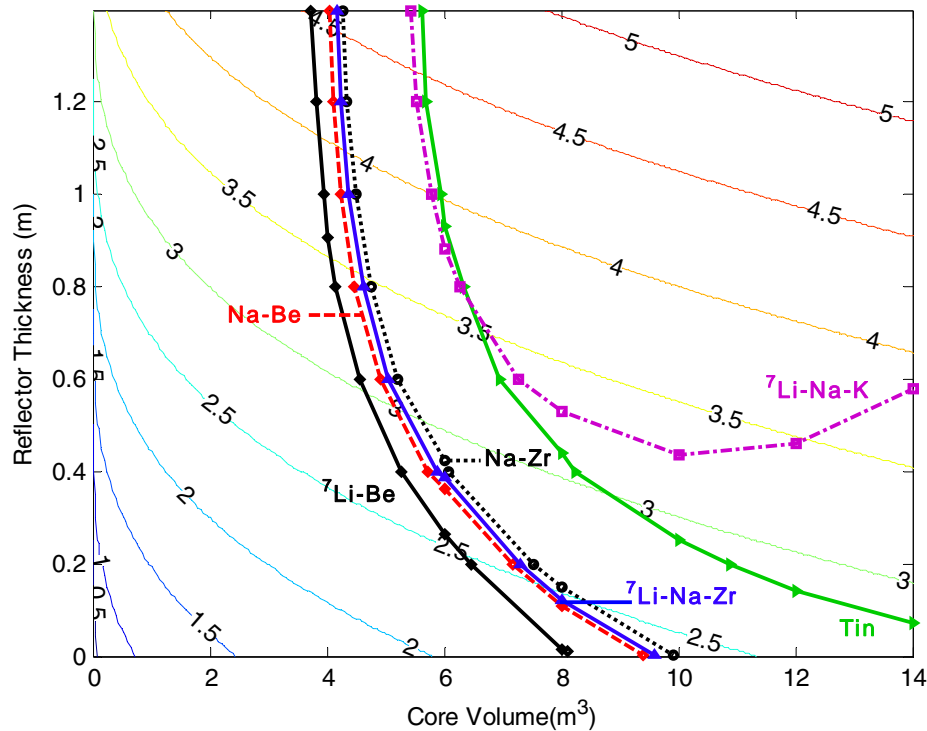
Core volume and reflector thickness combinations to achieve  $k_{\text{eff}} = 1$  at EOC



- No feasible reflector and core volume combinations can be found with a tin coolant volume fraction of 5%
- Solutions can be found for a 3.5% coolant volume fraction
- The heterogeneous calculation (in red) confirms 3.5% result

# Results all salts and tin, 10 years

Core volume and reflector thickness combinations to achieve  $k_{\text{eff}} = 1$  at EOC



- For each coolant except  $^7\text{Li-Na-K}$  a wide range of reflector and core volume combinations can be found
- $^7\text{Li-Be}$  provides largest range of solutions
- Na-Zr and Tin are also promising candidates due to absence of toxic Be and isotopic separation of  $^7\text{Li}$

# Temperature and void coefficients

Results of uniform temperature and complete voiding reactivity coefficients calculated for  $^7\text{Li}$ -Be fluoride, Na-Zr fluoride and tin.

Coolant	Core volume (m <sup>3</sup> )	Coolant volume fraction	$k_{\text{eff}}$	uniform temperature coefficient (10 <sup>-5</sup> K <sup>-1</sup> )			Complete voiding reactivity (\$)
				973-1073 K	1073-1173 K	Avg.	
$^7\text{Li}$ -Be fluoride	4	0.1	1.38	-7.07	-8.66	-7.86	-1.66
Na-Zr Fluoride	6	0.1	1.39	-5.64	-4.66	-5.15	3.55
tin	6	0.035	1.29	-3.84	-4.46	-4.16	12.0

- All coolants will have negative uniform temperature coefficient
- Only  $^7\text{Li}$ -Be has a negative complete voiding reactivity coefficient
- If reactivity increases due to complete voiding is compensated by Doppler effect ( $\sim -7$  pcm/K) temperature must increase:
  - 400 K for Na-Zr case
  - 1300 K for tin case

# Conclusions Neutronics Feasibility

- $^7\text{Li}$ -Be fluoride provides most design freedom for U-Battery.
- Na-Zr and tin are good alternatives due to lack of toxic Be and isotopical separation of  $^7\text{Li}$ .
- All coolants have negative uniform temperature coefficient, only  $^7\text{Li}$ -Be fluoride also has negative complete voiding coefficient.
- Tin has large voiding reactivity, measures should be taken to prevent complete voiding at all times.

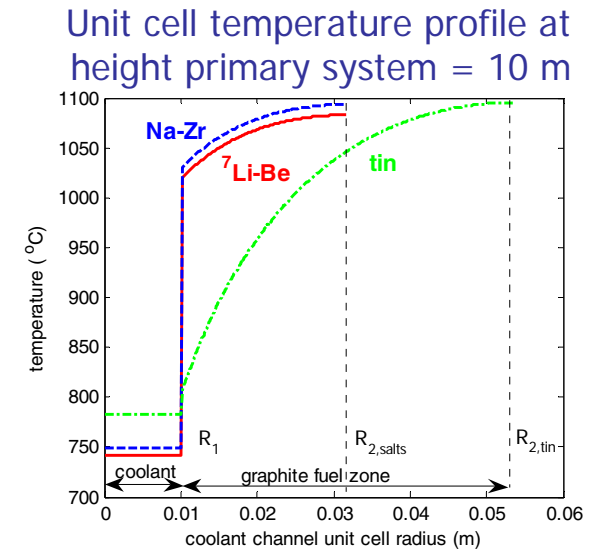
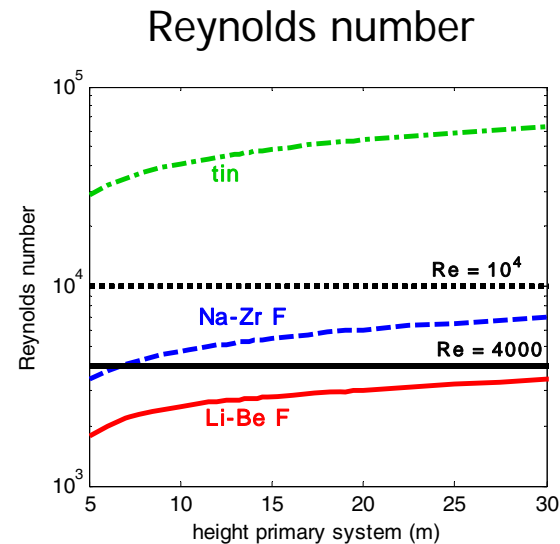
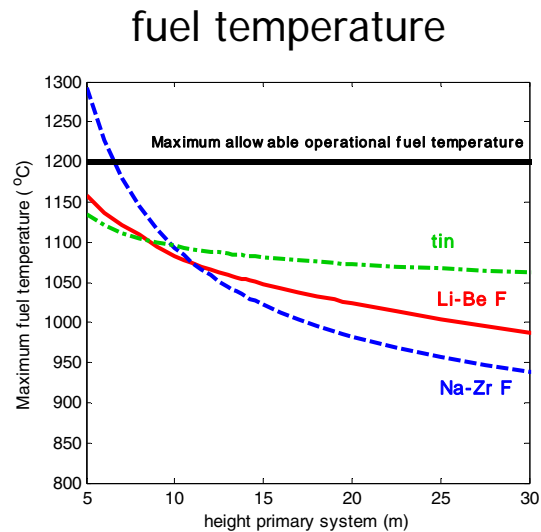
# Calculation Parameters

Fuel Temperatures and Reynolds numbers were calculated as a function of the height of the Primary System (riser + core)

## Input parameters

Parameter	Value
Core Power (MWt)	20
Core volume (m <sup>3</sup> )	6
Height heat exchanger (m)	Core height
Diameter coolant channel (m)	0.02
Diameter riser and down comer (m)	0.2
Coolant inlet temp (K)	973
System pressure (bar)	1

# Maximum fuel temperatures & Reynolds as a function of primary system height



- All coolants except provide fuel temperatures lower than 1200 °C for primary system heights larger than 7.5
- Only tin has  $Re > 10,000$  while  ${}^7\text{Li-Be}$  has  $Re < 4000$
- Large  $\Delta T$  between coolant and graphite coolant wall for liquid salts
- Large temperature gradient in graphite for tin; increases thermal stresses in graphite

# Modifying parameters improves thermal hydraulic performance

Modified parameter	old	new	old	new
	<sup>7</sup> Li-Be fluoride	<sup>7</sup> Li-Be fluoride	Na-Zr fluoride	Na-Zr fluoride
Diameter coolant channel (m)	<b>0.02</b>	<b>0.03</b>	<b>0.02</b>	<b>0.03</b>
Height primary system (m)	<b>10</b>	<b>20</b>	<b>10</b>	<b>15</b>
Coolant inlet temperature (K)	<b>973</b>	<b>1073</b>	<b>973</b>	<b>1073</b>
Core height (m) (abandon H=0.92D)	<b>1.87</b>	<b>4</b>	<b>1.87</b>	<b>3</b>
Modified Results	<sup>7</sup> Li-Be	<sup>7</sup> Li-Be	Na-Zr	Na-Zr
Reynolds number	<b>2505</b>	<b>8940</b>	<b>4700</b>	<b>15600</b>
Nusselt Number	<b>11.0</b>	<b>66.0</b>	<b>24.4</b>	<b>116</b>
Maximum fuel temperature (K) (1473 K allowed)	<b>1356</b>	<b>1376</b>	<b>1367</b>	<b>1405</b>

- Acceptable results can be found when modifying parameters
- Modifying the core shape will have negative effects on neutronics
- height of primary system could be limiting factor (now 20 m)

# Conclusions Thermal Hydraulics

- Li-Be is not very good candidate for natural circulation cooling, due to low Reynolds numbers
- Na-Zr has better characteristics, but still modifications of primary system are needed for proper natural circulation
- Tin is an excellent coolant for natural circulation, large temperature drop in graphite can be a problem

# Overall Conclusions & Recommendations

## Summary results

	${}^7\text{Li-Be}$	Na-Zr	Tin
Neutronic properties	good	fair	poor
Neutronic design freedom	good	good	fair
Natural circulation potential	poor	fair	good

- Feasible core designs can be made for a liquid cooled U-Battery
- From neutronics point of view  ${}^7\text{Li-Be}$  fluoride is the best coolant , while from thermal hydraulics point of view, tin has largest potential.
- Future work will contain:
  - New material research, possibly there are better coolant candidates
  - Thermal hydraulics, burnup and shielding calculations
  - Passive reactivity control, using burnable poisons
  - Coupled neutronics and thermal hydraulics calculations to assess accident scenarios