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

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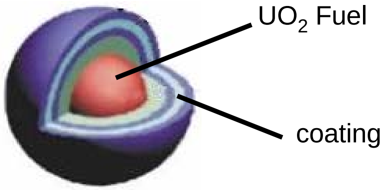
Introduction

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
  - $H_{core} = 0.924 D_{core}$ (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_{eff} calculation at the end of the cycle (EOC).

If $k_{eff} < 1$ 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

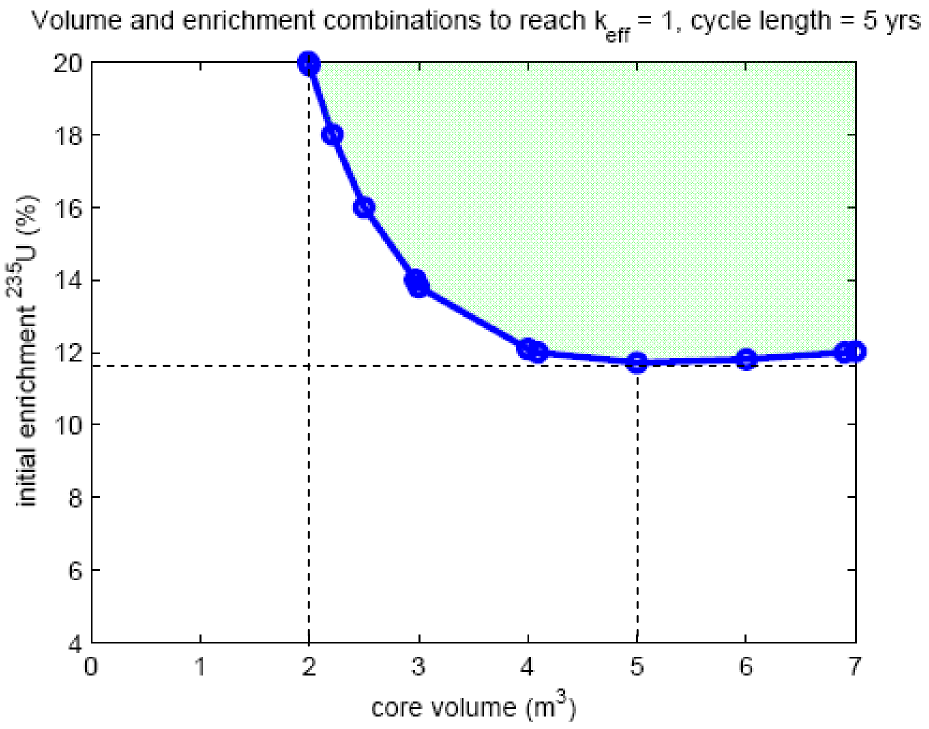
Input parameters for burn up and eigenvalue calculations

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^3
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, ^{7}Li-Na-Zr, ^{7}Li-Na-K, ^{7}Li-Be	tin

Results burnup and k_{eff} calculations

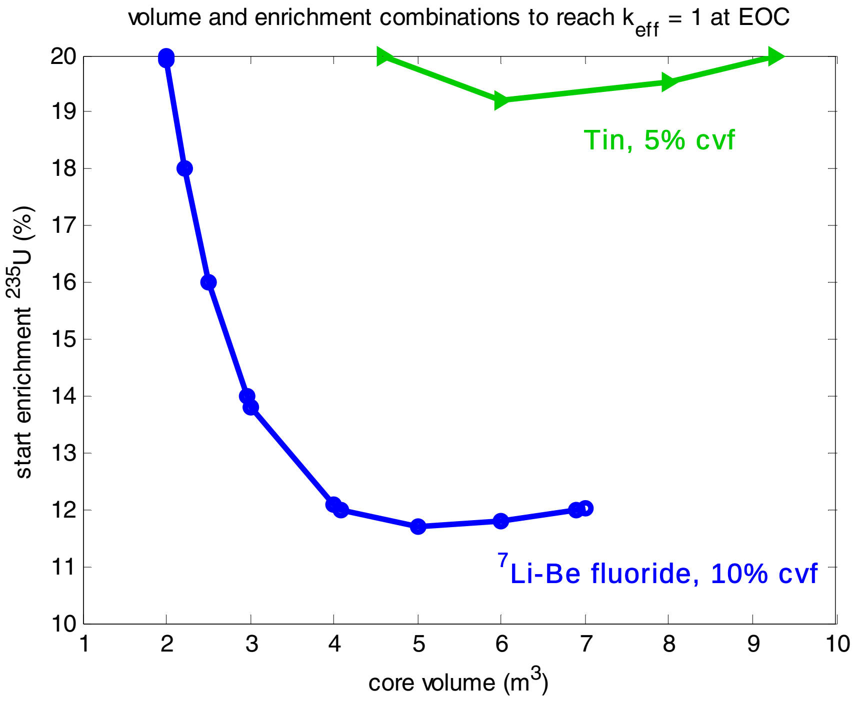
Core volume vs enrichment, ^{7}Li-Be fluoride 5 yrs, refl = 1.2 m, cvf = 0.1



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

Results burnup and k_{eff} calculations

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

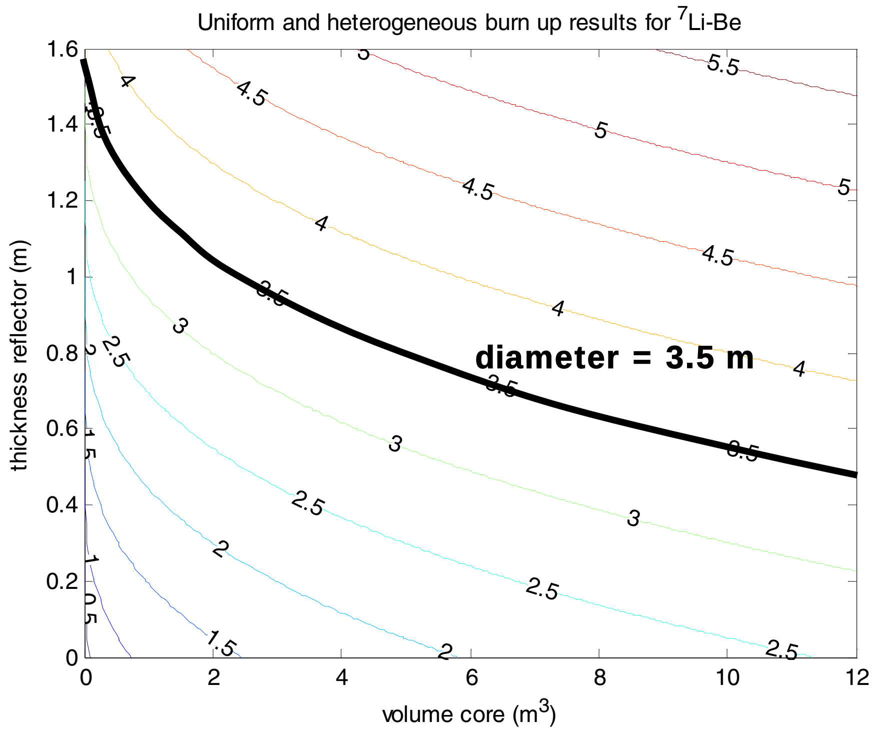


- Tin coolant volume fraction 5% because with larger coolant fractions no feasible solutions were found

- Minimum fuel enrichment is much larger for tin than for ^{7}Li-Be fluoride due to absorption

Core volume and reflector thickness

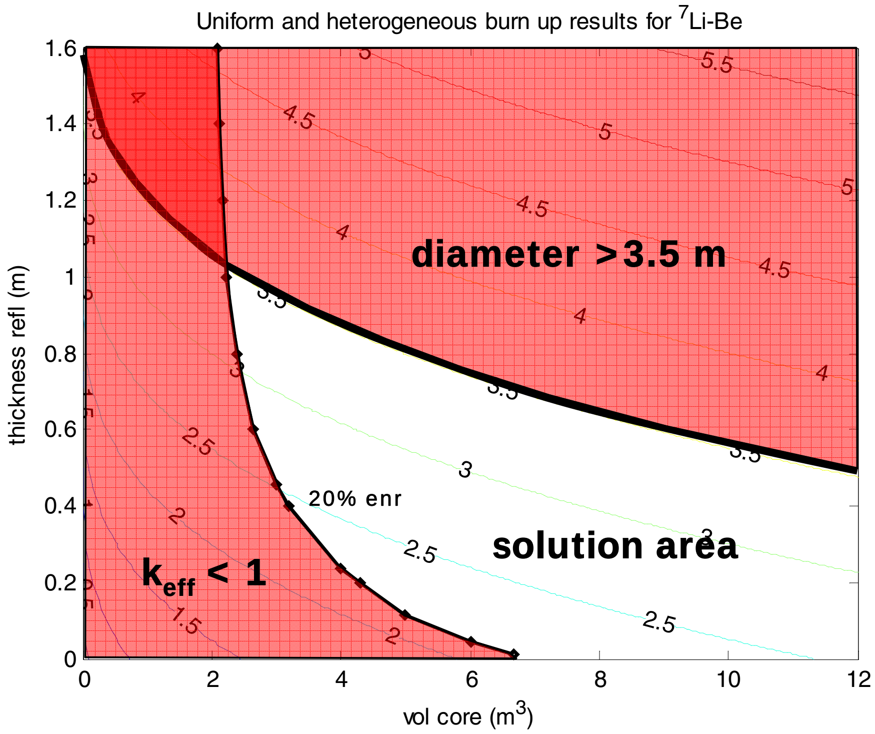
Contour plot of diameter core and reflector combined



- 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}Li-Be fluoride, 20 % enr, 5yrs

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



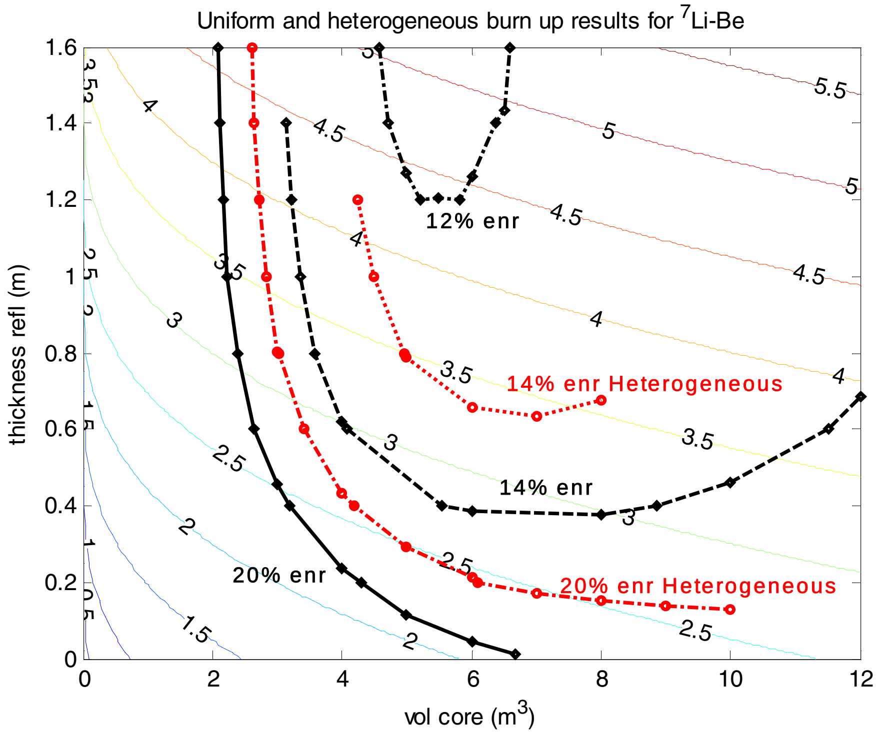
- When using larger core volumes, smaller reflectors are needed to give same k_{eff} with smaller total diameter

The solution must be found:

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

Results ^{7}Li-Be fluoride , 5yrs

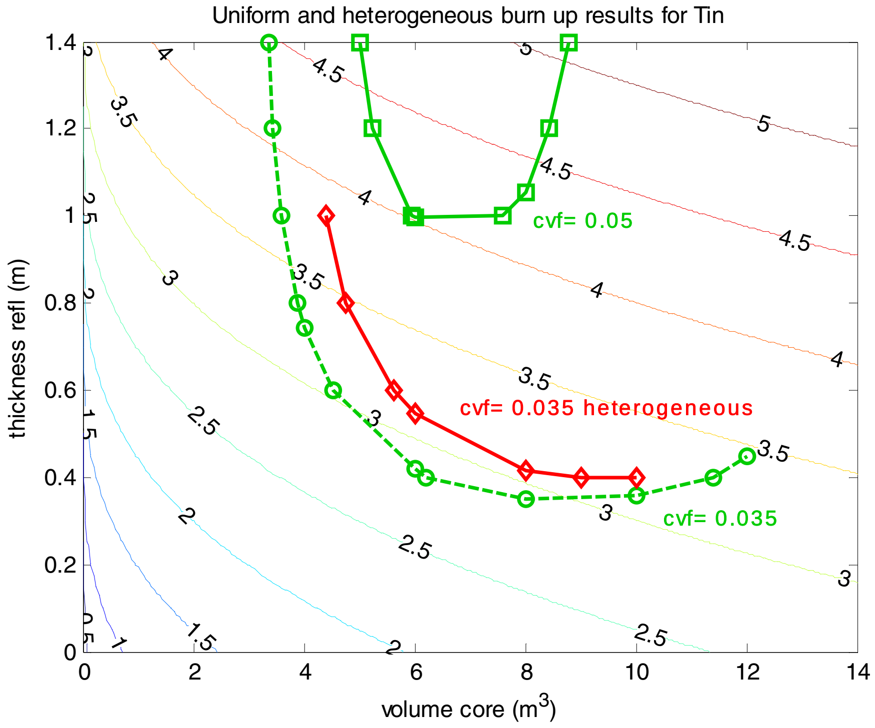
Core volume and reflector thickness combinations to achieve k_{eff} =1 at EOC



- 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}Li-Be as coolant is 14 % ^{235}U

Results tin, 5yrs

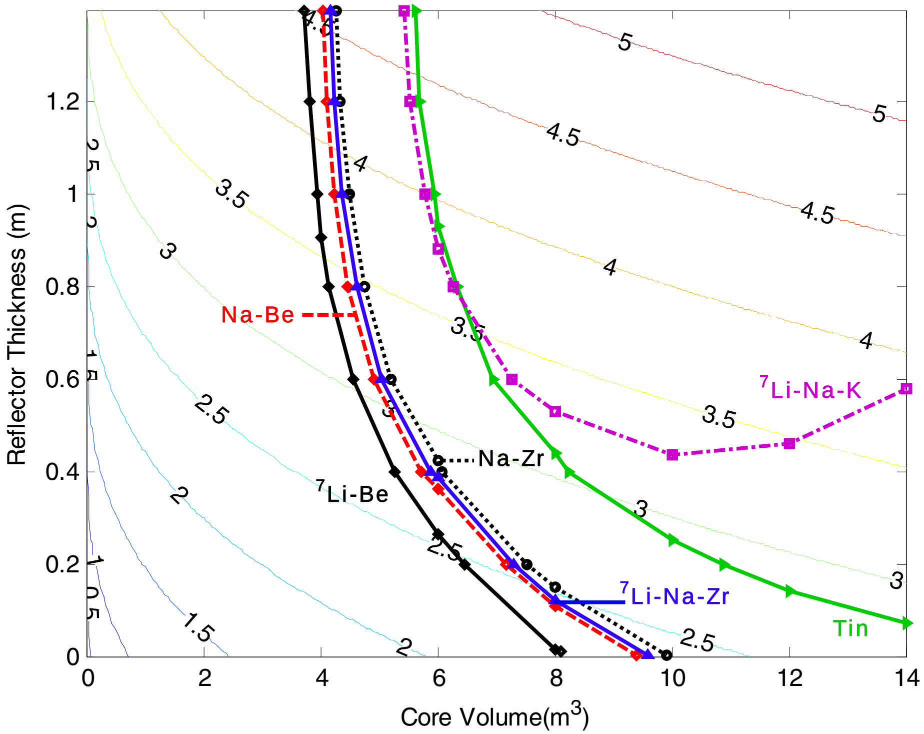
Core volume and reflector thickness combinations to achieve $k_{eff} = 1$ at EOC



- 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 $k_{eff} = 1$ at EOC



- For each coolant except ^{7}Li-Na-K a wide range of reflector and core volume combinations can be found
- ^{7}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}Li

Temperature and void coefficients

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

Coolant	Core volume (m^3)	Coolant volume fraction	k_{eff}	uniform temperature coefficient (10^{-5} K^{-1}) 973-1073 K	1073-1173 K	Avg.	Complete voiding reactivity ($)
^{7}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}Li-Be has a negative complete voiding reactivity coefficient
- If reactivity increases due to complete voiding is compensated by Doppler effect (~ -7 pcm/K) temperature must increase:
  - 400 K for Na-Zr case
  - 1300 K for tin case

Conclusions Neutronics Feasibility

- ^{7}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 seperation of ^{7}Li.
- All coolants have negative uniform temperature coefficient, only ^{7}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

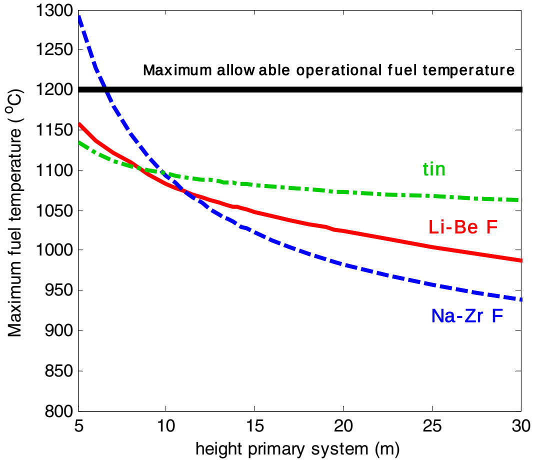
Fuel Temperatures and Reynolds numbers were calculated as a function of the height of the Primary System (riser + core)

Input parameters

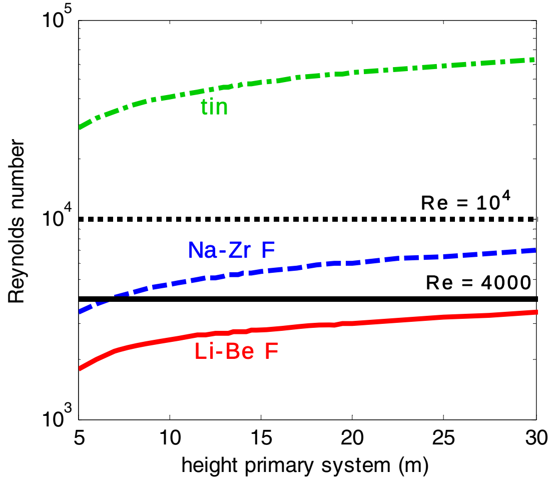
Parameter	Value
Core Power (MWt)	20
Core volume (m^3)	6
Height heat exchanger (m)	Core height
Diameter coolant channel (m)	0.02
Diameter riser and down comer (m)	0.2
Coolant inlet temp (K)	973
System pressure (bar)	1

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

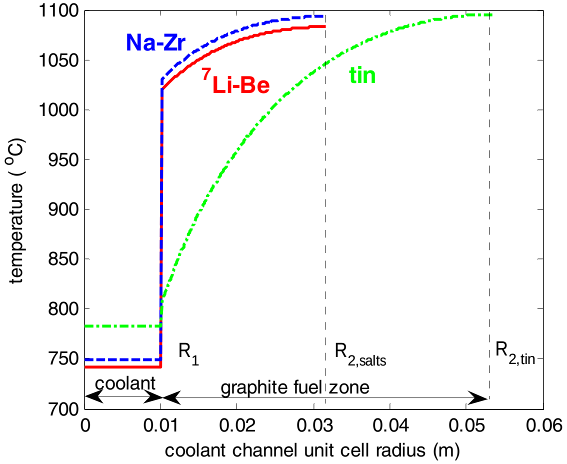
fuel temperature



Reynolds number



Unit cell temperature profile at height primary system = 10 m



- All coolants except provide fuel temperatures lower than 1200 ^{o}C for primary system heights larger than 7.5
- Only tin has Re>10,000 while ^{7}Li-Be has Re<4000
- Large ΔT 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

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

- 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}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}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