Neutronic Design of a Liquid Salt-cooled Pebble Bed Reactor (LSPBR)

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Introduction

- Improve High Temperature Reactors by replacing Helium with a liquid salt-coolant. Benefits are:
  - Ambient pressure operation
  - Increased power density without compromise to safety
  - Lower fuel temperatures & higher outlet temperature
  - Better decay heat removal

- Oak Ridge National Laboratories design: AHTR / LS-VHTR
- TU Delft design: Liquid Salt-cooled Pebble Bed reactor (LSPBR)

Main differences:

AHTR / LS-VHTR	**LSPBR**
• **hexagonal matrix fuel** • **offline refueling** • **wide range in volume fractions**	• **pebble bed fuel geometry** • **online refueling** • **fixed coolant volume fraction (~39 %)**

Selection of Liquid Salt Coolant

Criteria for selection of liquid salt coolant:

- Good heat transfer coefficients
- Reasonably low melting points
- Compatible with moderator and structural materials
- Chemically inert, Low toxicity

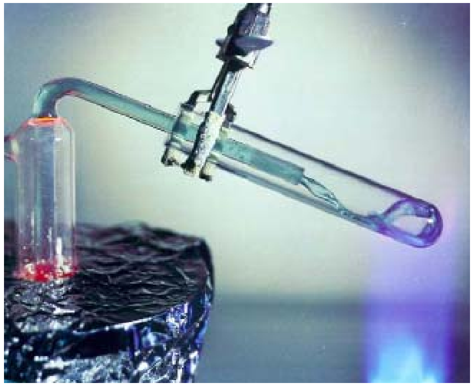
Neutronics and Liquid Salt Coolant

- Salts moderate and absorb neutrons
- Voiding of salt reduces: - moderation (reactivity decreases)
  - absorption (reactivity increases)
- **Liquid salt may not lead to positive voiding or temperature reactivity effect!**

Liquid Salt Coolant Candidates

Relevant physical properties of 7 candidate salts (Forsberg, ORNL)

Fluoride Salt	Melting point (°C)	heat capacity (kJ kg^{-1} K^{-1})	Moderating Ratio $\xi\Sigma s$ / Σa
Li-Be	458	2.38	63.0
Na-Be	360	2.18	9.8
Li-Na-K	454	1.88	1.7
Na-Zr	510	1.17	6.7
Na-Zr-K	385	1.09	2.9
Li-Na-Zr	460	1.47	12.5
Na-NaB	385	1.51	12.9



Liquid salt, source: ORNL

- Heat capacity at 700 °C
- Lithium is highly enriched with ^{7}Li, ^{6}Li concentration ~ 0.0007 %

Results Salt Selection Simulations (1/4)

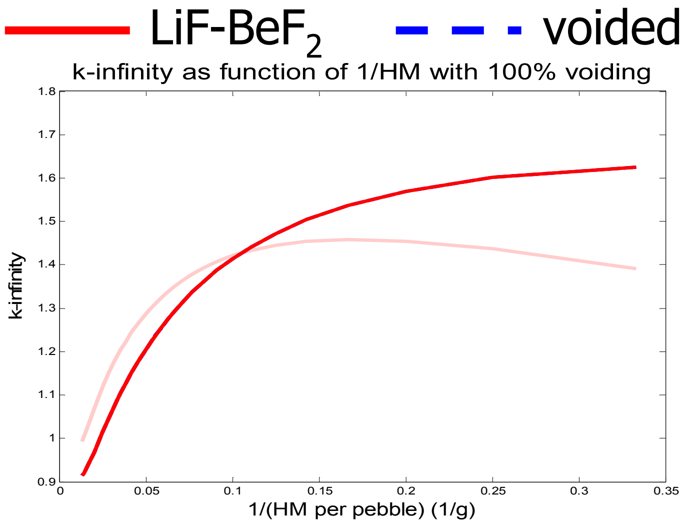
Reactivity coefficients for pebbles containing 12 g of uranium with 10% enrichment. All coolants at ambient pressure except Helium (7 MPa)

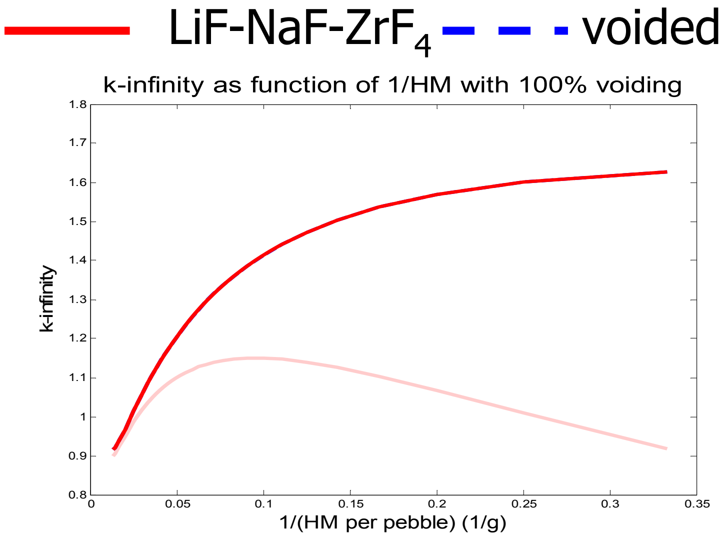
Fluoride salt	k_∞	**Complete voiding reactivity ($)**	**Uniform temperature reactivity coefficient (pcm/K)**	**Porosity reactivity coefficient (pcm/ % porosity)**
Li-Be	**1.39**	**-2.30**	**-7.68**	**+70**
Na-Be	**1.11**	**21.5**	**-2.53**	**-860**
Li-Na-K	**0.71**	**87.9**	**8.14**	**-1290**
Na-Zr	**1.10**	**23.0**	**-0.465**	**-870**
Na-Zr-K	**0.81**	**65.1**	**5.42**	**-1310**
Li-Na-Zr	**1.15**	**17.7**	**-1.53**	**-730**
Na-NaB	**0.86**	**56.2**	**8.32**	**-1250**
Helium	**1.36**	**-0.11**	**-8.58**	**+30**

- Voiding of salt introduces large positive reactivity, except for Li-Be salt (FLIBE)
- FLIBE has largest negative uniform temperature coefficient
- All salts have a negative porosity reactivity coefficient, except FLIBE

Results Salt Selection Simulations (2/4)

The k_∞ as a function of the fuel loadings per pebble for FLIBE (left) and Li-Na-Zr (right) combined with the complete voided case

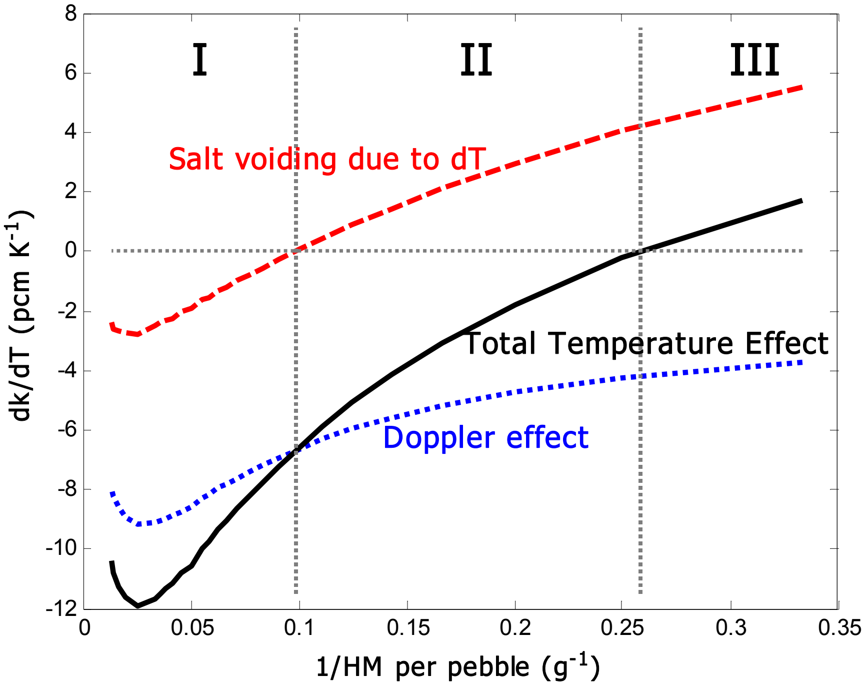




- For FLIBE with a fuel loading less than ~8.5 g per pebble, voiding leads to an increase of k_∞
- All other salts have behaviour similar to Li-Na-Zr Fluoride salt

Results Salt Selection Simulations (3/4)

The Uniform Temperature Coefficient (pcm/K) as a function of the fuel loadings per pebble for FLIBE



Three zones are identified:

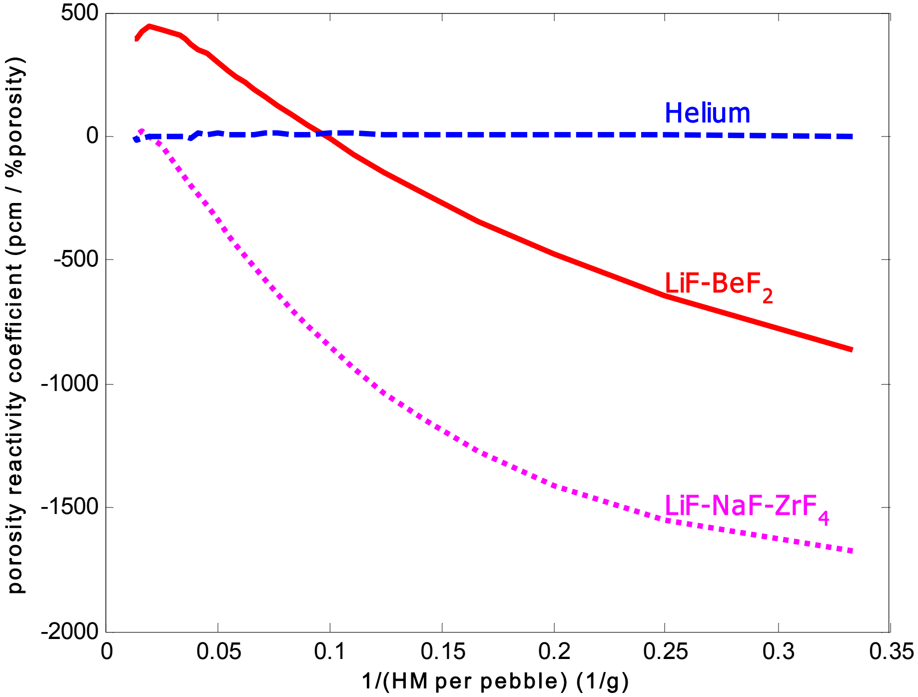
I. The Doppler reactivity coefficient and the coolant temperature feedback reinforce each other

II. Coolant temperature is positive but Doppler coefficient is negative and dominant

III. Coolant temperature (voiding) reactivity coefficient has become dominant

Results Salt Selection Simulations (4/4)

The Porosity Reactivity Coefficient (pcm/ % porosity) as a function of the fuel loadings per pebble for FLIBE and Li-Na-Zr salts compared to Helium



Loss of forced cooling might lead to floating of fuel pebbles:

- For a limited range of fuel loadings an increase in porosity can lead to increase in k_∞ for FLIBE
- Top reflector could be poisoned to avoid increase in k_∞
- Neutron leakage is expected to increase (decrease in k_{eff})

Conclusions Salt Selection

FLIBE is best candidate for application in LSBPR

- Best moderating quality
- Highest k_∞ values
- Strongly negative temperature reactivity coefficients

Disadvantages FLIBE

- Possible floating of the pebbles and effect on k
- Cost
- Toxicity

FLIBE was selected as primary coolant in LSPBR

Parameter Design of 2500 MWth LSPBR

- Pressure drop calculated with Ergun Relation:

$$\Delta p = \frac{1-\varepsilon}{\varepsilon^3}\left(170\frac{\mu A}{\dot{m} d_p}(1-\varepsilon)+1.75\right)\frac{H}{d_p \rho}\left(\frac{\dot{m}}{A}\right)^2$$

- Mass flow coolant salt is given by :

$$\dot{m} = \frac{P}{c_p \Delta T}$$

- P = 2400 MWth, ΔT = 100 K, c_p = 2.38 kJ kg^{-1} K^{-1} ➡ $\dot{m}$ = 10478 kg s^{-1}

- Two different core shapes have been investigated: Cilindrical & Annular
- Resultant pressure drop is less than 1 bar in both cases, pumping power less than 0.05 % of total power

Parameter Design of 2500 MWth LSPBR

Relevant dimensions of two core geometries

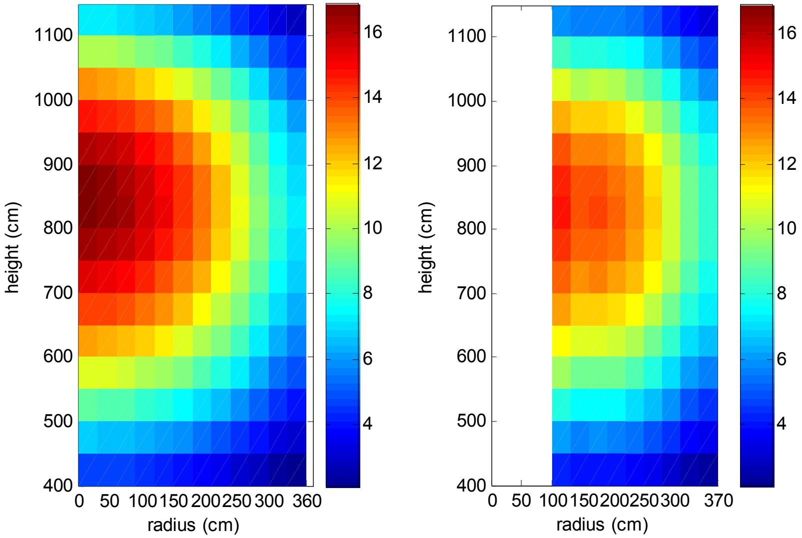
Parameter	Cylindrical core	Annular core
Core height (m)	7.5	7.5
Core outer diameter (m)	3.6	3.7
Inner reflector diameter (m)	n.a.	2.0
Core volume (m^3)	305.4	299.0
Average estimated power density (MW/m^3)	8.19	8.36
Vessel diameter (m)	9.0	9.2
Vessel height (m)	16.6	16.6
Vessel thickness (m)	0.1	0.1
Outer reflector thickness (m)	0.8	0.8
Top and bottom reflector thickness (m)	1.5	1.5

Steady State Operation (1/2)

Results of steady state calculations for annular and cylindrical core

Parameter	Cylindrical core	Annular core
Power level (MWth)	2500	2500
Average power density (MWth m^{-3})	8.19	8.36
Maximum power density (MWth m^{-3})	16.8	14.7
Peak factor	2.05	1.75
Average velocity of Salt (m s^{-1})	0.36	0.37
Reynolds number in pebble bed	15700	16100
Coolant inlet temperature (°C)	900	900
Coolant outlet temperature (°C)	1000	1000
Maximum coolant temperature (°C)	1051	1028
Maximum fuel Temperature (°C)	1190	1152

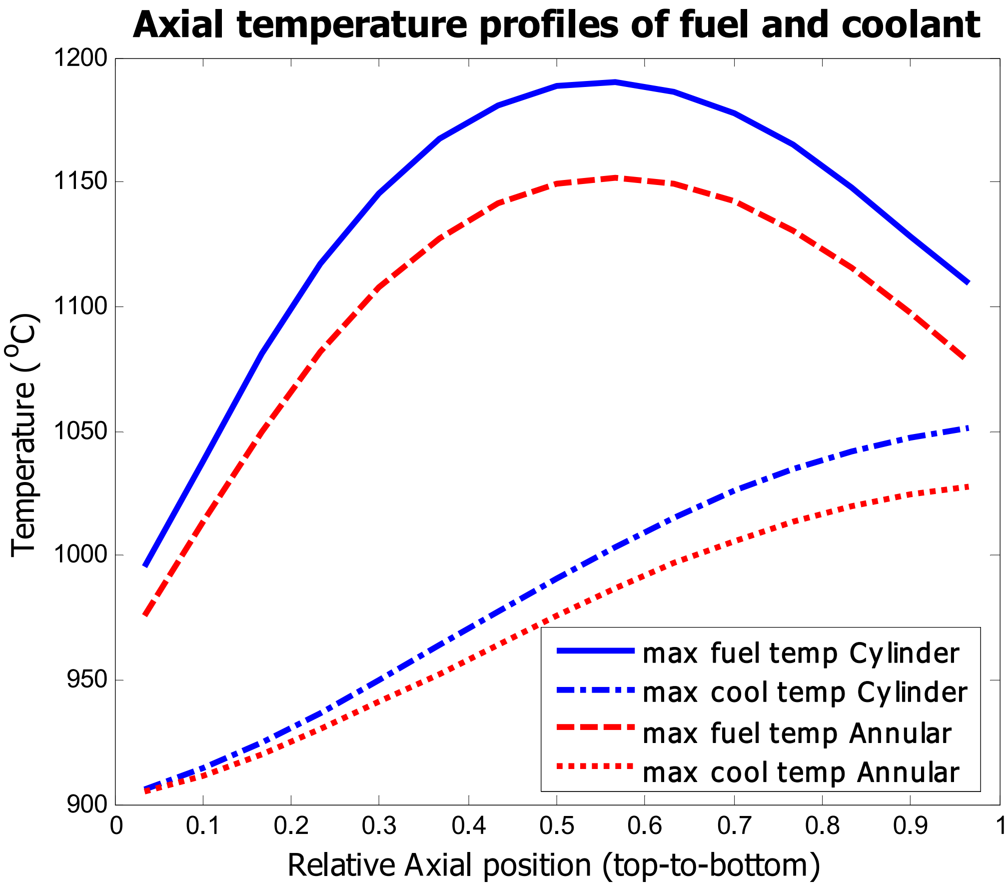
Power density profiles in cylindrical (left) and annular core (right)



- Compared to cylindrical core the annular core has: lower peak factor & lower corresponding maximum power density

Steady State Operation (2/2)

Maximum axial fuel and coolant temperatures of the 2500 MWth LSPBR

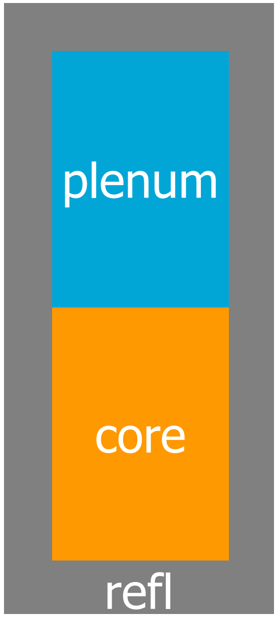


- Maximum fuel temperatures:
  Cylinder LSPBR ~1190°C
  Annular LSPBR ~1151°C
- Due to lower peaking in the annular core, maximum fuel and coolant temperatures are lower
- Calculations were performed with homogeneous core, continuous refueling moves maximum power density to top of core (the cooler region)

Decay Heat Removal Calculations

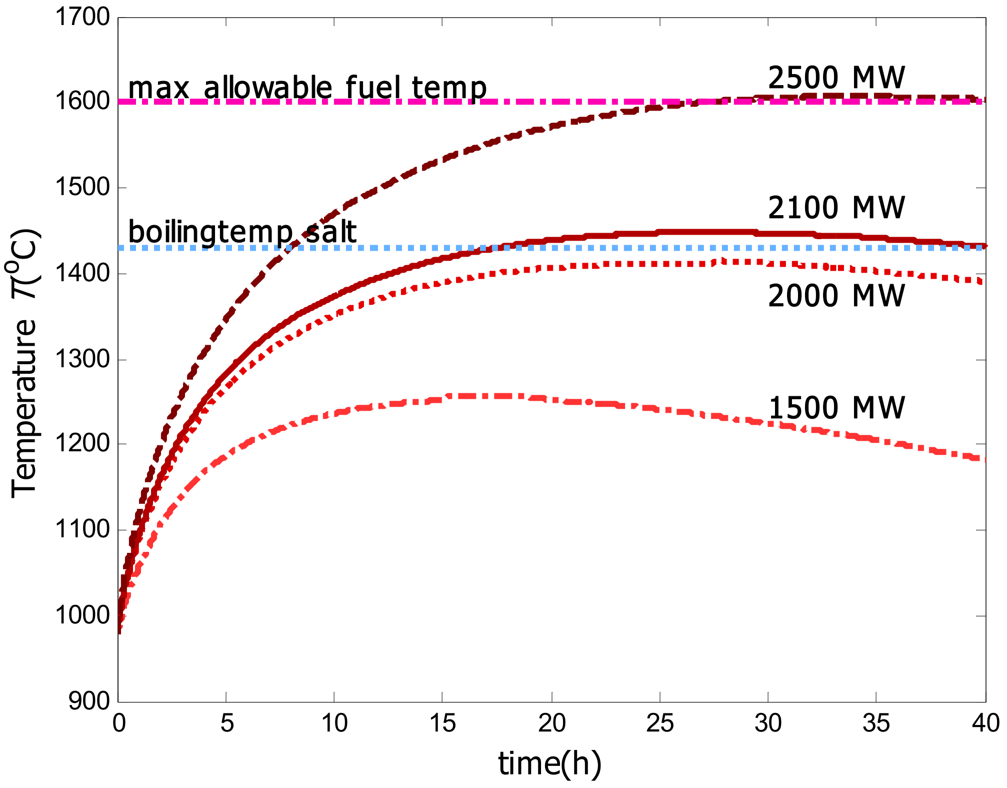
Various power levels were simulated to determine maximum power level without exceeding limits on fuel and coolant temperature

- Fuel failure at 1600 °C; FLIBE boiling at 1430 °C
- Cylindrical geometries simulated for 40 hrs of real time
- Two situations were simulated:
  - Pebble bed core
  - Pebble bed core with additional salt plenum



Decay Heat Removal Results (1/2)

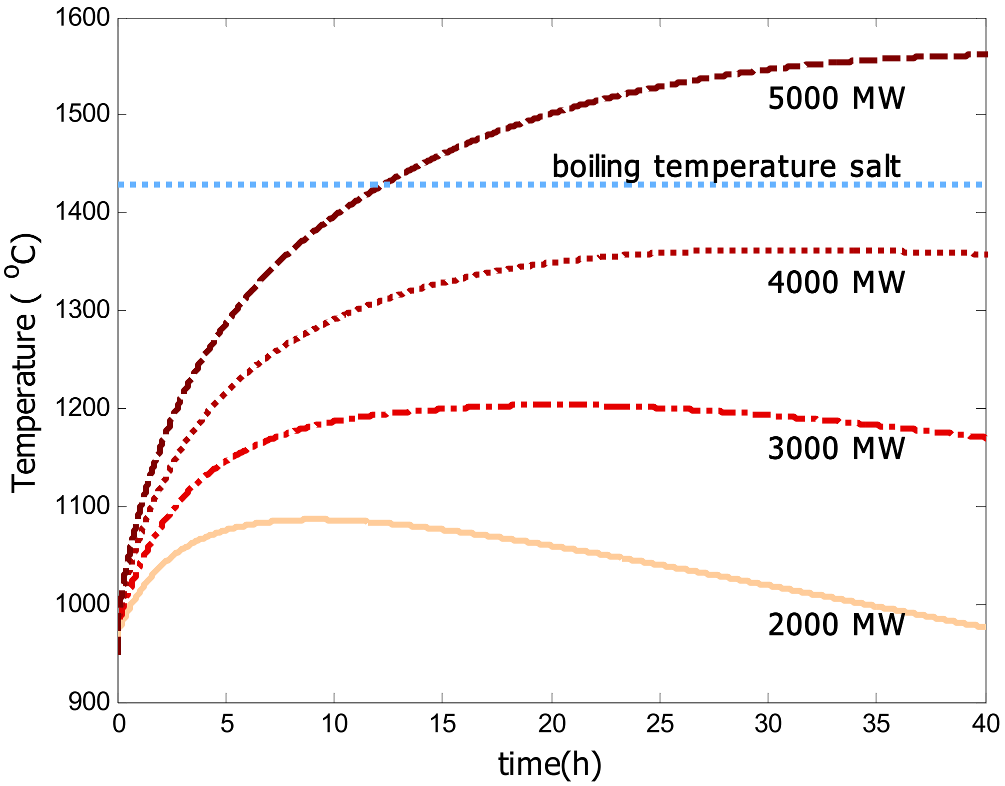
Maximum fuel temperatures as a function of time with initial power as parameter, geometry ***without*** additional salt plenum



- After initial increase in temperatures, natural convection flow develops
- With increase in natural convection flow, convective heat transfer increases
- Then coolant and fuel gradually cool
- Maximum power *without* additional salt plenum: **2000 MWth**

Decay Heat Removal Results (2/2)

Maximum fuel temperatures as a function of time with initial power as parameter, geometry ***with*** additional salt plenum



With the salt plenum:

- The total volume of salt is larger by a factor 3.5
- The thermal inertia of the reactor is increased
- The outer surface of the reactor is increased
- Maximum power *with* additional salt plenum: **4000 MWth**

Conclusions

- From the 7 liquid salt candidates considered, the best choice for the LSPBR is Li-Be fluoride salt (FLIBE)
- The height of the pebble bed was not restricted by the pressure drop (< 1 bar)
- Because of lower maximum fuel and coolant temperatures, the annular core shape has preference for the LSPBR
- Maximum allowable nominal power is 2000 MWth without salt plenum and 4000 MWth with additional 7.5 m high salt plenum

Further work

- Burnup analysis; simulation of on-line refuelling; other fuel types and fuel cycles
- Improved heat transfer modeling
- Improved modeling of floating pebbles
- Detailed transient analysis, including effects of floating pebbles, boiling salt etc.
- Possibility of natural convection salt-cooled reactor
- Possibility of other salts (less toxic, cheaper, etc)

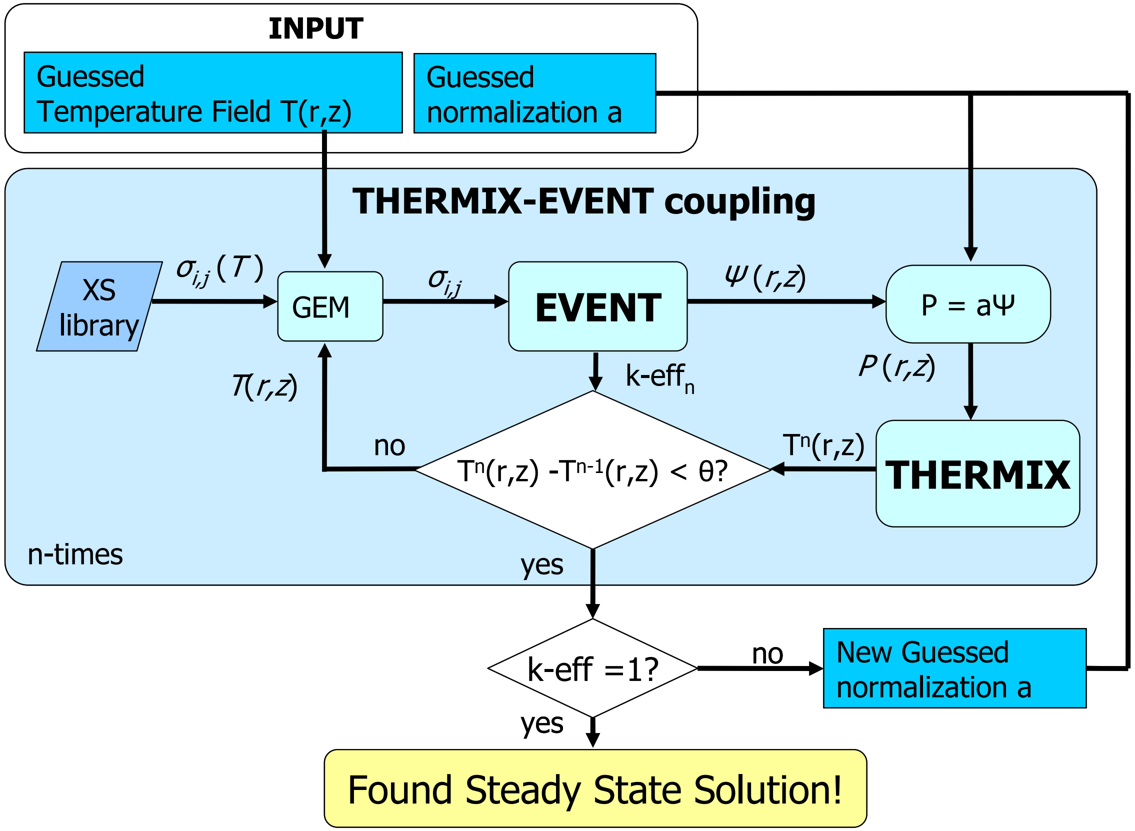
End of presentation

Thank you for your attention

Questions?

Steady State Operation

Thermal Hydraulics (THERMIX) and Neutronics (EVENT) Coupling



INPUT

Guessed Temperature Field T(r,z)

Guessed normalization a

THERMIX-EVENT coupling

XS library

$\sigma_{i,j}(T)$

GEM

$\sigma_{i,j}$

EVENT

$\Psi(r,z)$

P = aΨ

$P(r,z)$

k-eff$_n$

$T(r,z)$

no

$T^n(r,z) - T^{n-1}(r,z) < \theta$?

$T^n(r,z)$

THERMIX

n-times

yes

k-eff =1?

no

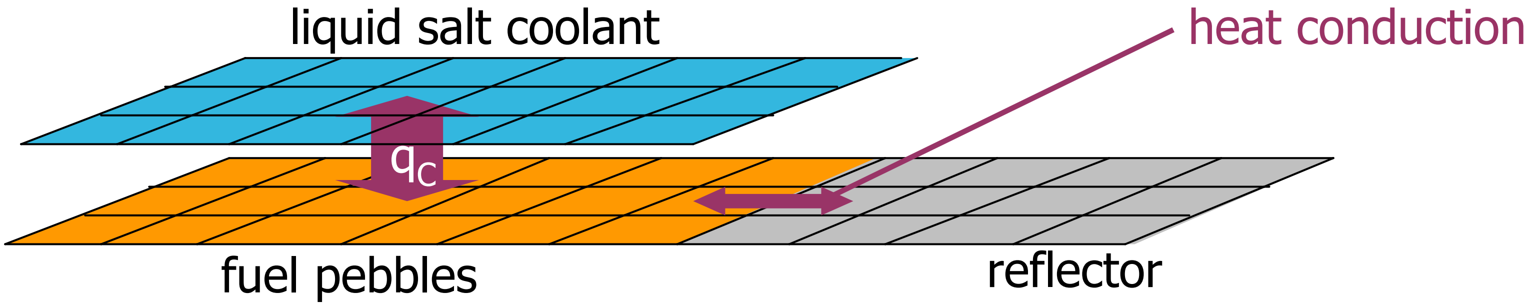
New Guessed normalization a

yes

Found Steady State Solution!

Difference between THERMIX and HEAT

THERMIX


liquid salt coolant

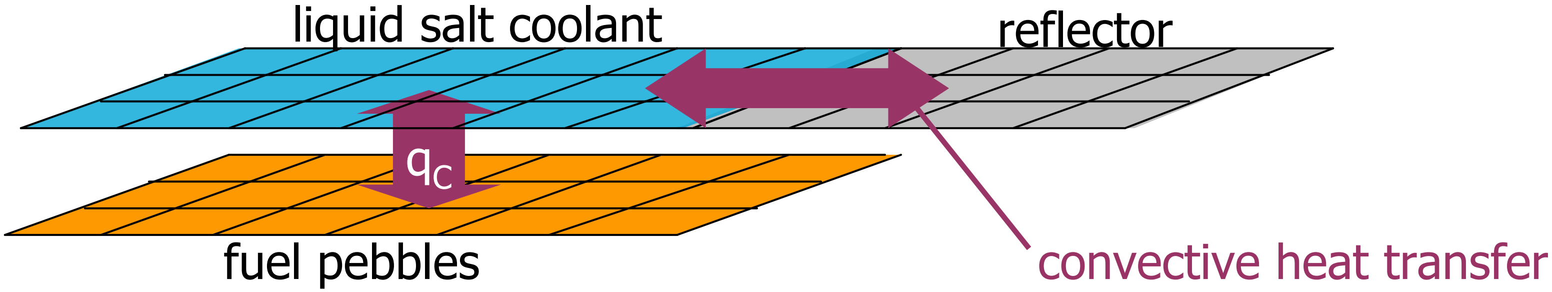
heat conduction

q_C

fuel pebbles

reflector

HEAT


liquid salt coolant

reflector

q_C

fuel pebbles

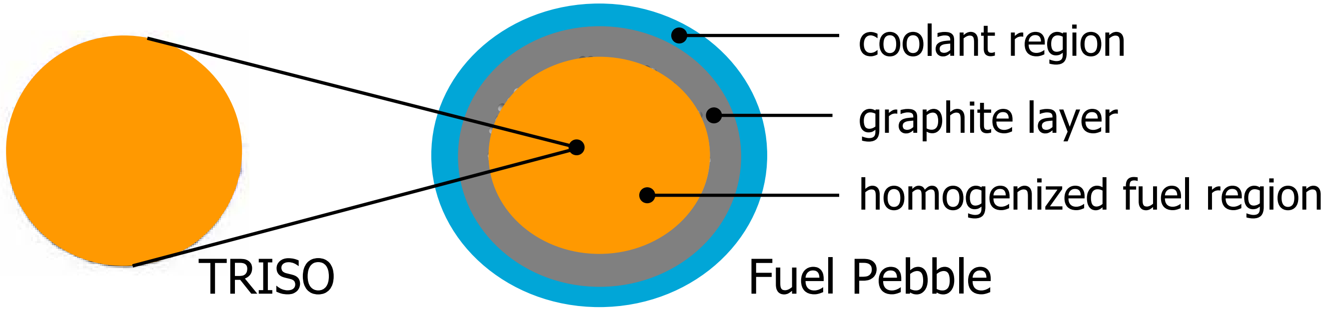
convective heat transfer

Salt Selection Simulations

To asses the effect of salt candidates on neutronics, simulations were performed on an infinite array of fuel pebbles with salt coolant:

- Effect of salt voiding on k_∞
- Effect of temperature on k_∞
- Effect of pebble packing fraction on k_∞

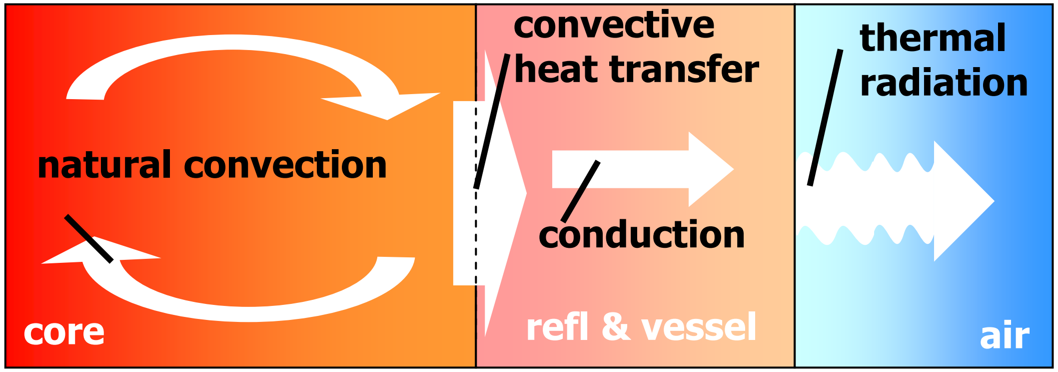
Calculations performed with SCALE code system using JEF2.2 data.

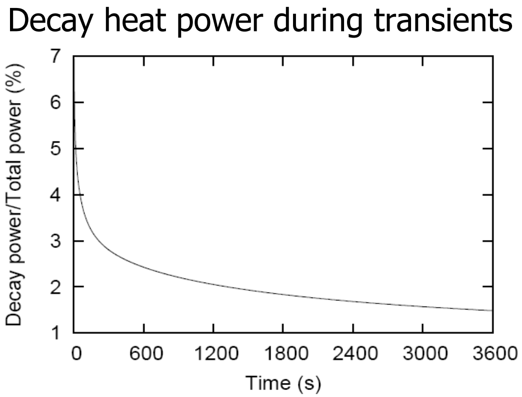


Passive Decay Heat Removal

In a Loss of Forced Cooling incident (LOFC) the fission decay heat is not removed by the coolant

- Decay Heat Power is 7 % directly after shutdown…
- Decay Heat must be removed by:





- To examine temperature distribution during a LOFC with SCRAM, simulations were performed with code HEAT