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PSI Studies on Advanced fuel cycle options for Fast/Thermal MSR Utilizing Thorium

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Content

- *Motivation and appealing MSR features*
- *Our research direction in MSR neutronics*
- *Spectral study for single-fluid MSR*
- *Reprocessing & some ideas*
- *Outlook*

Motivation: appealing MSR features

- ***Molten Salt Reactor (MSR) has excellent neutron economy.***
  (especially in U-Th cycle the capture of ^{233}U is low, but also the parasitic absorptions of carrier salt and graphite are small)

- ***Fuel in liquid state does not need fabrication.***
  (it enables TRU recycling, on-line refueling, on-line reprocessing, on-line gaseous and volatile fission removal)

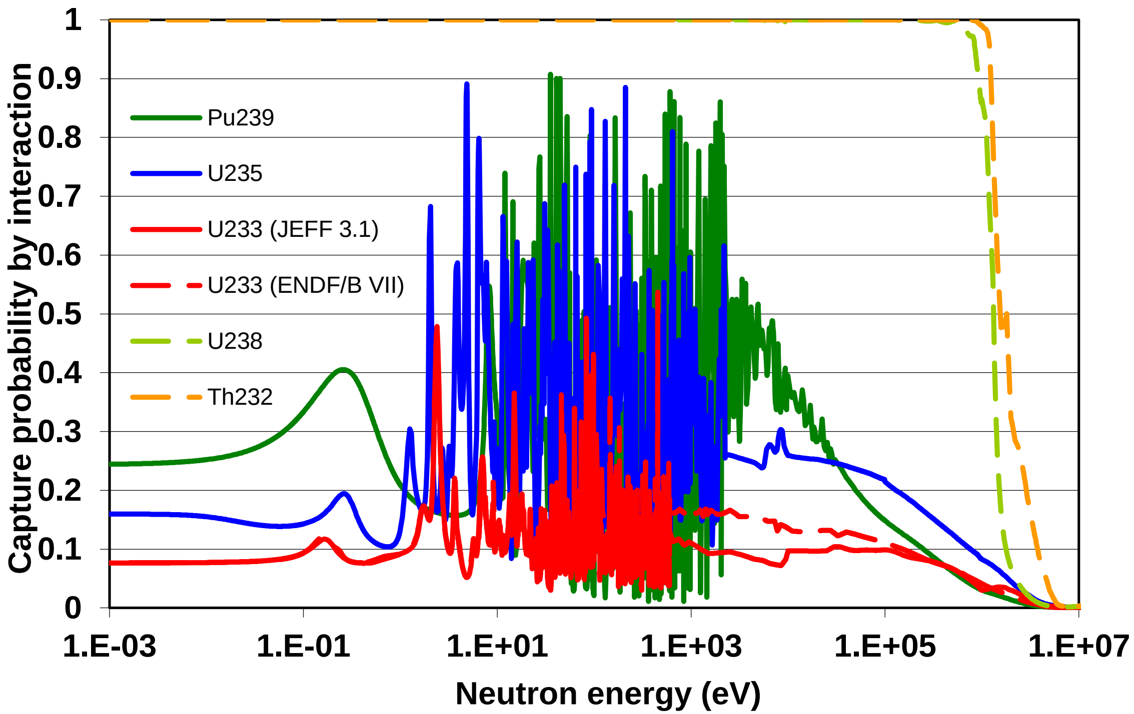
- ***MSR can be operated with flexible fuel cycle.***
  (as thermal, epithermal, or fast breeder and/or burner thanks to the Th-U cycle properties and liquid fuel)

- ***MSR can be designed as an inherently safe reactor with <u>reduced risk</u>.***
  (low inventory of gaseous and volatile fission products, negative temperature feedbacks, fail-safe fuel drainage)

Motivation: appealing MSR features

- ***Molten Salt Reactor (MSR) has excellent neutron economy.***

Capture probability (JEFF 3.1) of ^{233}U, ^{235}U, ^{239}Pu, ^{232}Th and ^{238}U



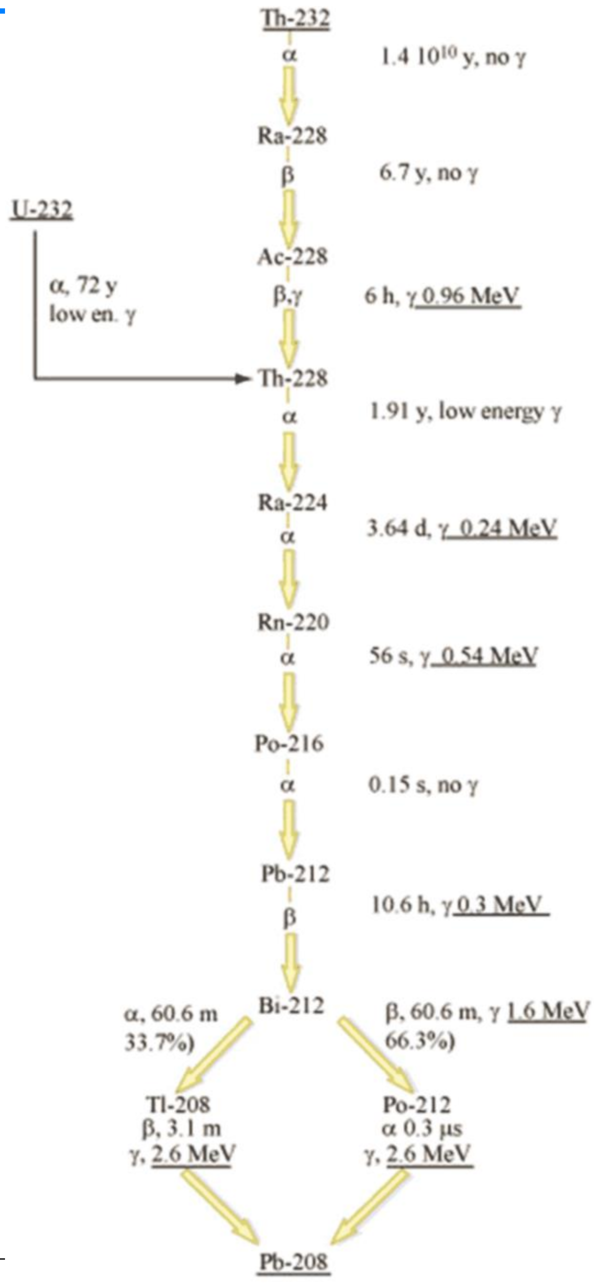
Motivation: appealing MSR features

- ***Fuel in liquid state does not need fabrication.***

- Th-U cycle issue:
  Hard gamma for instance from ^{212}Bi, ^{208}Tl, and ^{212}Po.

- U-Pu cycle issue:
  Higher production of minor actinides, for instance Am and Cm (high *α* and in Cm case also *n* emitting rate).

- Molten Salt Reactors (MSR)
  with liquid fuel (no fabrication)
  can accommodate both MA from U-Pu and U from Th-U cycles more easily.



Motivation: appealing MSR features

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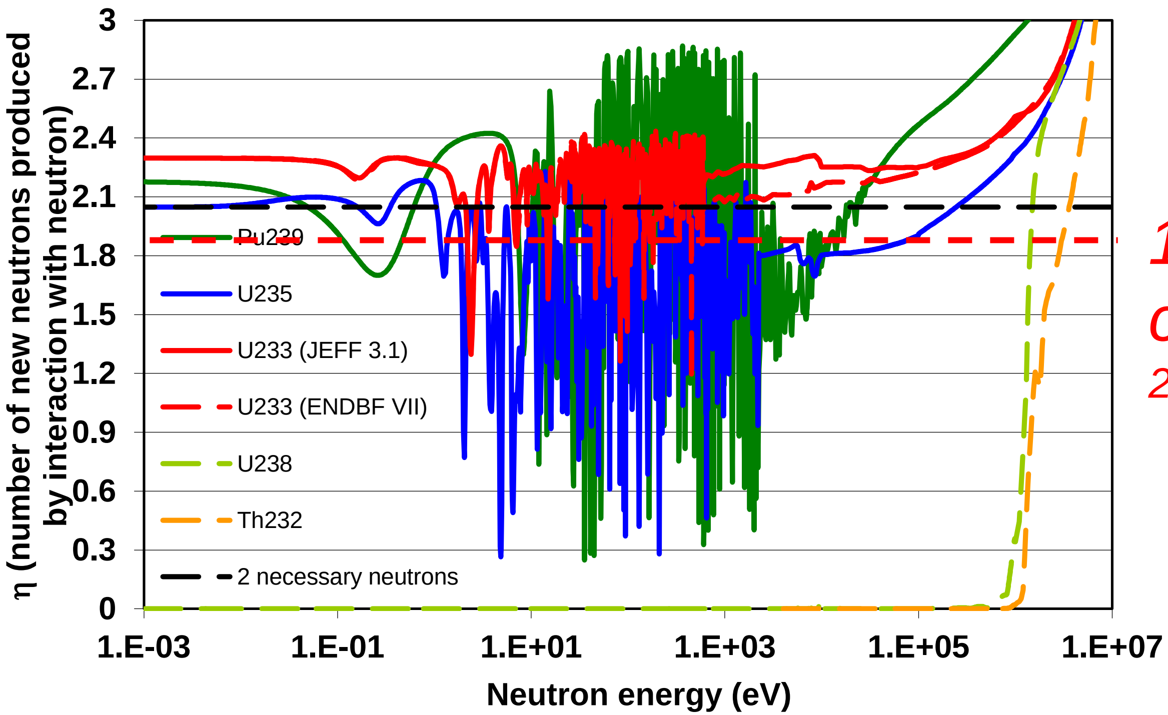
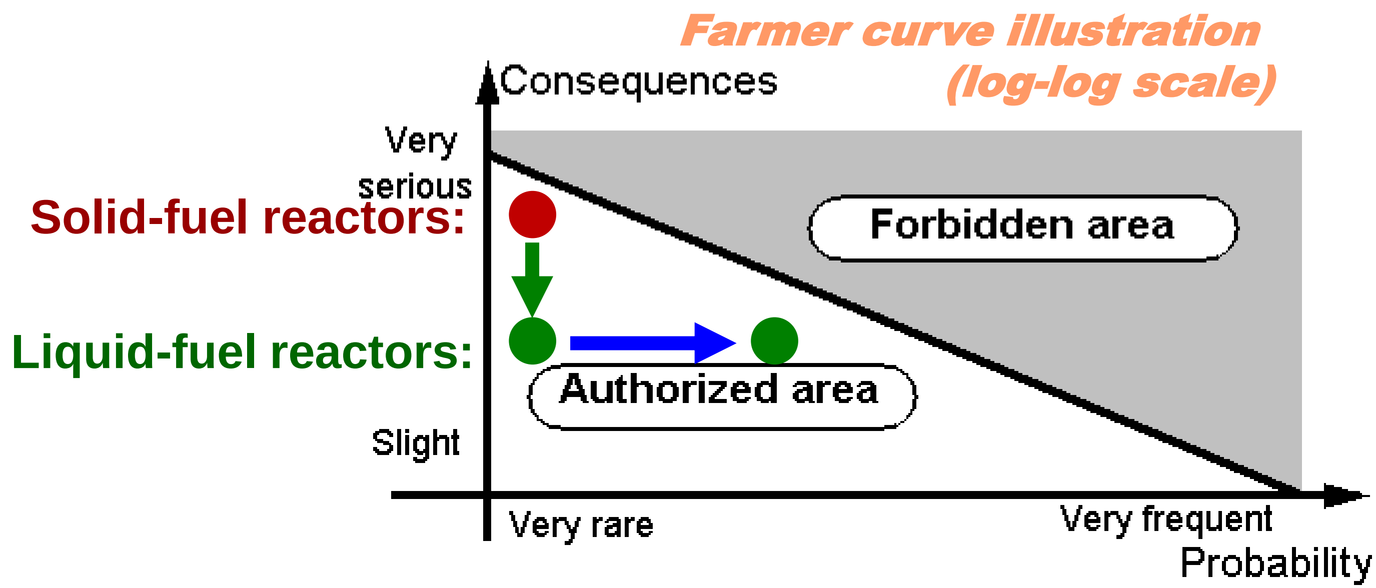


1.9 line in U-Pu cycle because of ^{238}U 10% fission

Motivation: appealing MSR features

- ***MSR can be an inherently safe reactor with <u>reduced risk</u>.***
  (low inventory of gaseous and volatile fission products, negative temperature feedbacks, fail-safe fuel drainage)



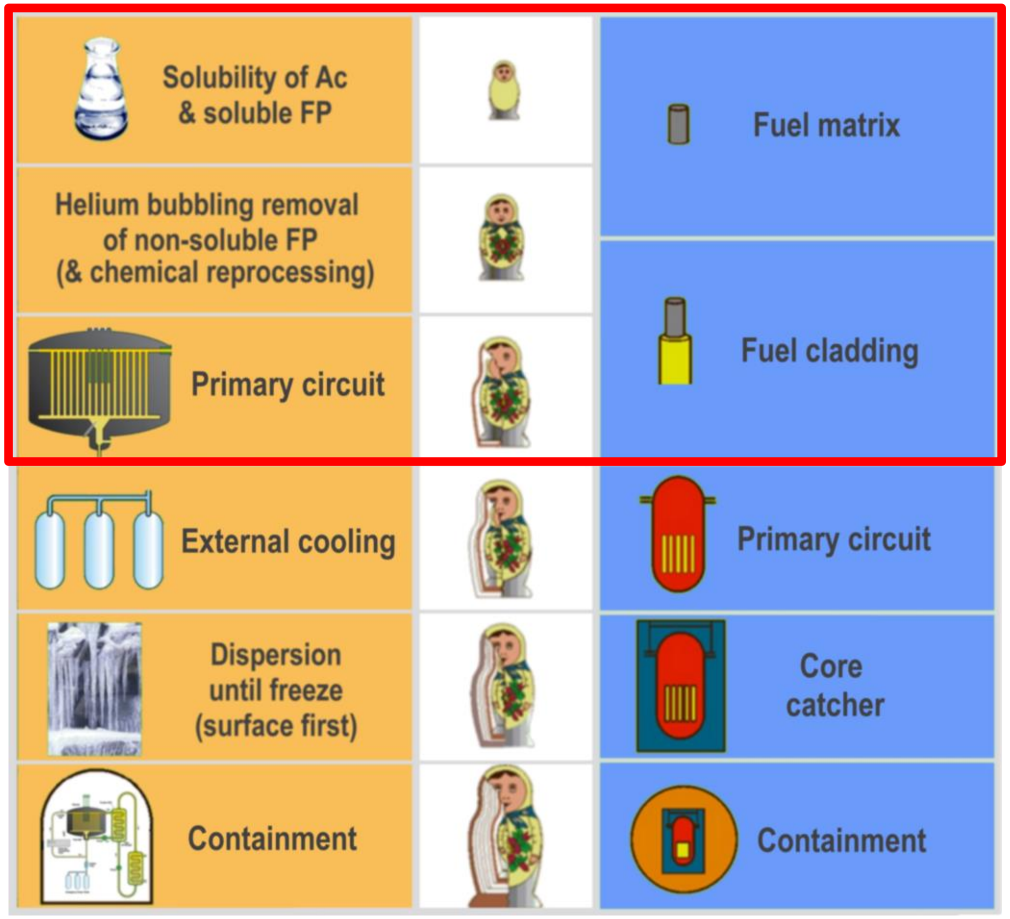
http://www.iaea.org/ns/tutorials/regcontrol/assess/assess3212.htm

Online removal of highly mobile gaseous and volatile FP
(Ac and remaining FP are embedded in the salt)

Reduction of classical barriers
(safety standards for reactor X reprocessing plant)

Motivation: appealing MSR features

- ***MSR can be an inherently safe reactor with reduced risk.***
  (low inventory of gaseous and volatile fission products, negative temperature feedbacks, fail-safe fuel drainage)



MSR drawbacks

- ***Structural materials corrosion and irradiation embrittlement.***
  (high Ni content alloys should be applied and
  redox potential must be controlled to prevent corrosion,
  furthermore in fast MSR the alloys suffer from radiation embrittlement.)

- ***Graphite, if applied, has limited lifespan.***
  (its mechanical stability also suffers by fast neutron irradiation)

- ***Complicated molten salt reprocessing techniques.***
  (fluoride volatilization techniques, Electro-separation processes,
  Molten salt / liquid metal reductive extraction)

- ***Fuel salt chemical treatment and possible proliferation risk.***
  (redox potential control, on-line refueling, He bubbling
  to remove gaseous and volatile fission products,
  proliferation risk related to ^{233}Pa or ^{233}U relatively easy separation)

Our idea for reactor physics designing of MSR

- ***Lets design MSR with so appealing fuel cycle and safety****-related characteristics that it will be worth to overcome the drawbacks.*

- *In the same time,* ***lets sacrifice part of the "freedom"*** *in reactor physics designing to help* ***to reduce the drawbacks****.*

- *Lets integrate the* ***MSc students', PhD students', and post-docs'*** *work in into a students' reactor designing project.*
  - *PSI supports the joint EPFL-ETHZ Master of Science in nuclear engineering and several MSc theses already were or are related to MSR.*
  - *One PhD student will start to work on SMSR this year.*

- *The project may be in the future extended to other relevant fields (thermal-hydraulics, salt chemistry, materials behavior, etc.) and supported by senior researchers.*

Several very first steps of the project already done

✓ *1)* ***Tools preparation:***

EQL3D *extension by:*

- *adding capability for liquid fuel on-line treatment,*
- *model of asynchronous blanket treatment,*
- *and by model of long-term radiotoxicity evolution.*

EQL0D *development:*

- *Serpent-MATLAB based or ERANOS-MATLAB based equilibrium procedure to cross-check and accelerate the EQL3D.*

FAST code *modification for liquid fuel:*

- *Adding the salt properties*
- *Modeling the delayed neutrons precursors drift for channel-wise core and primary circuit*

OpenFOAM *learning phase and assimilation*

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Several very first steps of the project already done

✓ *2) **Establish of cooperation** with research centers and universities:*

- *PSI is an official observer of the EU FP7 **EVOL project**.*
- *Cooperation with Politecnico di Milano - **POLIMI** (EQL3D modification, Serpent MSR burn-up model, OpenFOAM).*
- *Cooperation with **TU Prague** (on EQL0D development).*

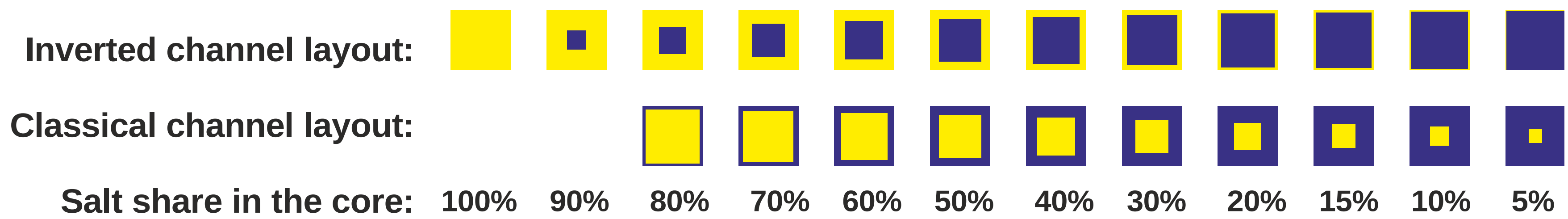
✓ *3) Accomplished **studies and simulation**:*

- *Parametric **spectral study of a single-fluid** Molten Salt Reactor with **EQL3D** o a core level*
- *Lattice **heterogeneity study** with **EQL0D** (the respective MSc thesis defended in 2013)*
- *Preliminary analysis of hybrid spectra MSR*
- *Preliminary analysis of simplified uranium recycling without reprocessing of the once through salt*

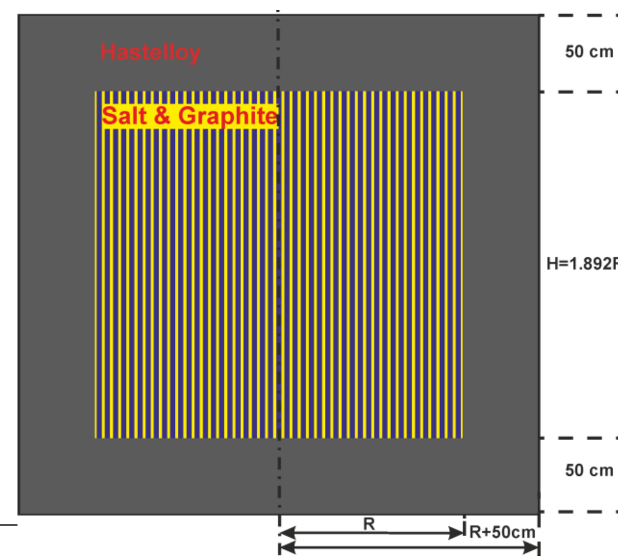
Spectral study of a single-fluid MSR with EQL3D

Novelty of the study are:

- ***Equilibrium closed cycle*** *was simulated by ERANOS based* ***EQL3D*** *procedure (modified at POLIMI by C. Fiorina for MSR) for full core geometry and several salt-graphite ratio.*
- ***Salt and graphite feedback coefficients*** *are evaluated for classical and inverted channel geometry:*



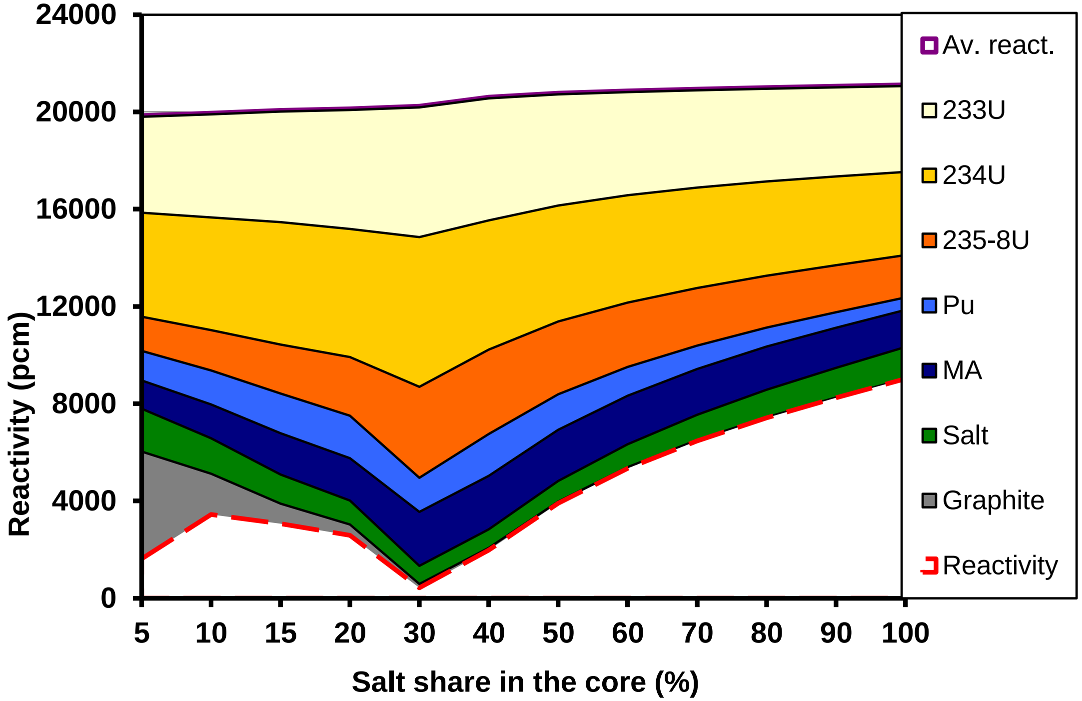
- ***Criticality conditions*** *are obtained, if possible, by adjusting the core radius. Limit for the radius is set to 5 meters.*
- *MSFR* ***salt composition*** *was adopted (77.5 molar % of LiF enriched in ^{7}Li (99.999 at%) and 22.5 molar % of Ac).*

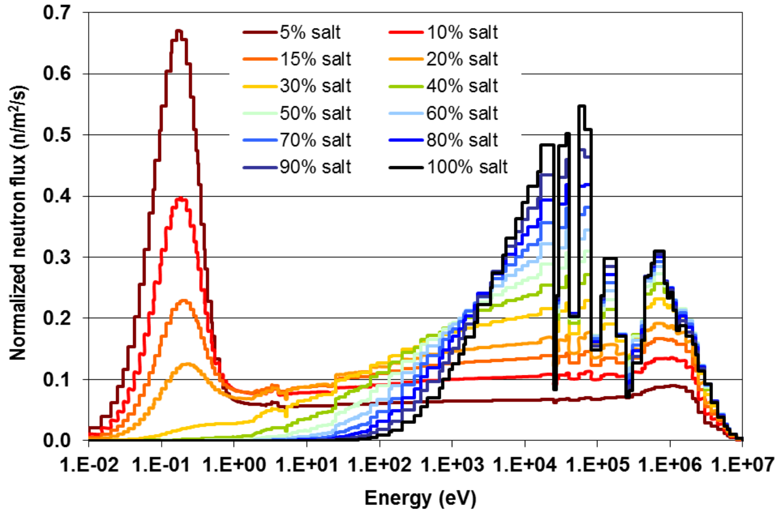


Results: 1) Excess reactivity & k_{inf}

- *Both fast (100% salt) and thermal (10-20% salt) MSR breeder are possible.*
- *However, the thermal MSR breeder require frequent FP removal*

Excess reactivity in Th-U equilibrium cycle for different spectra (salt share)

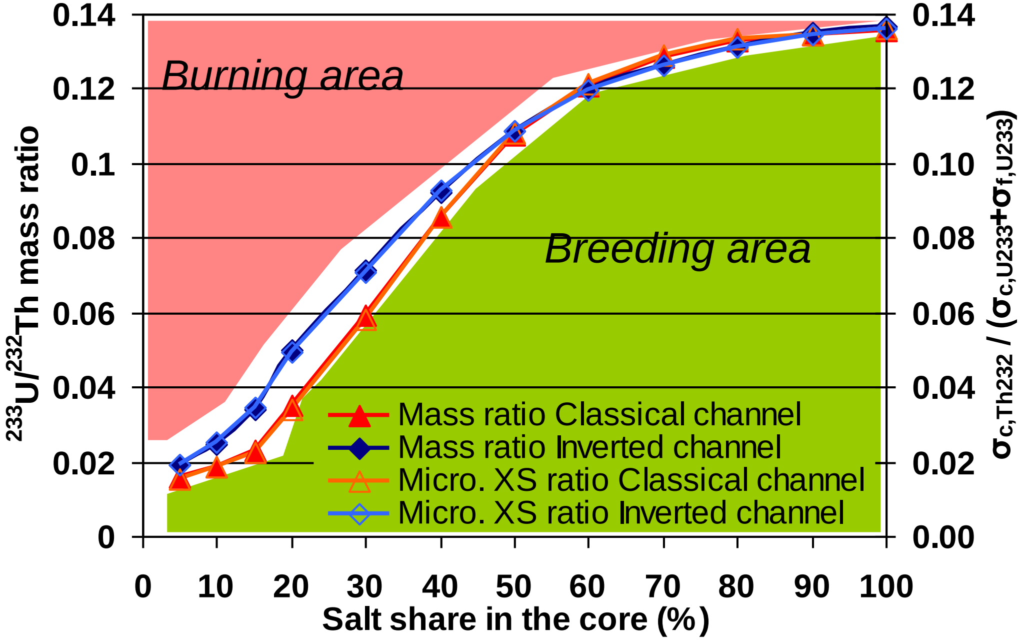




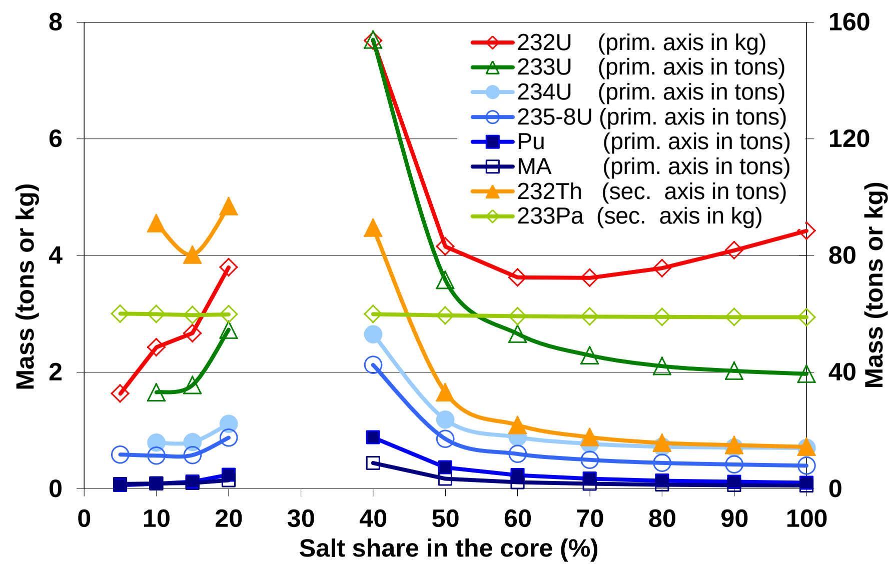
Results: 2) Relative and absolute masses

- *Relative ^{233}U mass is lower in thermal MSR breeder.*
- *The absolute ^{233}U mass is however comparable with fast breeder.*
- *Other absolute masses are also comparable, just ^{232}Th mass is 7 x higher and ^{232}U mass slightly lower.*

^{233}U/^{232}Th ratio



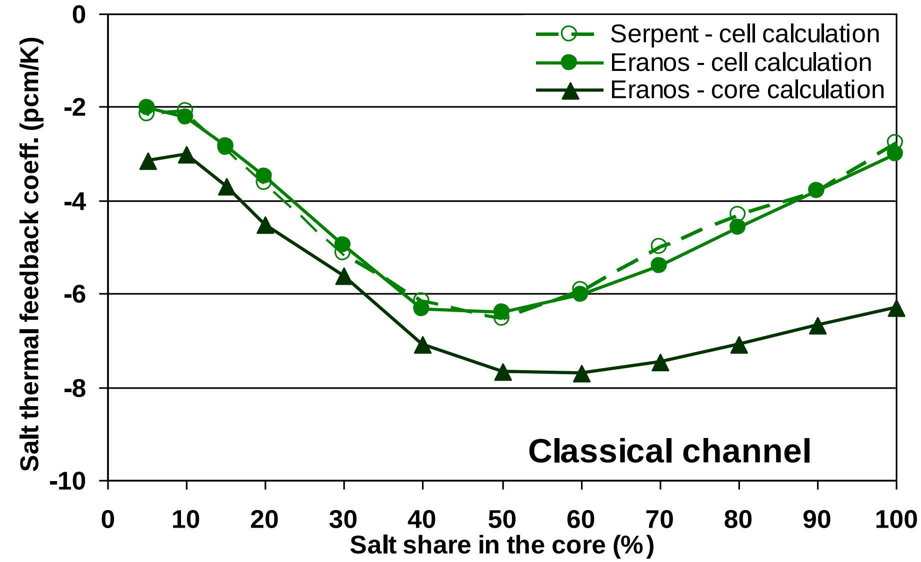
Absolute masses

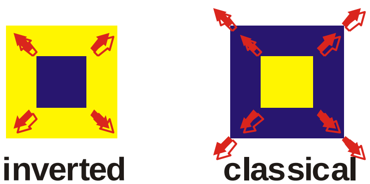


Results: 3) Thermal feedback coefficient

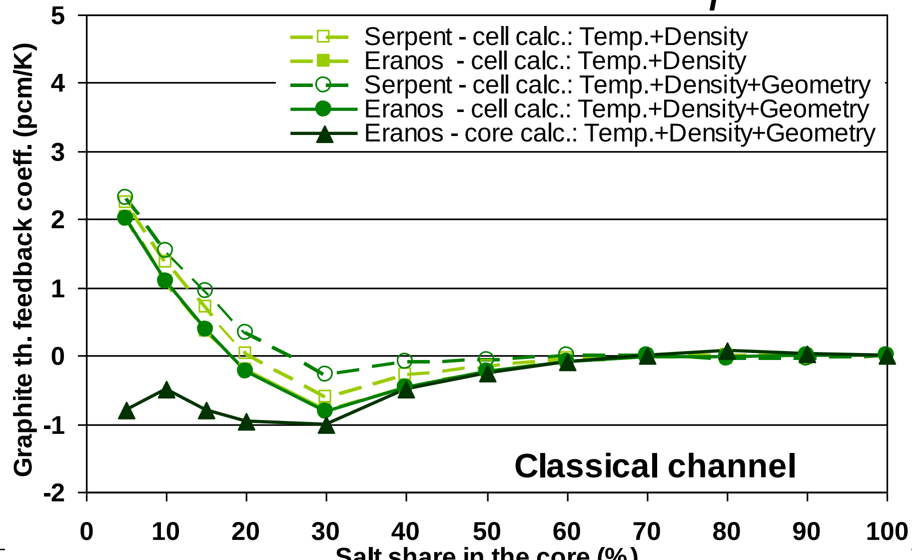
- *Salt thermal feedback coefficient is negative for all spectra.*
- *Graphite therm. feedback coefficient may be positive in thermal spectrum for some core configurations.*
- *For classical channel geometry and hastelloy reflector it was negative.*

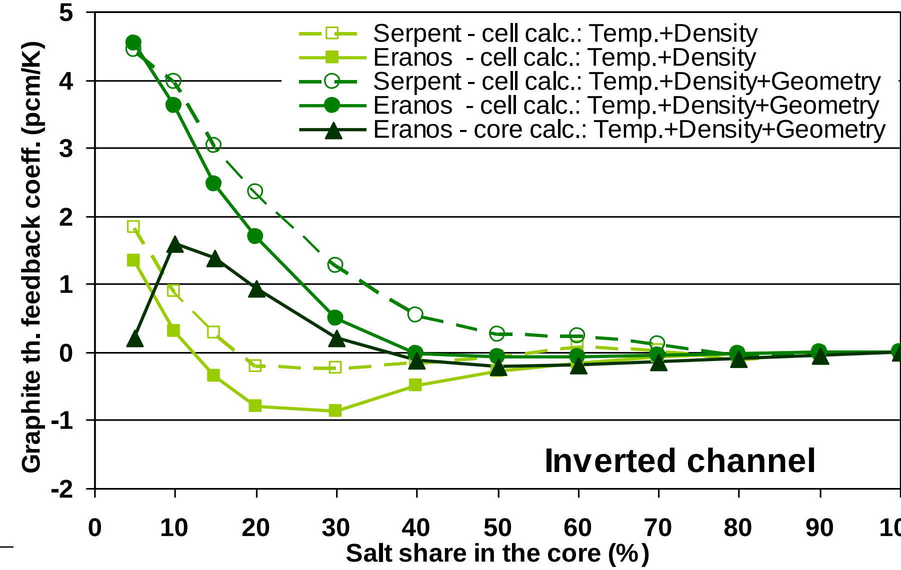
Salt thermal feedback coefficient





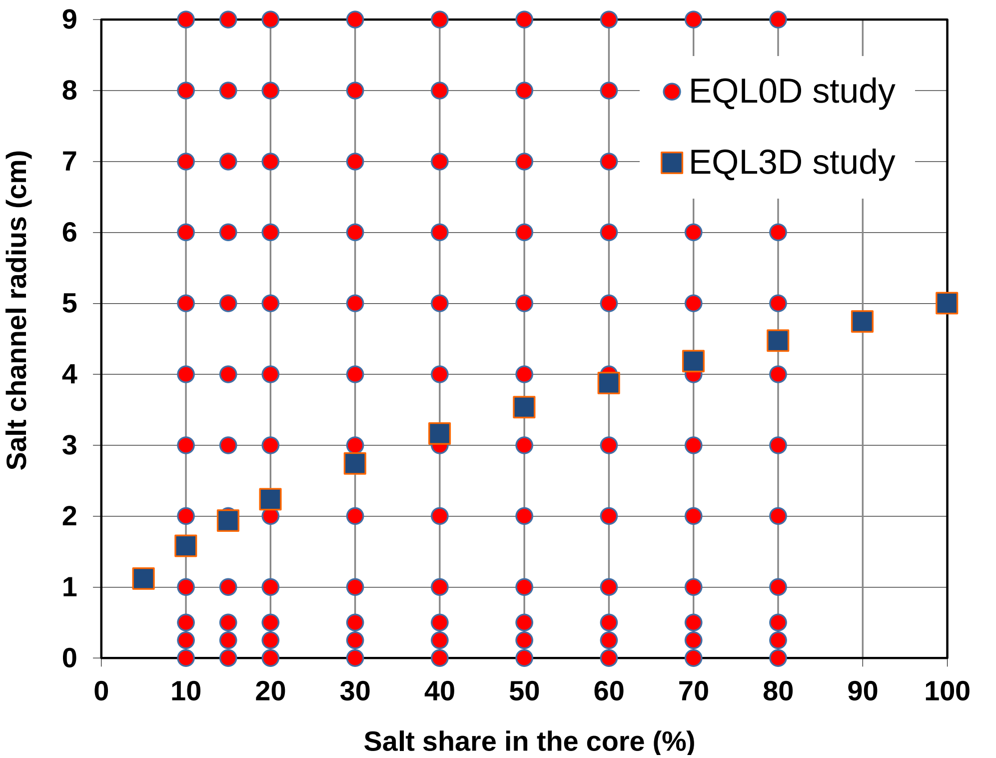
Graphite thermal feedback coefficient

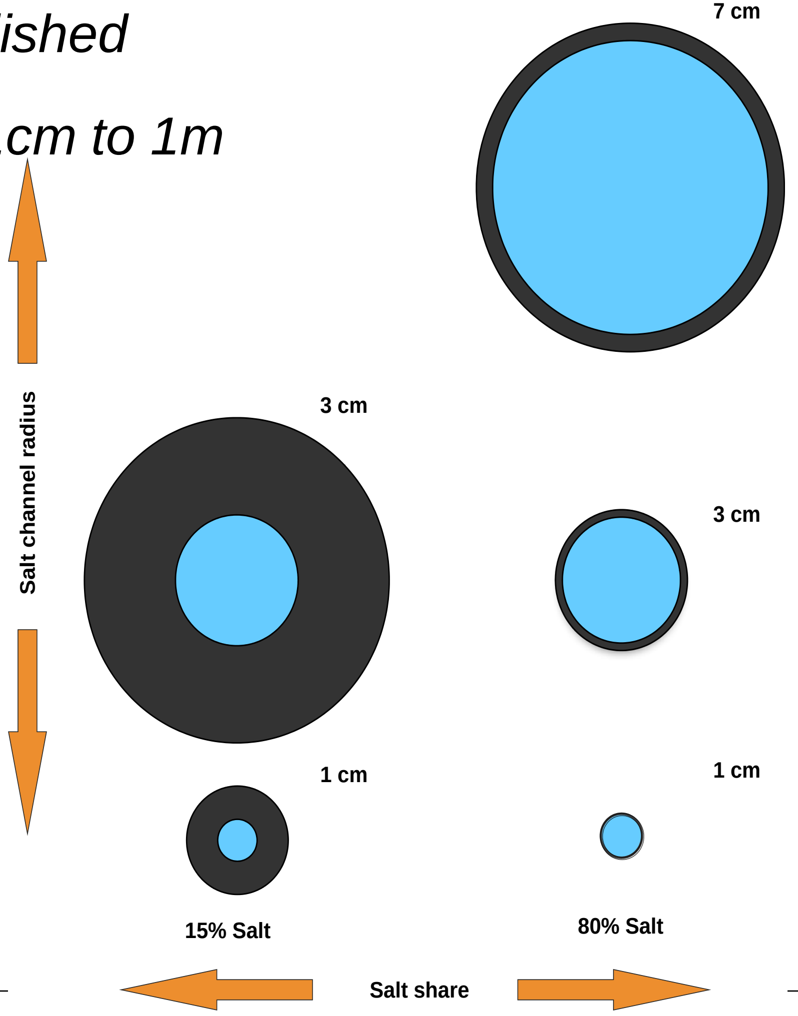




Lattice heterogeneity study with EQL0D

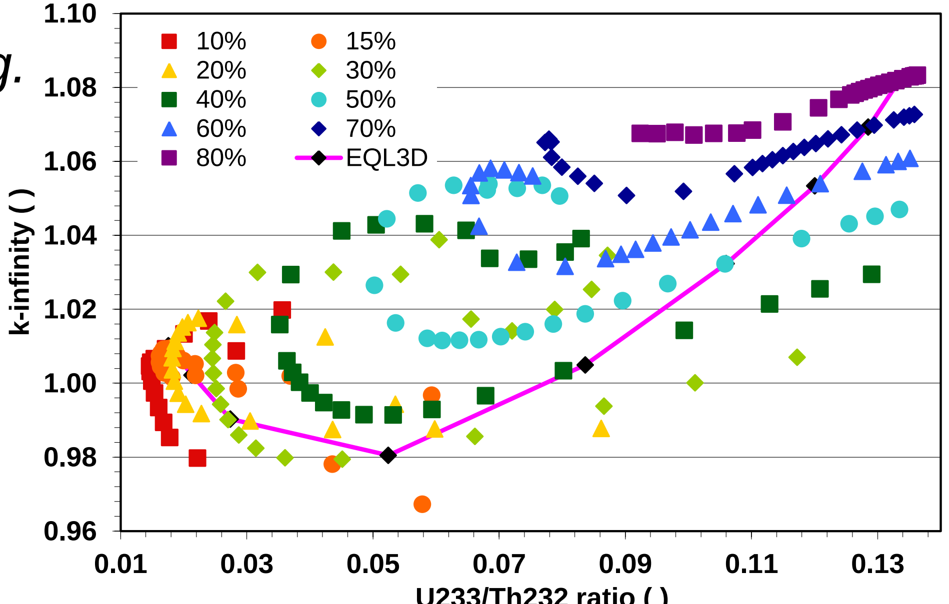
- ***Equilibrium closed cycle** was also simulated by ECCO-Matlab or Serpent-Matlab based **EQL0D** procedure on a cell level .*
- *Previous study covers only a line in 2D space; therefore lattice heterogeneity study was accomplished*
- *Salt channel radius was changed from 1cm to 1m*



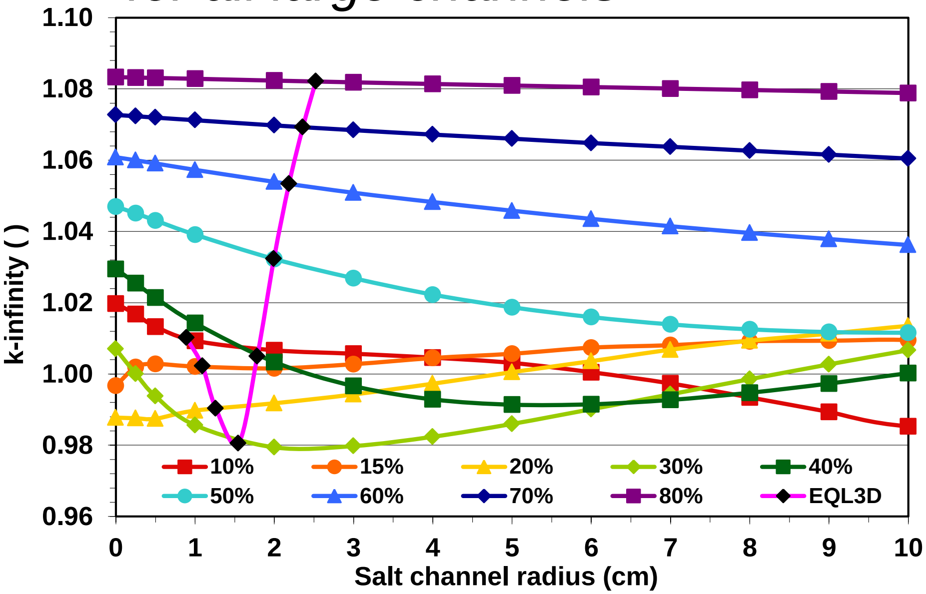


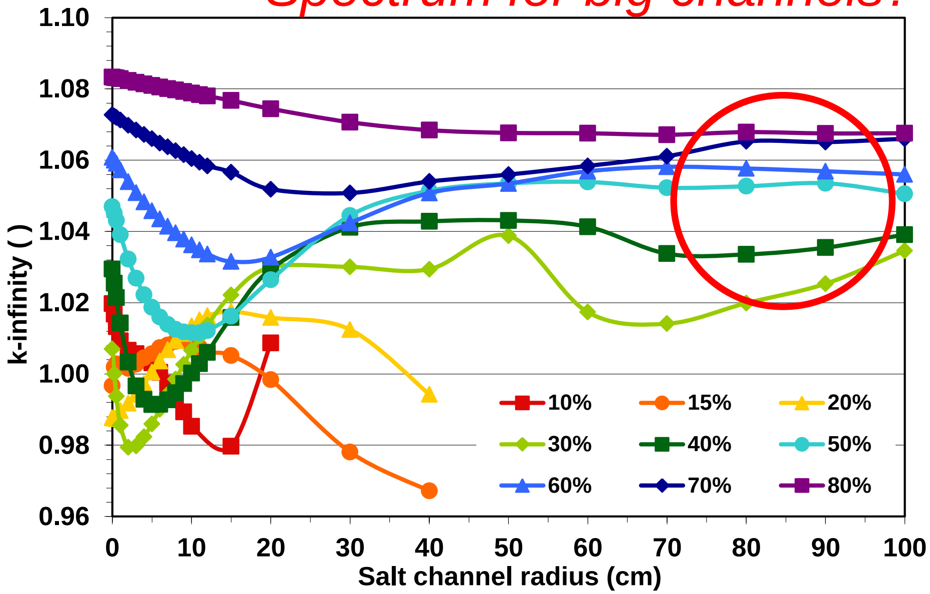
Results: 4) Lattice heterogeneity study – EQL0D

- *The heterogeneity effect is strong.*
- *EQL3D results seems arbitrary.*
- *The results are more coherent if $^{233}U/^{232}Th$ is used as a spectral index.*
- *Independently of the salt share, k_{inf} converges to similar value for all large channels*



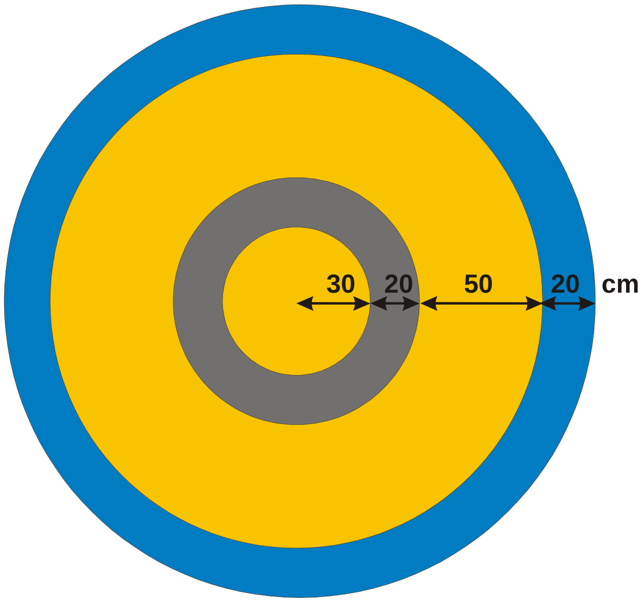
Spectrum for big channels?

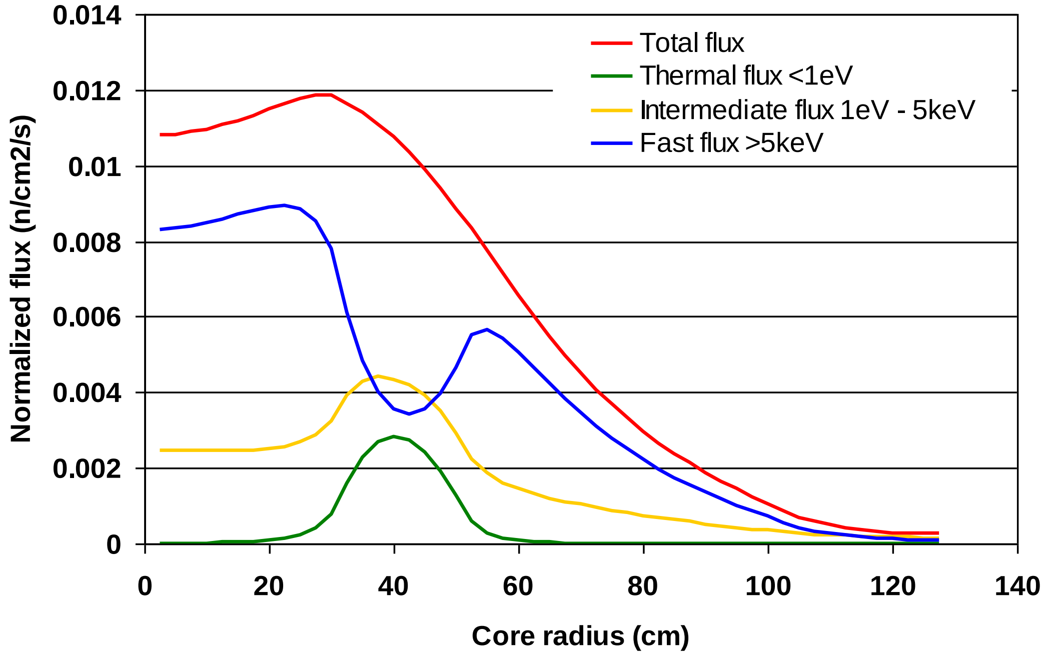




Hybrid spectra: MSR driven by central thermal zone

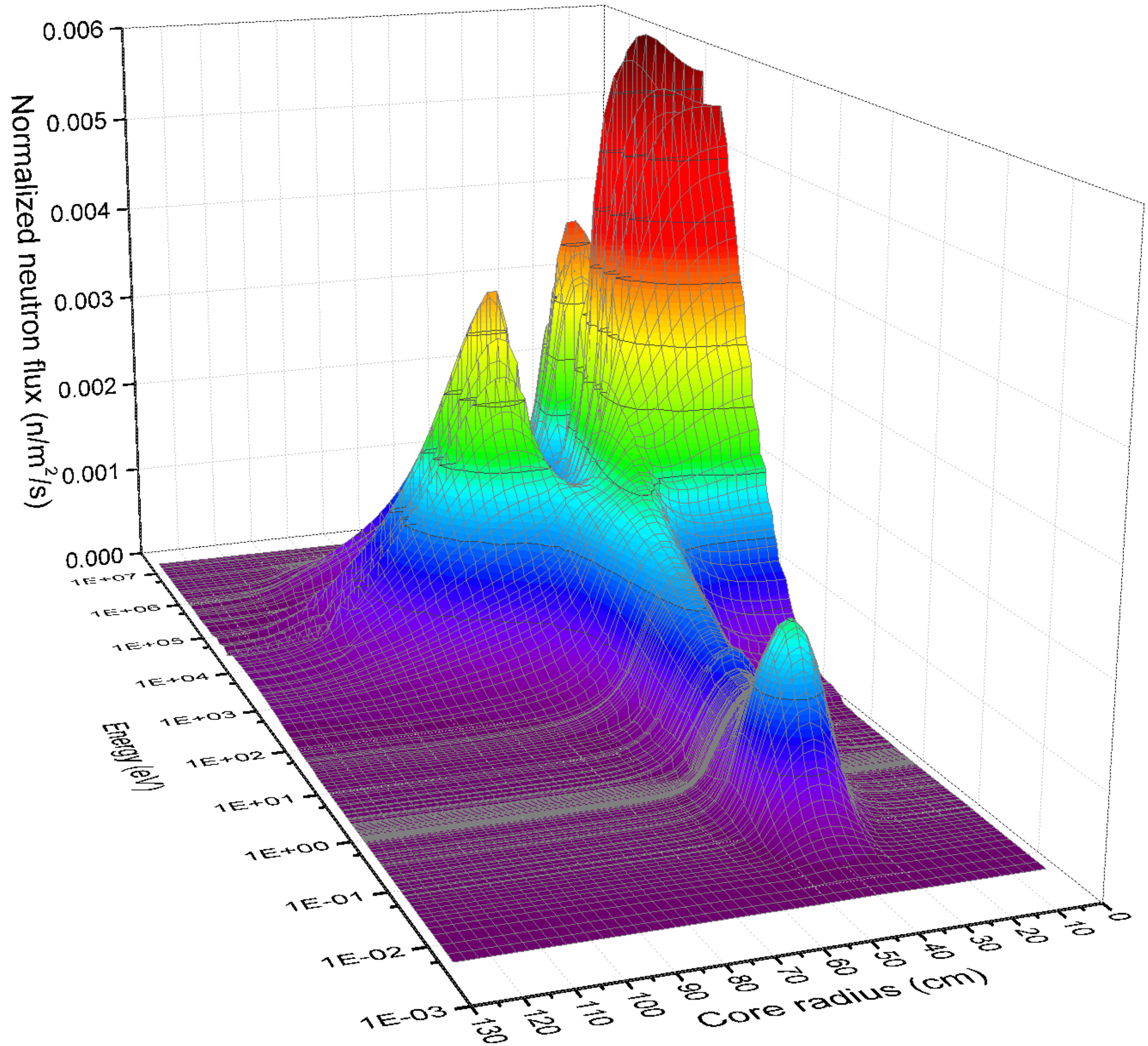
- *Central massive tube from graphite. (ring of power)*
- *It can be also central fine lattice from previous study.*
- *It is surrounded by subcritical (driven) fast zone.*
- *Advantages:*
  1) *may reduce irradiation of the hastelloy*
  2) *may reduce initial fissile material load*
  3) *may localize fission reaction in a big pool*





Example core layout:
yellow = salt
(the same salt is in both zones),
gray = graphite,
blue = hastelloy

Why to call it hybrid spectra…



MSR designing ⇔ Separation techniques selection

1) Fluoride volatilization techniques (Fluorination)

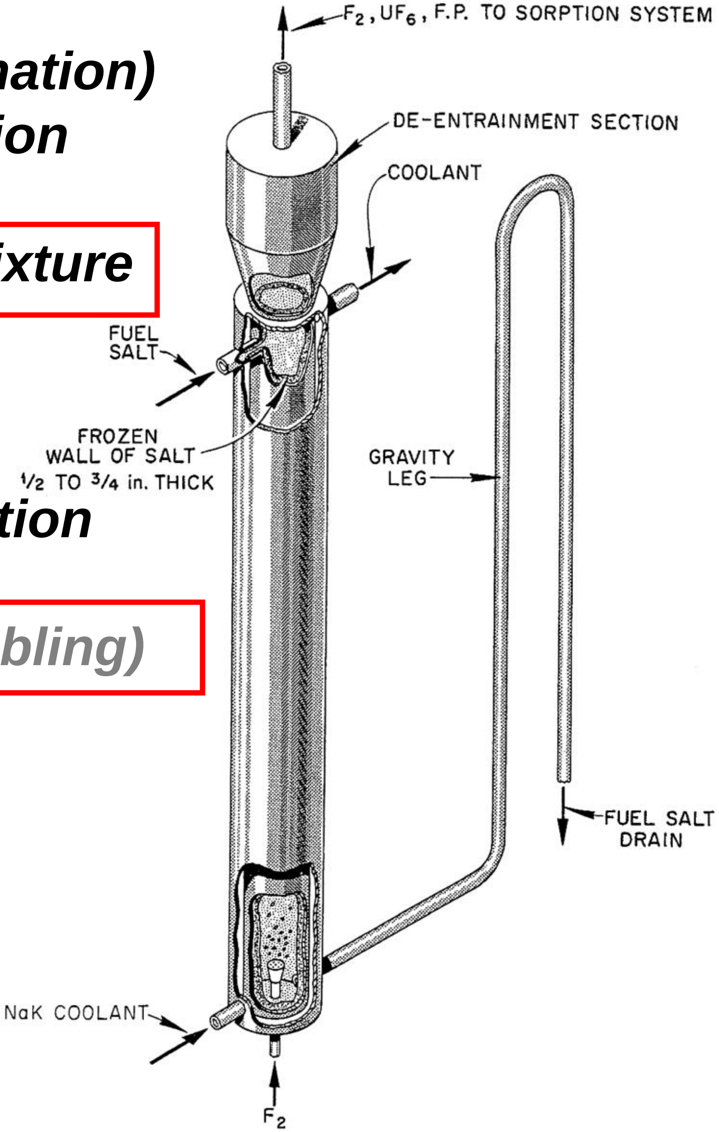
a) volatilization and fraction distillation of solid spent fuel

b) volatilization of the molten salt mixture

2) Electro-separation processes

3) Molten salt / liquid metal reductive extraction

4) Gaseous and volatile FP removal (He bubbling)



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New idea: "Recycling without carrier salt reprocessing"

The aim of almost all classical reprocessing schemes is to remove FP and keep everything else in the core.

Unfortunately, FP can be usually removed as one of the last components *(...and it may require all previously named techniques)****.***

Disadvantage, at least form the classical point of view, is that the uranium is the first to be removed by the volatilization technique.

Lets make from the disadvantage an advantage!

Lets recycle just uranium and throw away the rest…!?

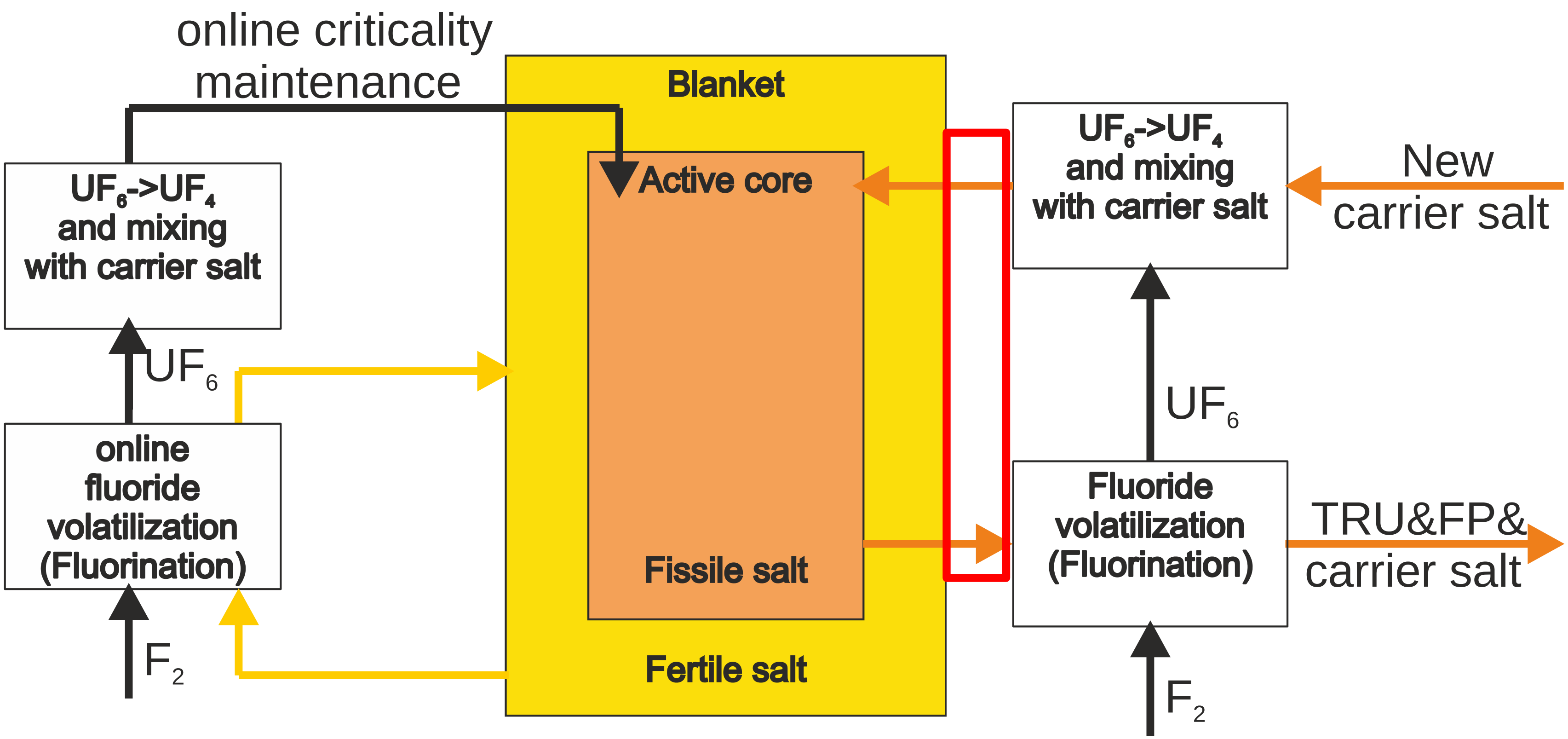
The "rest" may be reprocessed with long delay and cleaned salt reused in the same or in another reactor.

Carrier salt without enriched ^{7}Li, e.g. NaF-BeF_2, may be needed; however, ^{7}Li price may be acceptable – C. Forsberg 2013:

Future Cost of Isotopically Separated Lithium for PWRs, Fluoride-salt-cooled High-temperature Reactors (FHRs) and Lithium Batteries
American Nuclear Society Annual Meeting Transactions Paper: 8712; Washington D.C., November 10-14, 2013

New idea: "Recycling without carrier salt reprocessing"

Illustration for two-fluid fast MSR

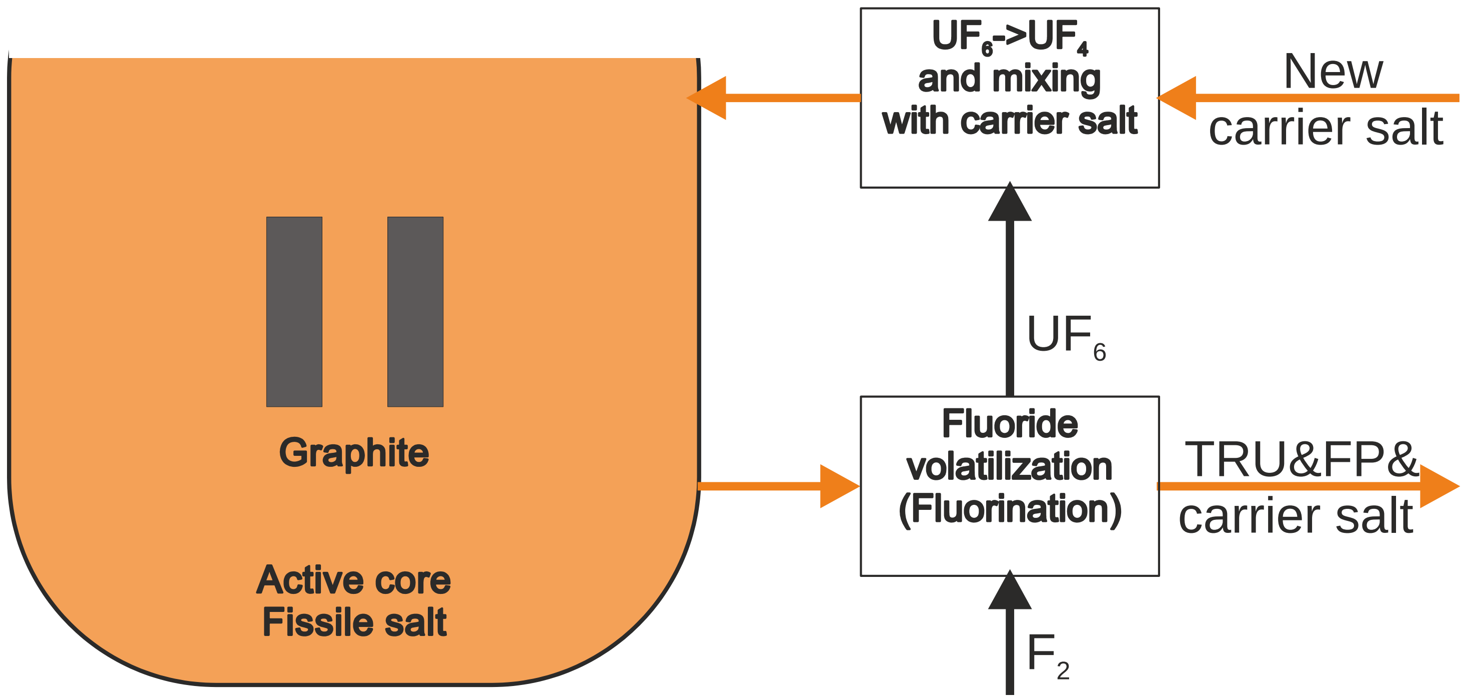


The salt exchange can be:

- *Online*
- *Batch-wise or*
- *Once in a time whole salt volume :*
  every few months or years (replacement together with the hastelloy.?)

New idea: “Recycling without carrier salt reprocessing”

Illustration for single-fluid hybrid spectra pool MSR



What will be possibly left in the salt?

Equilibrium U233 chain

RR: total reaction rate with neutrons relative to U233 (without n,2n).

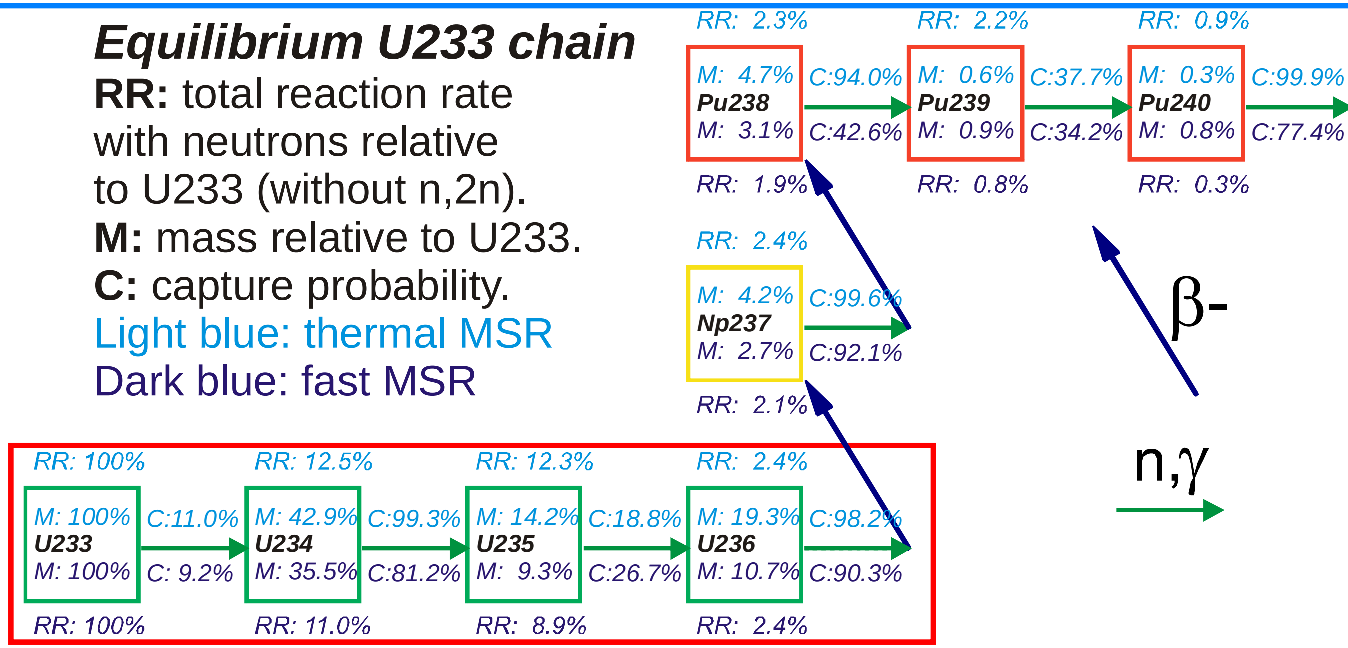
M: mass relative to U233.

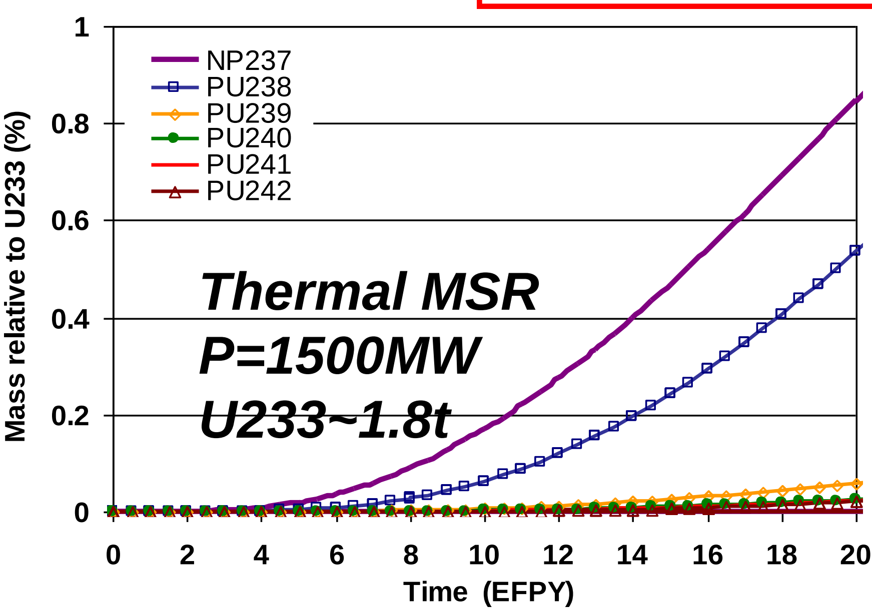
C: capture probability.

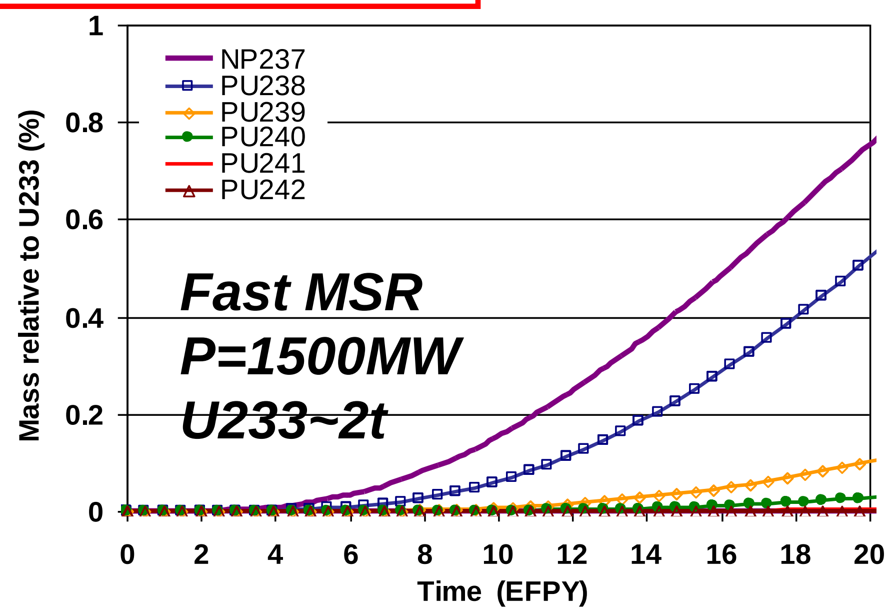
Light blue: thermal MSR

Dark blue: fast MSR

U recycling by volatilization







Several ongoing steps and outlook of the project

- ***1) Students' work:***

Two new MSc students:

- *MSR heat exchangers simulation*
- *Blanket salt simulation*

New PhD student:

- *Designing of small modular MSR*
- *Development of multi-parametric optimization tool for MSR core designing*

- *2)* ***Planned studies:***

Evaluation of the ideas:

- *Simplified uranium recycling without reprocessing of the carrier salt.*
- *Hybrid spectra MSR with central thermal zone surrounded by subcritical fast zone.*

Evaluation of pool type solution:

- *Pool type MSR design with passive decay heat removal from the pool walls with possible corrosion protection (freezing).*

Thank you

Two very different schools of reactor design have emerged since the first reactors were built. One approach, exemplified by solid fuel reactors, holds that a reactor is basically a mechanical plant; the ultimate rationalization is to be sought in simplifying the heat transfer machinery.

The other approach, exemplified by liquid fuel reactors, holds that a reactor is basically a chemical plant; the ultimate rationalization is to be sought in simplifying the handling and reprocessing of fuel.

R.C. Briant & Alvin Weinberg, “Molten Fluorides as Power Reactor Fuels,” *Nuc. Sci. Eng*, 2, 797-803 (1957).