GEN IV International Forum℠

COMPARISON OF 16 REACTORS NEUTRONIC PERFORMANCE IN CLOSED TH-U AND U-PU CYCLES

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Meet the Presenter

Dr. Jiri Krepel, is a senior scientist in Advanced Nuclear Systems group of Laboratory for Scientific Computing at Paul Scherrer Institut (PSI) in Switzerland. He earned his PhD degree in 2006 from CTU Prague / Helmholtz-Zentrum Dresden-Rossendorf for the thesis entitled Dynamics of Molten Salt Ractors (MSR).

At PSI, he is responsible for fuel cycle analysis and related safety parameters of Gen IV reactors. He is coordinator of the PSI MSR research and representative of Switzerland at the GIF MSR project. He has experience in the neutronics of liquid-metal and gas-cooled fast reactors and in neutronics and transient analysis of thermal and fast MSRs.

He participated in several national and international R&D programs: MOST, ELSY, EUROTRANS, GCFR, ESFR, GoFastR, LEADER, PINE, ESNII+, SAMOFAR, ESFR-SMART, SAMOSAFER.

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   b) Closed cycle ≠ breeding
   c) Open cycle ≠ burning
   d) Transition to equilibrium

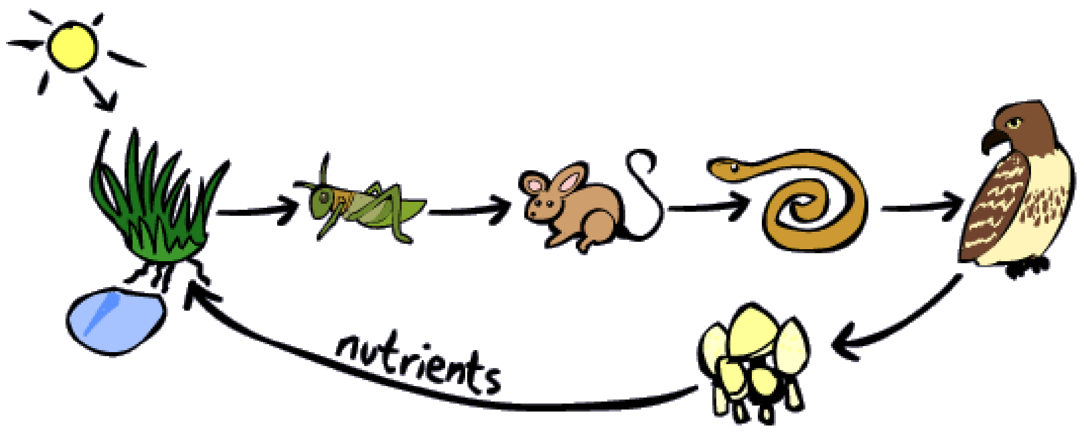
1. Closed cycle ⇔ sustainability ⇔ resources

What is Closed Fuel Cycle?

- Fuel cycle, in general, is a process chain to obtain energy.
- In closed cycle some substances (re)cycle and does not leave the cycle.

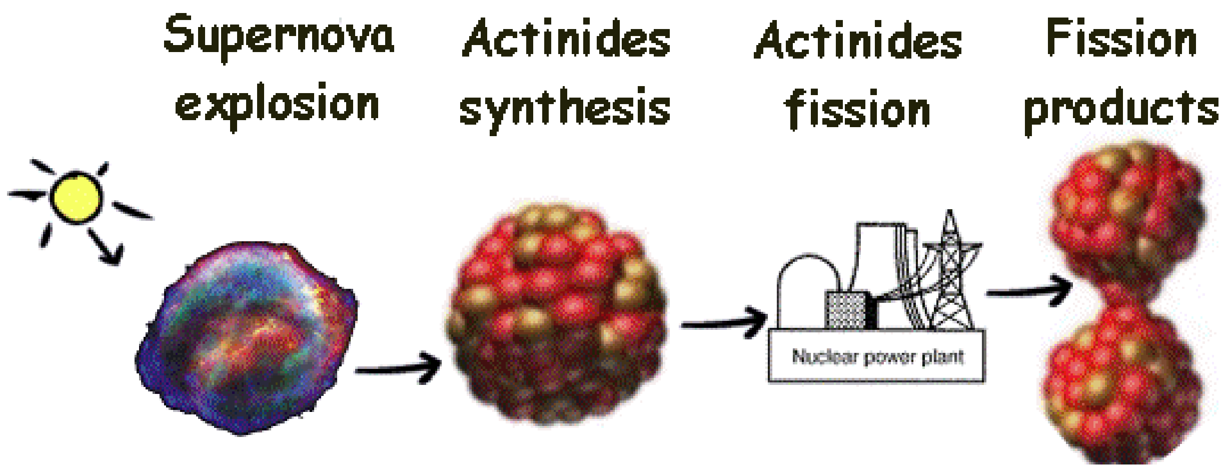
“Closed fuel cycle” in nature:

The actual waste is He and elements up to Fe.



“Open” nuclear fuel cycle:

The actual waste are e.g. lanthanides.



sheppardsoftware.com/content/animals/kidscorner/foodchain/foodchain2.htm

Nuclear Fuel Cycle Parts:

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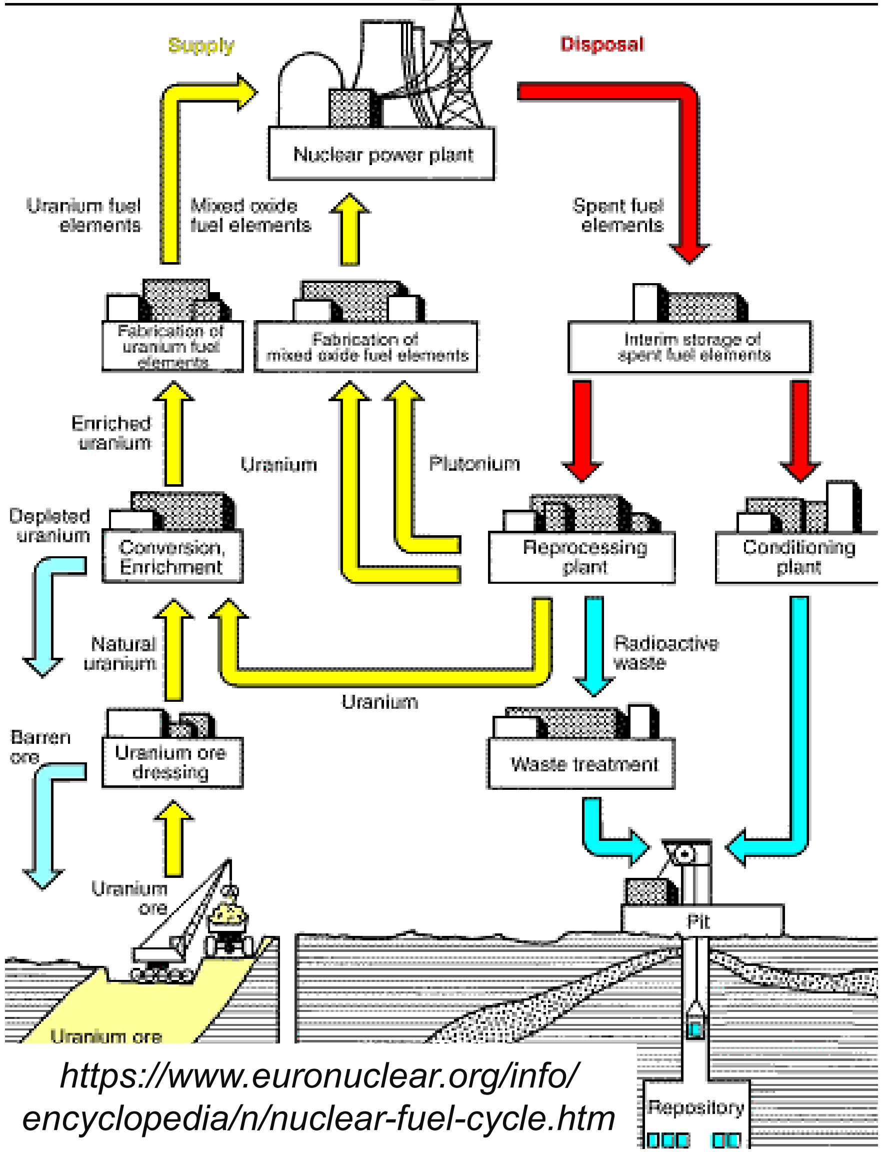
Front end:	Back end:
○ Exploration	○ Interim storage
○ Mining	○ Transportation
○ Milling	○ Reprocessing
○ Conversion	○ Partitioning
○ Enrichment	○ Transmutation
○ Fabrication	○ Waste disposal

This presentation focus on the reactor physics aspects of irradiation and recycling of actinides.

Closed cycle = closed for actinides.



https://www.euronuclear.org/info/encyclopedia/n/nuclear-fuel-cycle.htm

Closed Cycle X Sustainability

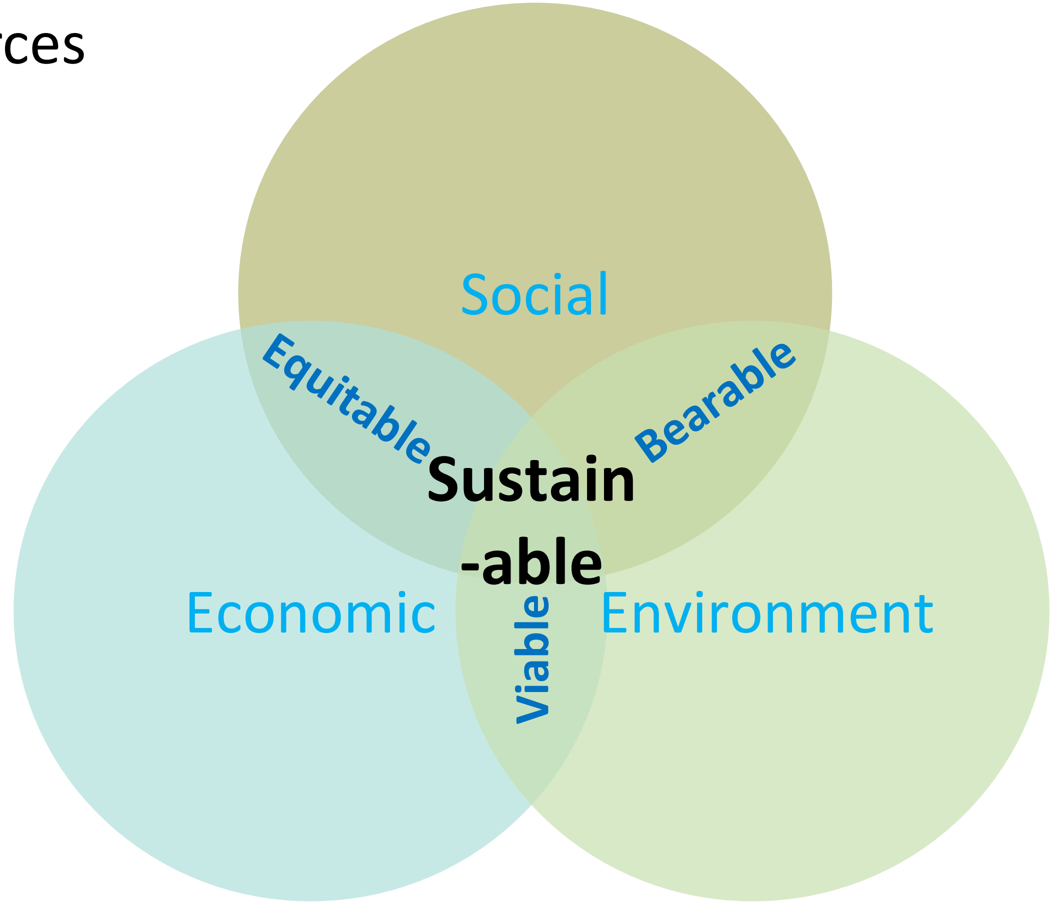
- Sustainability from general perspective has three pillars:

  I. **Environment:** sustainable rate of natural resources consumption without damage to environment.

  II. **Economic:** efficient and responsible use of resources to profit in long term.

  III. **Social:** maintaining social well being in a long term

- **Sustainable**: viable & equitable & bearable.
- **Closed cycle** can potentially contribute to all three pillars of sustainability.



http://www.circularecology.com/sustainability-and-sustainable-development.html#.XOUBmWeP5Hg

Sustainability as Gen-IV Goals

- **Sustainability-1**
  Generation IV nuclear energy systems will provide sustainable energy generation that meets clean air objectives and provides **long-term availability** of systems and **effective fuel utilization** for worldwide energy production.

- **Sustainability-2**
  Generation IV nuclear energy systems will **minimize and manage** their **nuclear waste** and notably **reduce the long-term stewardship burden**, thereby improving protection for the public health and the environment.

- These two goals relate mainly to
  Environmental sustainability: **High resources utilization & waste minimization**

- **Economical sustainability:** clear life-cycle costs and financial risk comparable to LWR.

- **Social sustainability:** elimination of offsite emergency response and **waste minimization**.

(Does proliferation resistance belong to social sustainability…?)

https://www.gen-4.org/gif/jcms/c_9502/generation-iv-goals

Our resources are actinides

(fuel for nuclear cycle)

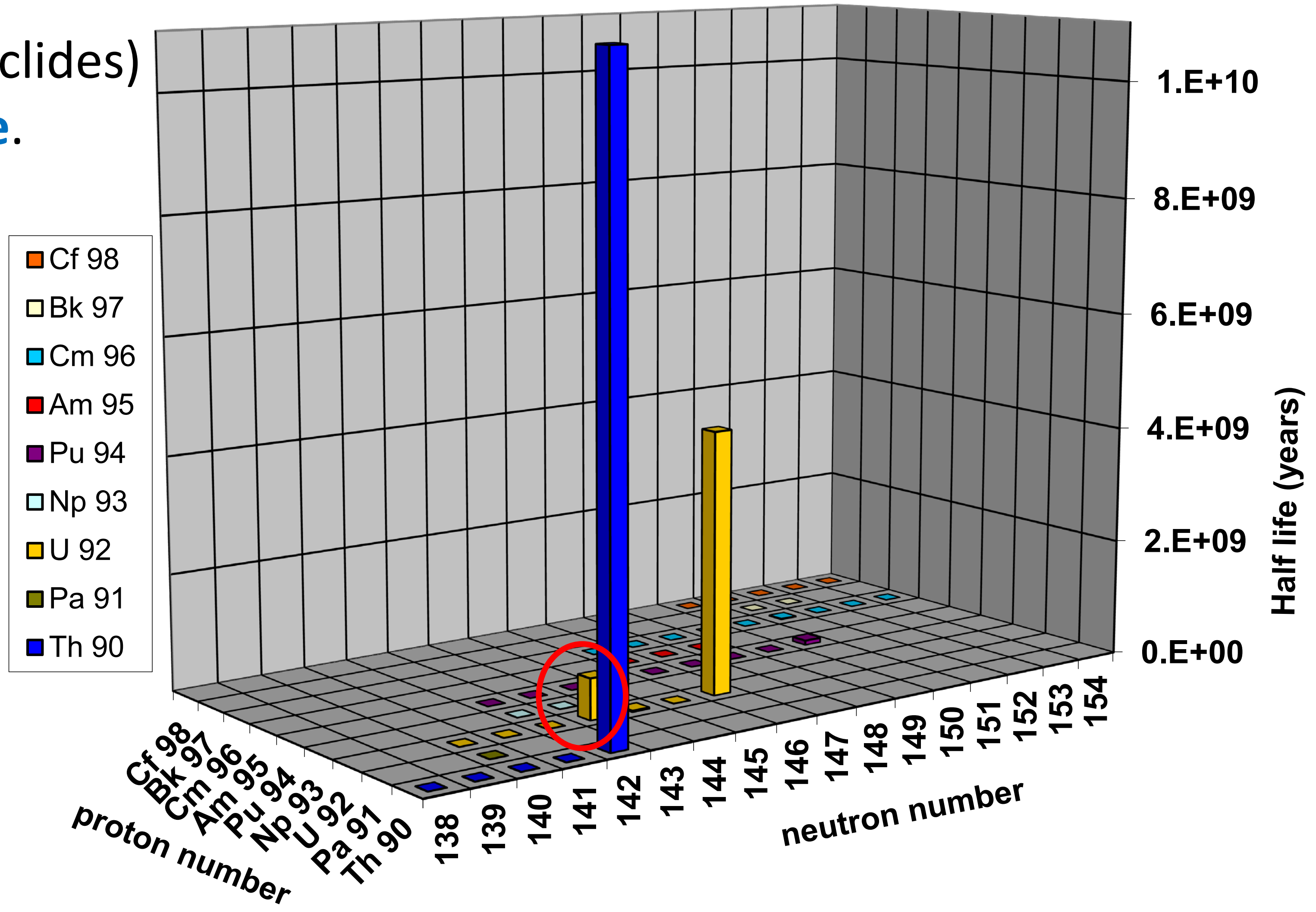
- Actinides, the heaviest elements (nuclides) in the periodic table, **are all unstable**.
- But three of them have relatively long half-life:

  ^{235}U: 0.7 x10^{9} years

  ^{238}U: 4.5 x10^{9} years

  ^{232}Th: 14 x10^{9} years

- Accordingly:
  they are still present in nature as primordial actinides.
- ^{235}U, the only fissile primordial nuclide, has the shortest half-live and its **reserves** are the **smallest**.

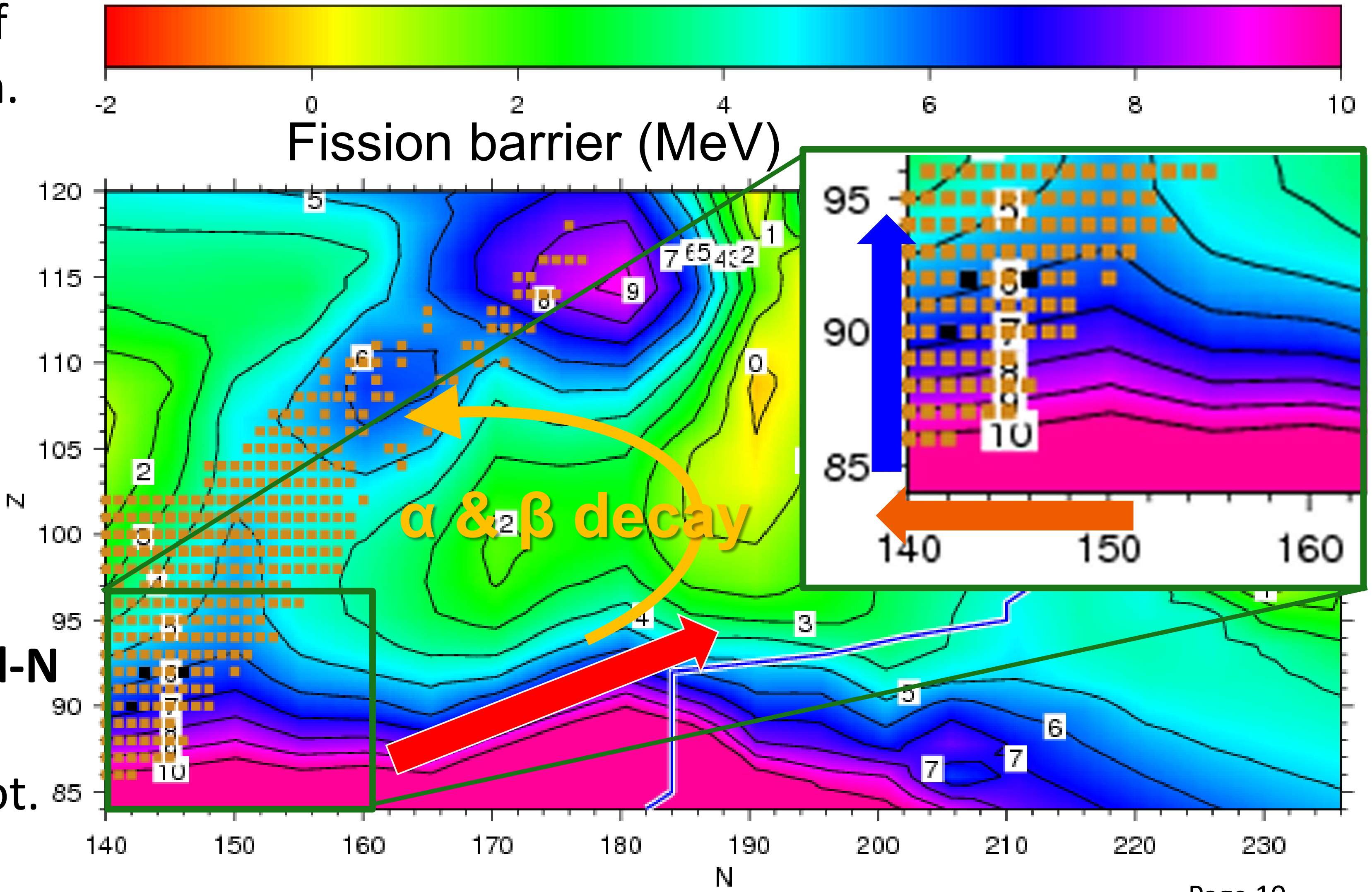


Actinides half-life in linear scale.

Actinides origin by Supernova:
rapid neutron capture X fission barrier

- Fission barrier along the path of **R-process** (in supernova) is high.
- The fission barrier **in our fuel area** is lower:

  when more protons
  are closer to each other.
- Fissile isotope means that **barrier < binding energy** of the interacting neutron.
- Binding energy is higher for **odd-N isotopes**; thus ^{233}U, ^{235}U, ^{237}U are fissile and ^{234}U, ^{236}U ^{238}U not.



http://inspirehep.net/record/1122713/plots
Have Superheavy Elements been Produced in Nature? - Petermann, I. et al. Eur.Phys.J. A48 (2012) 122 arXiv:1207.3432 [nucl-th]

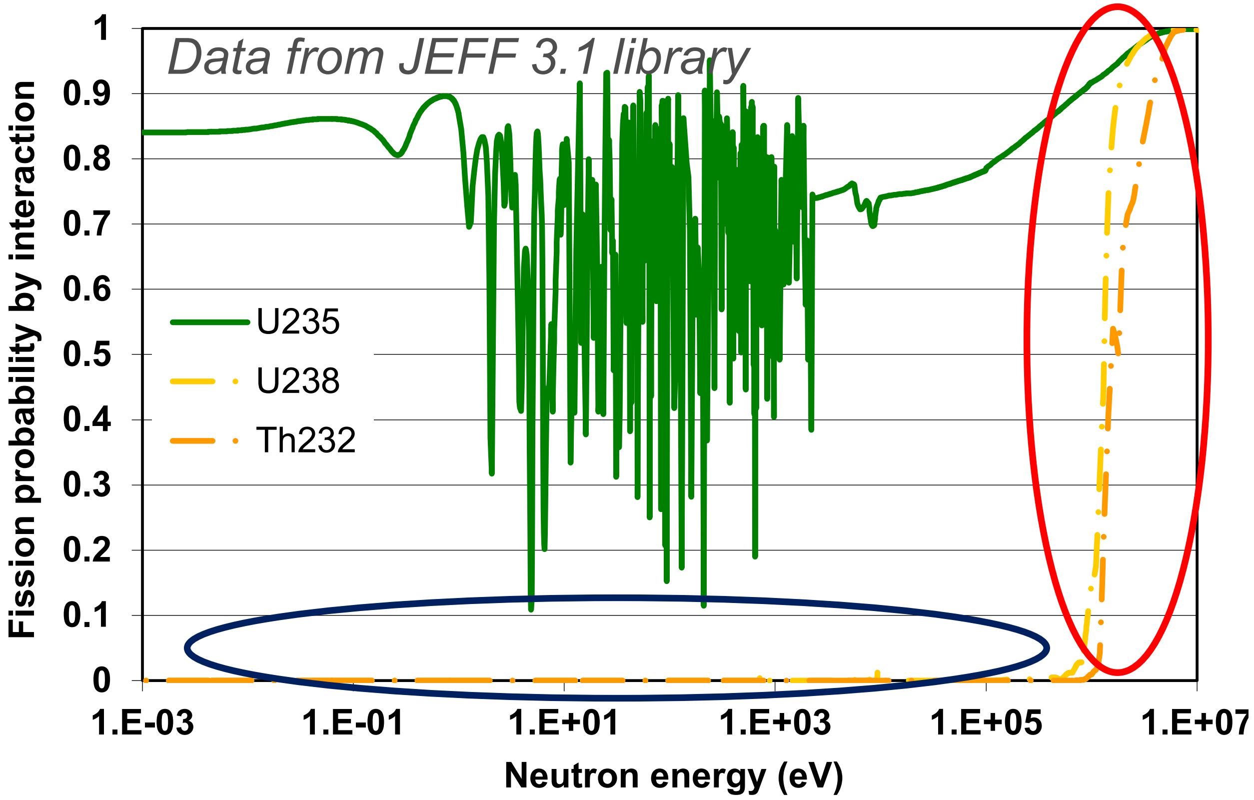
Primordial Actinides

- Primordial **actinide** reserves, as a Supernova product, are **not renewable!**
- ^{235}U
- ^{238}U
- ^{232}Th

https://en.wikipedia.org/wiki/Thorium over 3x more abundant

Reserves seems to be correlated with half-lives:
^{235}U: 0.7 x10^9 years
^{238}U: 4.5 x10^9 years
^{232}Th: 14 x10^9 years

Relative size (surface) represents masses.



- **^{235}U** is the only **primordial fissile nuclide** and it is now the main working horse.
- **^{232}Th** and **^{238}U** are **fissionable** by fast neutrons (^{238}U up to 10x more than ^{232}Th).
- Both of them mainly capture neutrons, what leads to their **transmutation**.

2. Synthetic actinides ⇔ waste

Synthetic Actinides

$$ {}^{235}_{92}U \ (\text{odd-n}) + {}^{1}_{0}n \longrightarrow {}^{236}_{92}U \ (\text{even-n}) + {}^{1}_{0}n \longrightarrow {}^{237}_{92}U \ (\text{odd-n}) \xrightarrow{\beta^{-}\ 6.7\,day} {}^{237}_{93}Np \ (\text{even-n}) + {}^{1}_{0}n \rightarrow \ldots $$

$$ {}^{232}_{90}Th \ (\text{even-n}) + {}^{1}_{0}n \longrightarrow {}^{233}_{90}Th \ (\text{odd-n}) \xrightarrow{\beta^{-}\ 22\,\min} {}^{233}_{91}Pa \ (\text{even-n}) \xrightarrow{\beta^{-}\ 27\,day} {}^{233}_{92}U \ (\text{odd-n}) + {}^{1}_{0}n \rightarrow \ldots $$

$$ {}^{238}_{92}U \ (\text{even-n}) + {}^{1}_{0}n \longrightarrow {}^{239}_{92}U \ (\text{odd-n}) \xrightarrow{\beta^{-}\ 24\,\min} {}^{239}_{93}Np \ (\text{even-n}) \xrightarrow{\beta^{-}\ 2.4\,day} {}^{239}_{94}Pu \ (\text{odd-n}) + {}^{1}_{0}n \rightarrow \ldots $$

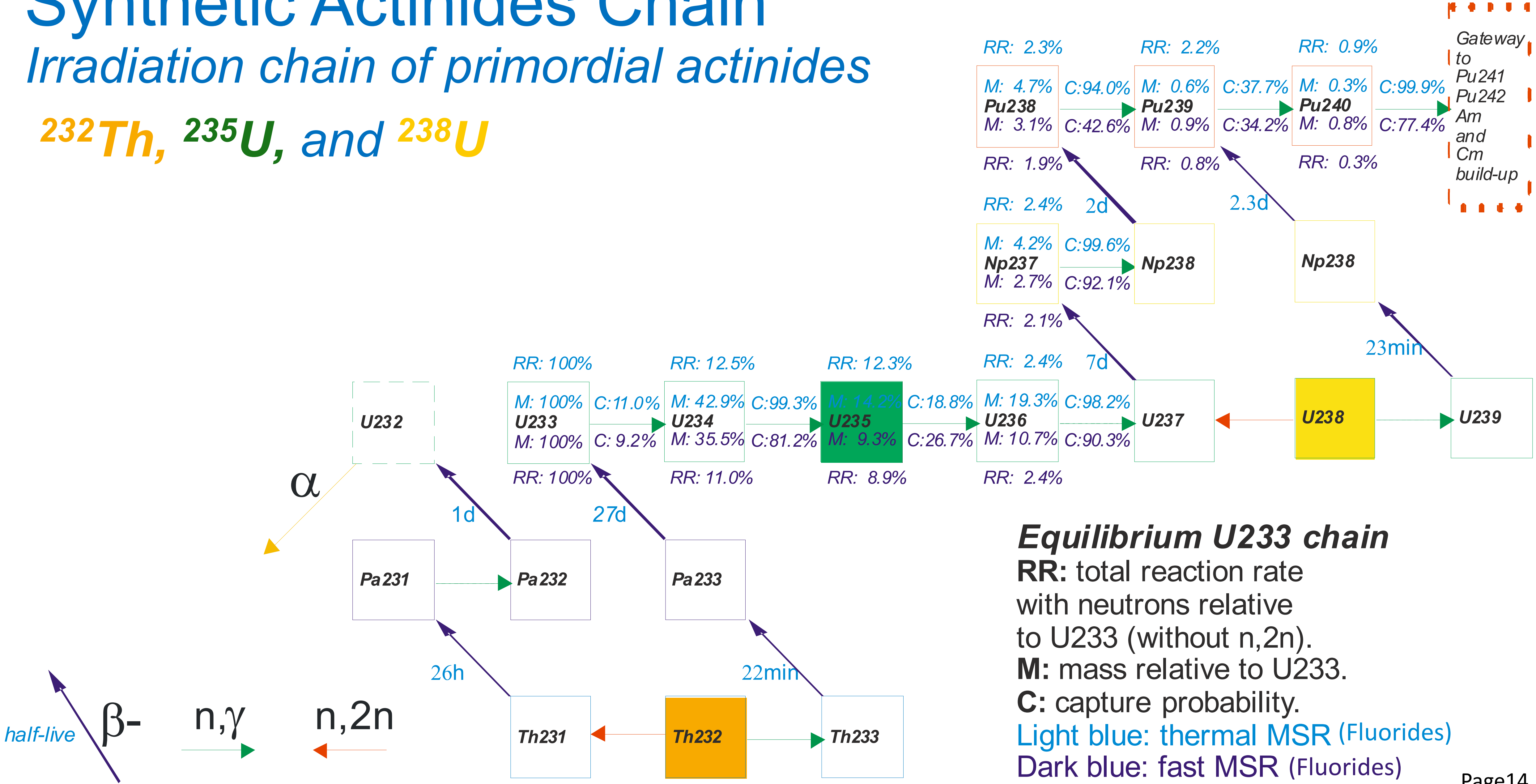
Neutron absorption by an actinide nuclide usually results in:

- **Burning** = actinide fission.
- **Breeding** = transmutation increasing fission probability (even -> odd n).
- **Parasitic neutron capture** = transmutation decreasing fission probability (odd -> even n).

Synthetic Actinides Chain

Irradiation chain of primordial actinides

^{232}Th, ^{235}U, and ^{238}U



Equilibrium U233 chain

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

M: mass relative to U233.

C: capture probability.

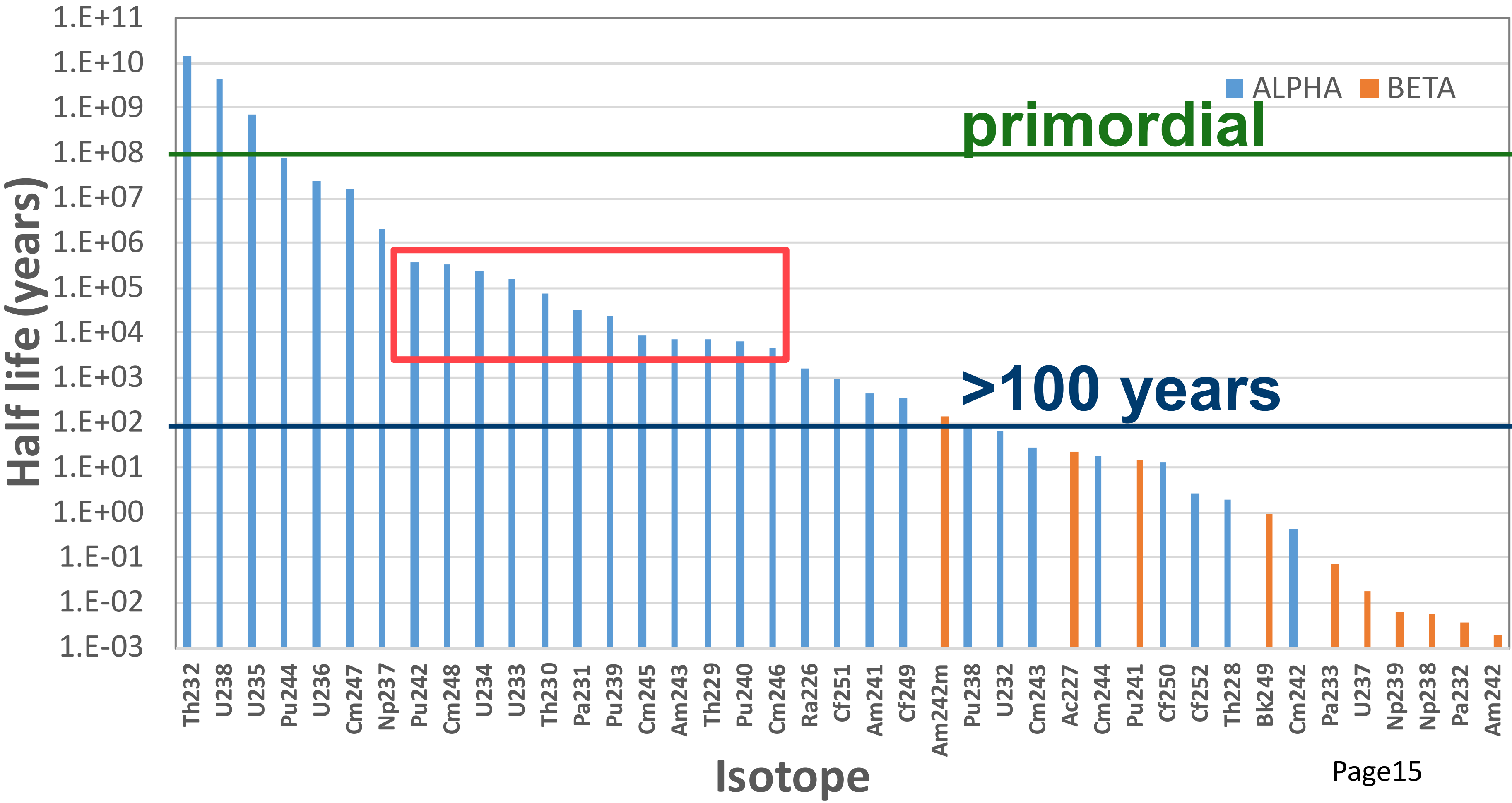
Light blue: thermal MSR (Fluorides)

Dark blue: fast MSR (Fluorides)

Actinides as Unwanted Waste

- Primordial actinides have long half-live.
- Half-lives of synthetic actinides are **too short** for them to be **primordial**.
- At the same time, they are **too long** to **disappear swiftly** once originated.
- Long-term stewardship burden is caused by actinide isotopes with **"medium" half-life.**
- Plutonium isotopes are dominating. (e.g. Pu 239, 240, 242)
- However, actinides are decaying in chains, e.g.:

Fast->Medium->Long: Cm243->Pu239->U235



3. Equilibrium ⇔ Bateman matrix eigenstate

Sustainability ↑ ⇔ Burnup ↑

- Actinides, as a **fuel** for the **nuclear cycle**, are **not renewable**.
- Sustainability, from reactor physics perspective, has two components:

  I. High resources utilization, we should **fission** at best **all primordial actinides**.

  II. Waste minimization, we should **minimize synthetic actinides** amount in the **waste**.

- In ideal case, actinides should not leave the reactor:
- In reality, they must regularly leave the reactor and sustainability can be increased by two option:

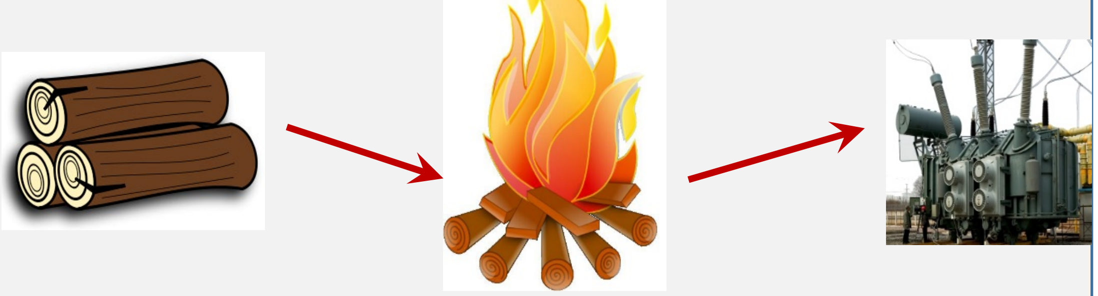
  I. Higher burnup in **open** fuel **cycle**

  II. Actinides **recycling** in **closed cycle**

  (it also leads to higher burnup)

Emissions (FPs) should be at best removed, keeping fuel in the core.

Fuel: ^{238}U or ^{232}Th

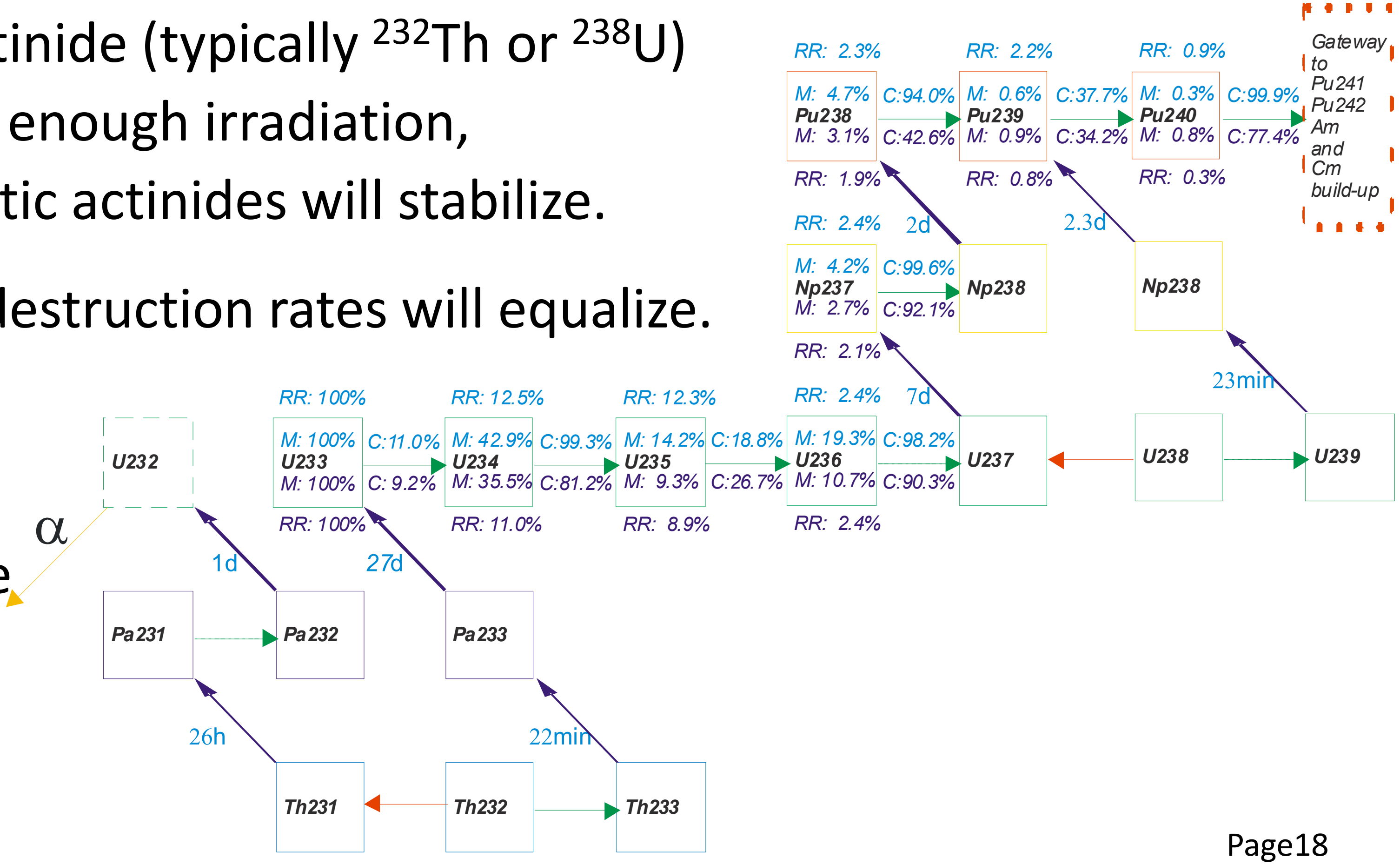


Reactor “catalyzed” by ^{239}Pu or ^{233}U

Higher burnup => Equilibrium

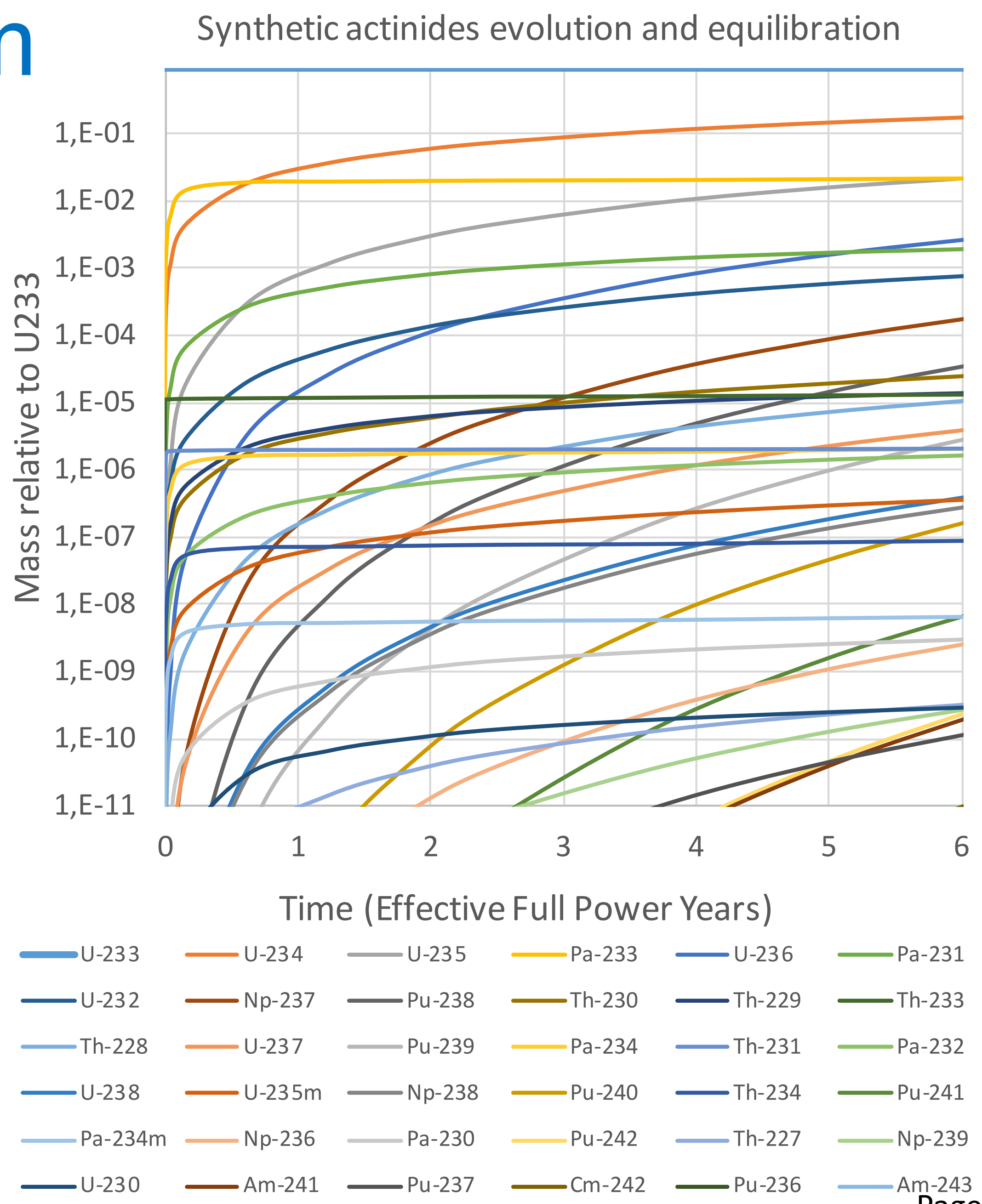
- Both options to increase sustainability, **higher burnup** and **actinides recycling**, result in **longer irradiation** of respective actinide vector.
- If the mass of major (primordial) actinide (typically ^{232}Th or ^{238}U) is kept reasonably constant for long enough irradiation, the compositions of induced synthetic actinides will stabilize.
- For each isotope, the creation and destruction rates will equalize.
- **Example 1**:

  In **LWR** fuel the mass of ^{238}**U** is practically **constant** and the ^{239}**Pu** amount is **equalized** after **2 or 3 years** of irradiation.



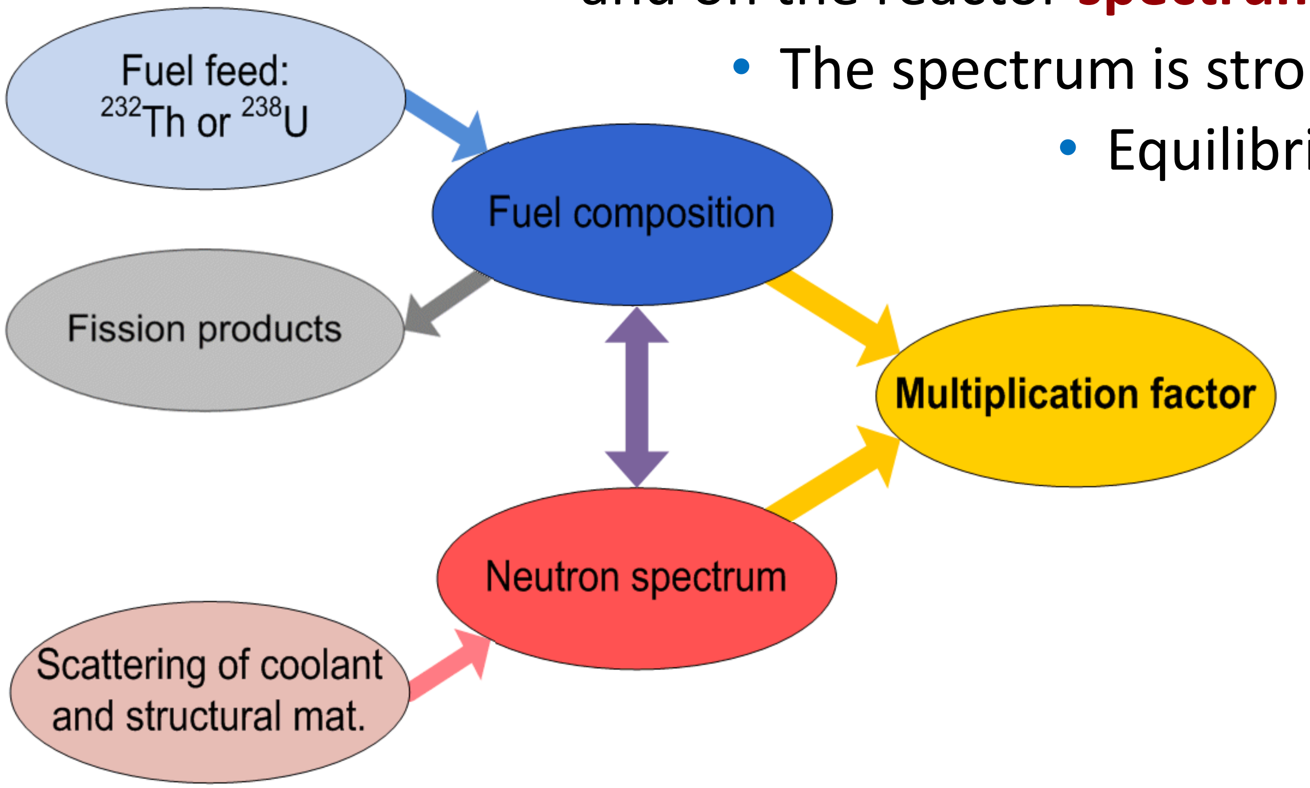
Higher Burnup => Equilibrium

- **Example 2:** Irradiation of fresh fuel in MSFR. (hypothetical fuel with only ^{232}Th and ^{233}U).
- After 6 years of irradiation many nuclides are “almost” equalized =>
- Others will need “century” to stabilize.
- Should the same actinides vector be repetitively recycled/irradiated, all nuclides will be equalized.
- Necessary condition to reach equilibrium is:
  1) Stable feed or actually ^{232}Th or ^{238}U mass
  2) Constant neutron flux
- When imposing the constant flux, **equilibrium** can be reached also for **subcritical systems!**



Repetitive Recycling => Equilibrium

- When fuel cycle **parameters**: power, reprocessing scheme, feed composition, etc. are **fixed**, reactor will converge to equilibrium state / **fuel composition**.
  - The composition depends on **feed** type ^{238}U or ^{232}Th (or TRU for burners)
    - and on the reactor **spectrum**.
      - The spectrum is strongly (co)determined by **scattering materials**.
        - Equilibrium composition and spectrum determine the **multiplication factor**.



- Equilibrium is **inherent core state.** *(Bateman's matrix eigenstate: composition, spectrum, reactivity)*
- Equilibrium **reactivity** indicates neutron **efficiency** and reactor **capability** for sustainable **breeding** or **burning**.

Křepel, J., Losa, E., 2019. Closed U-Pu and Th-U cycle in sixteen selected reactors: evaluation of major equilibrium features. Ann. Nucl. Energy.

Bateman matrix eigenstate
(as an equilibrium)

- In Bateman matrix eigenstate (equilibrium) Breeding Gain (BG) is per definition 0.
- k_{eff} is indicator of neutron economy and does not need to be 1.
  It can be also negative!!!
- Reactivity excess can be used to estimate breeding performance.
- *Perturbing capture rate of fertile material so that $k_{eff} = 1$ and $BG \neq 0$ =>*
- These four equation can be combined to obtain the k_{eff} and BG relation

$$BG = 0 \cong \frac{C^{fertile} - F^{total}}{F^{total}}$$

$$k_{\mathrm{eff}} \cong \frac{\bar{\nu} F^{total}}{F^{total} + C^{total}}$$

$$k_{\mathrm{eff,per}} \cong \frac{\bar{\nu} F^{total}}{F^{total} + C^{total} + \Delta C^{fertile}} = 1$$

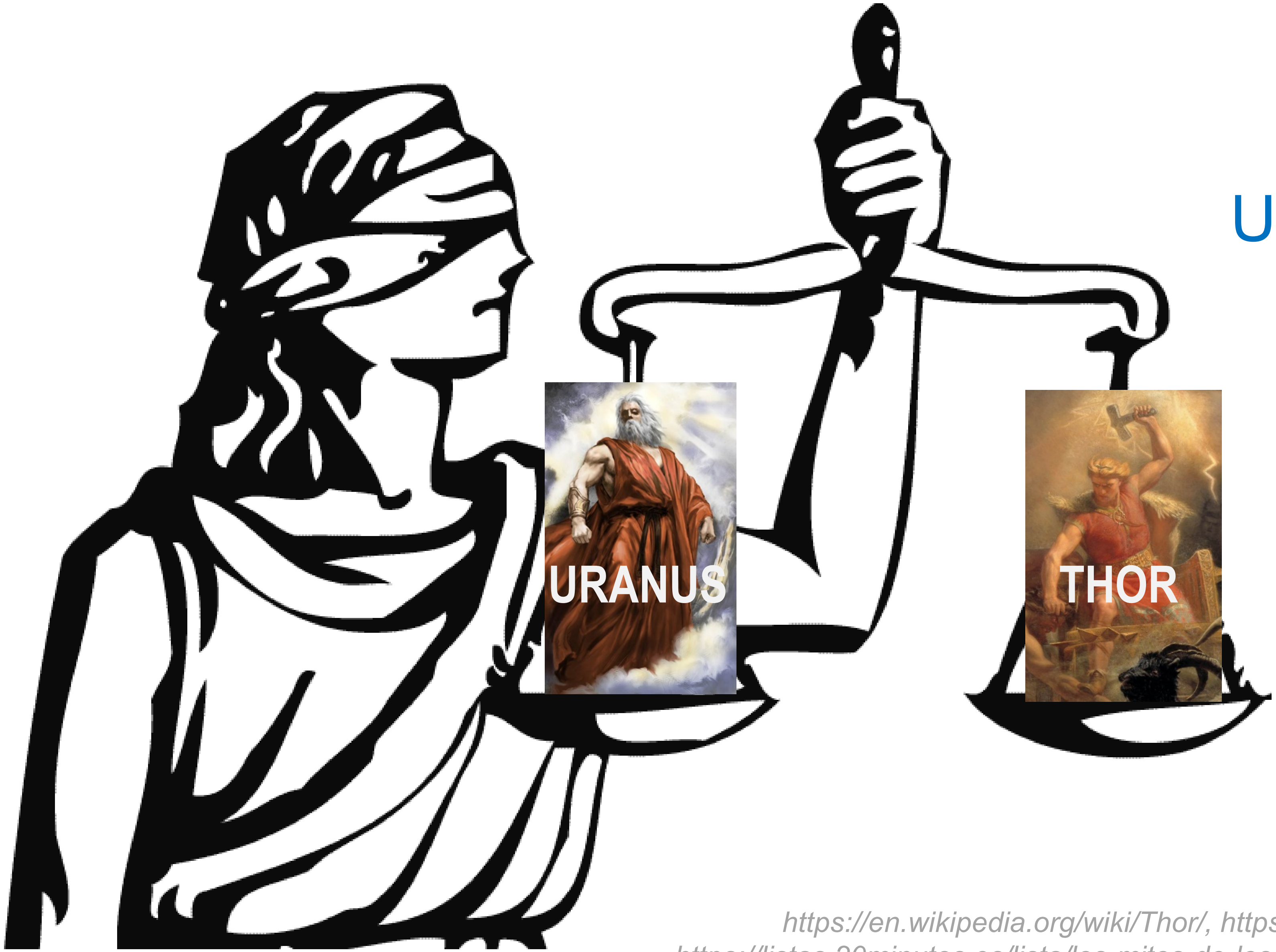
$$BG_{per} \cong \frac{C^{fertile} + \Delta C^{fertile} - F^{total}}{F^{total}}$$

$$BG_{per} \cong \bar{\nu} \frac{k_{\mathrm{eff}} - 1}{k_{\mathrm{eff}}}$$

J. Krepel, B. Hombourger, E. Losa, Fuel cycle sustainability of Molten Salt Reactor concepts in comparison with other selected reactors, PHYTRA4, Marrakech, Morocco, September 17-19, 2018.

4. Performance of 16 reactors in equilibrium for U-Pu or Th-U cycles

Disclaimer:



The comparison of U-Pu & Th-U closed cycles is done **purely** from neutronic perspective of “equilibrium cycle”

https://en.wikipedia.org/wiki/Thor/, https://ru.kisspng.com/kisspng-9rim3q/
https://listas.20minutos.es/lista/los-mitos-de-los-astros-342311/, https://www.maxpixel.net /

^{232}Th and ^{238}U irradiation

$$\underset{\textit{even-n}}{{}^{232}_{90}Th} + {}^{1}_{0}n \longrightarrow \underset{\textit{odd-n}}{{}^{233}_{90}Th} \xrightarrow{\beta^- \, 22\,\text{min}} \underset{\textit{even-n}}{{}^{233}_{91}Pa} \xrightarrow{\beta^- \, 27\,day} \underset{\textit{odd-n}}{{}^{233}_{92}U}$$

$$\underset{\textit{even-n}}{{}^{238}_{92}U} + {}^{1}_{0}n \longrightarrow \underset{\textit{odd-n}}{{}^{239}_{92}U} \xrightarrow{\beta^- \, 24\,\text{min}} \underset{\textit{even-n}}{{}^{239}_{93}Np} \xrightarrow{\beta^- \, 2.4\,day} \underset{\textit{odd-n}}{{}^{239}_{94}Pu}$$

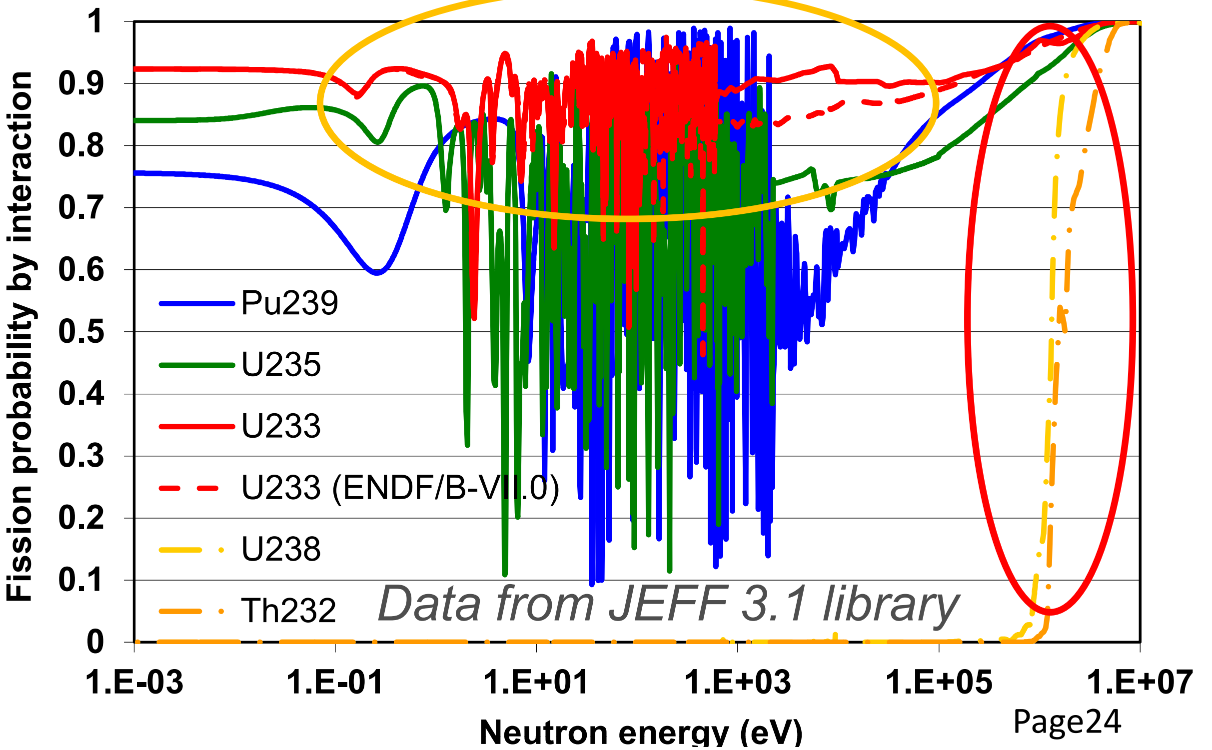
- ^{233}U high fission probability (up to **90%**) is the biggest advantage of Th-U cycle. (for ^{239}Pu it is **60-75%**)

It depends on the XS library:

—— JEFF 3.1 X

- - - ENDF/B VII.0

- ^{238}U is up to 10x more fissionable than ^{232}Th.



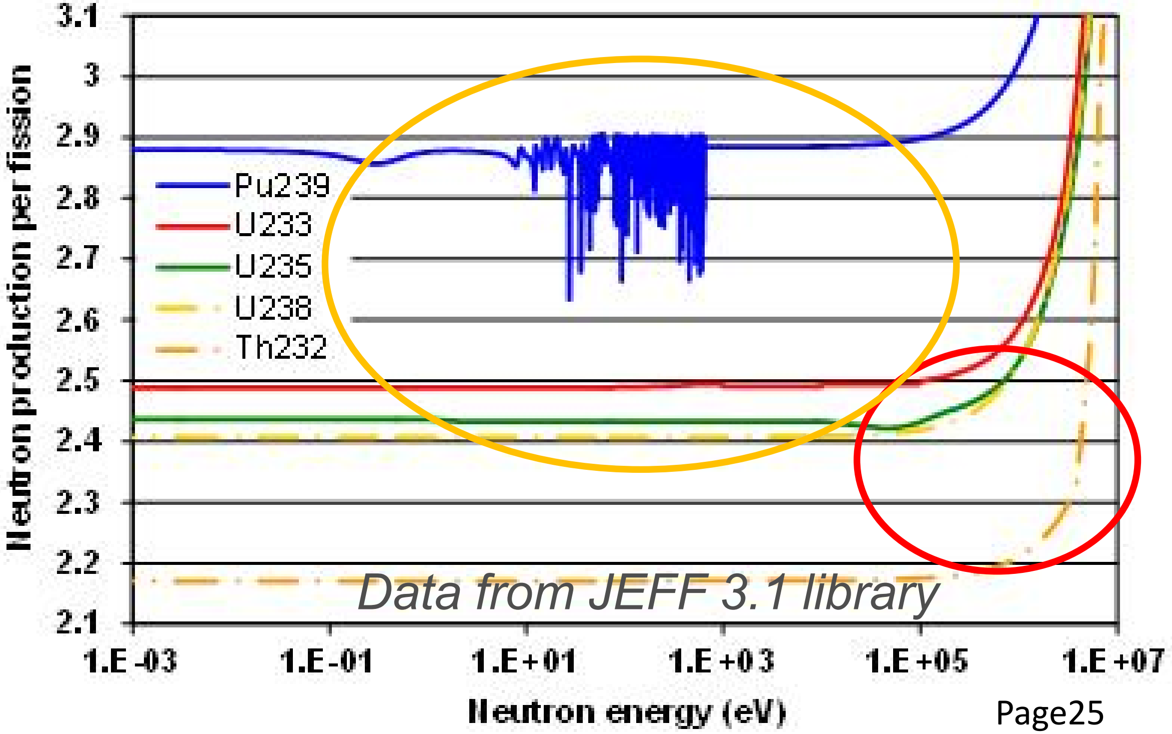
^{232}Th and ^{238}U irradiation

$$\underset{\text{even-n}}{^{232}_{90}Th} + {}^{1}_{0}n \longrightarrow \underset{\text{odd-n}}{^{233}_{90}Th} \xrightarrow{\beta^- \, 22\,\text{min}} \underset{\text{even-n}}{^{233}_{91}Pa} \xrightarrow{\beta^- \, 27\,day} \underset{\text{odd-n}}{^{233}_{92}U}$$

$$\underset{\text{even-n}}{^{238}_{92}U} + {}^{1}_{0}n \longrightarrow \underset{\text{odd-n}}{^{239}_{92}U} \xrightarrow{\beta^- \, 24\,\text{min}} \underset{\text{even-n}}{^{239}_{93}Np} \xrightarrow{\beta^- \, 2.4\,day} \underset{\text{odd-n}}{^{239}_{94}Pu}$$

- **^{239}Pu** high production of neutrons per fission (**~2.9**) it is the biggest advantage of U-Pu cycle (for **^{233}U** it is only **~2.5**).
- **^{238}U** produce slightly more neutrons than **^{232}Th**.
- **^{233}Pa parasitic capture**: for equal ^{238}U and ^{232}Th transmutation rate, there will be **11x more ^{233}Pa** in Th-U than ^{239}Np in U-Pu cycle.

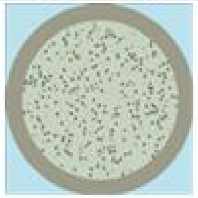
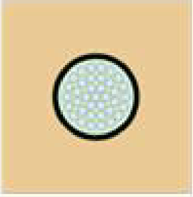
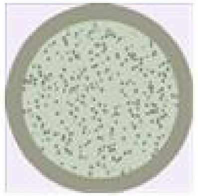
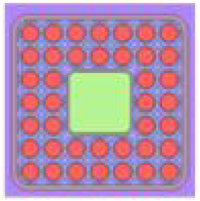
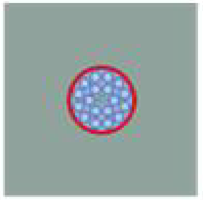
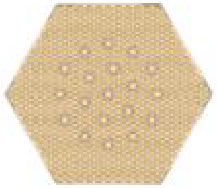
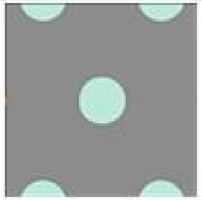
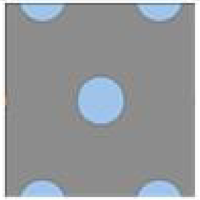
^{233}Pa / ^{239}Np = T_{Pa} / T_{Np} = 11.2

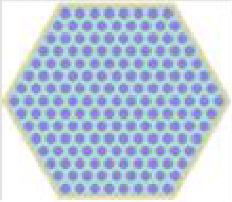
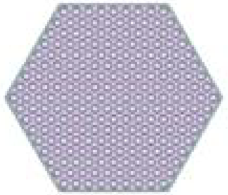
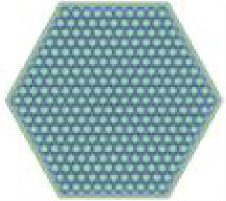
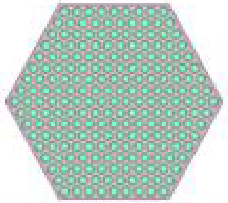
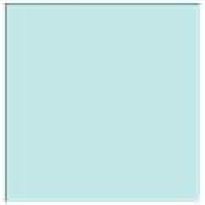
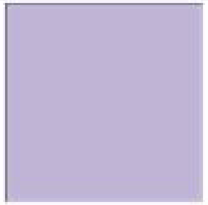
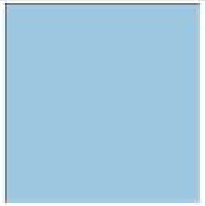
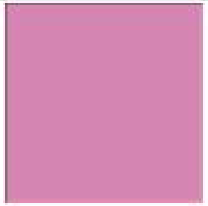


Equilibrium cycle comparison
for 16 reactors and 2 fuel cycles

- **16 reactors** have been selected for the comparative study in both **U-Pu and Th-U** cycle.
- The idea was to cover **major neutron spectrum** types.
- **Gen-IV** reactors and major **commercial** reactors were included.
- **8 thermal and 8 fast** reactors were selected. :(Magnox was forgotten)
- The **Bateman matrix equilibrium** was obtained for strongly simplifying **assumptions**:
  1) infinite lattice.
  2) neglected fission products, each fission results in ^{232}Th or ^{238}U refiling.
     (as a consequence, there is no batch-wise oscillation, everything is smooth)
  3) design as is, no additional optimization.
  4) ENDF/B-VII.0 library

16 Selected Reactors

Reactor name (and label)	Lattice geometry	Name and short name	Lattice geometry
Solid fuel thermal reactors			
Fluoride high temperature reactor PB-AHTR (**FHR**)		Pressurized heavy water reactor (**PHWR**)	
High temperature reactor (**HTR**)		High performance light water reactor (**HPLWR**)	
Reaktor balshoi moshnosti kanalnyj (**RBMK**)		Light water reactor VVER-1000 (**LWR**)	
Liquid fuel thermal reactors			
Thermal MSR fueled by $LiF\text{-}BeF_2\text{-}AcF_4$ (**MSR-FLIBE**)		Thermal MSR fueled by $LiF\text{-}AcF_4$ (**MSR-FLI**)	

Reactor name (and label)	Lattice geometry	Name and short name	Lattice geometry
Solid fuel fast reactors			
European lead system (**LFR**)		Gas cooled fast reactor (**GFR**)	
European sodium fast reactor (**SFR**)		Metal fueled fast breeder reactor (**MFBR**)	
Liquid fuel fast reactors			
Molten salt fast reactor fueled by $LiF\text{-}BeF_2\text{-}AcF_4$ (**MSFR-FLIBE**)		Molten salt fast reactor fueled by $NaCl\text{-}AcCl_4$ (**MCFR-NaCl**)	
Molten salt fast reactor fueled by $LiF\text{-}AcF_4$ (**MSFR-FLI**)		Molten salt fast reactor fueled by $AcCl_4$ (**MCFR-AcCl**)	

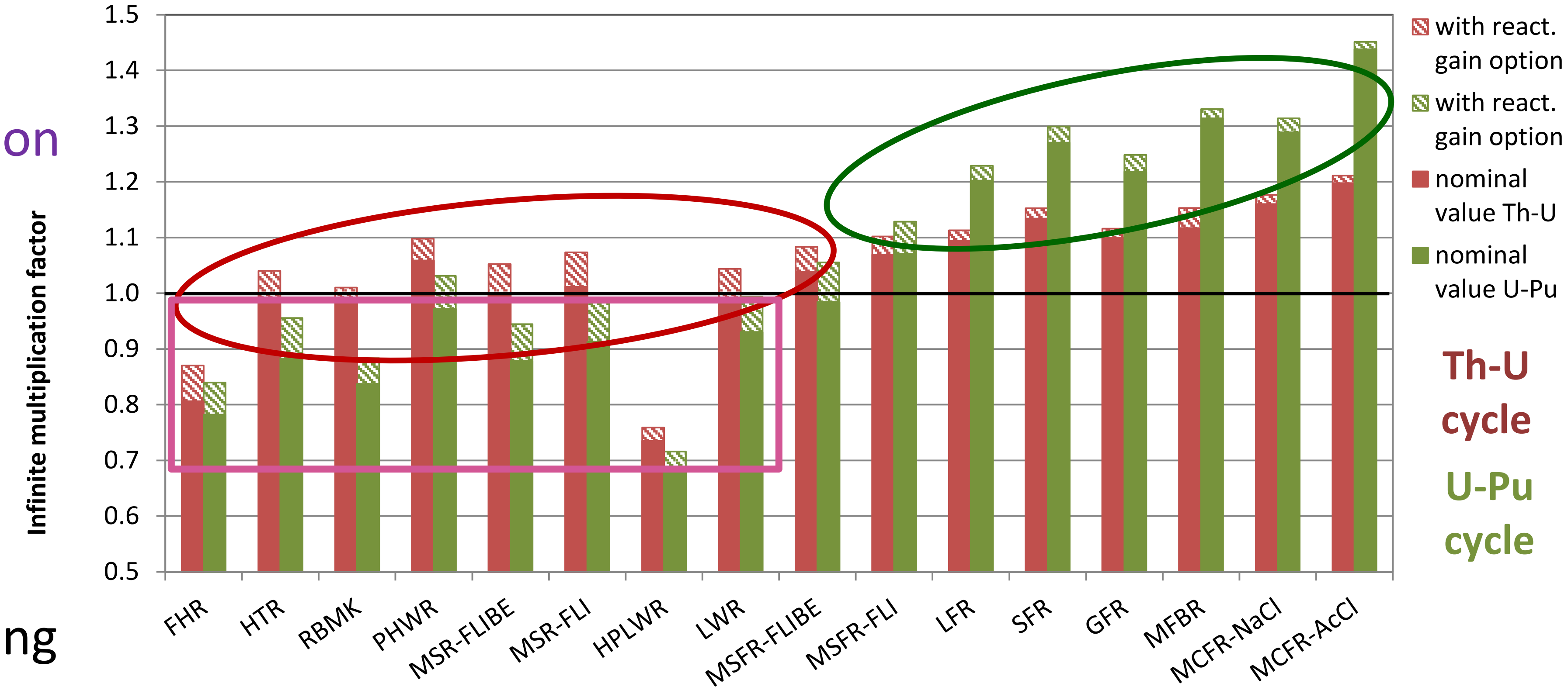
Křepel, J., Losa, E., 2019. Closed U-Pu and Th-U cycle in sixteen selected reactors: evaluation of major equilibrium features. Ann. Nucl. Energy.

4a. Equilibrium reactivity

Equilibrium multiplication factor (reactivity)

- Better performance:
  Th-U in thermal spectra,
  U-Pu in fast spectra.
- Actinides Eigen-composition in U-Pu cycle is subcritical in all thermal reactors.
- Reactivity gain option =

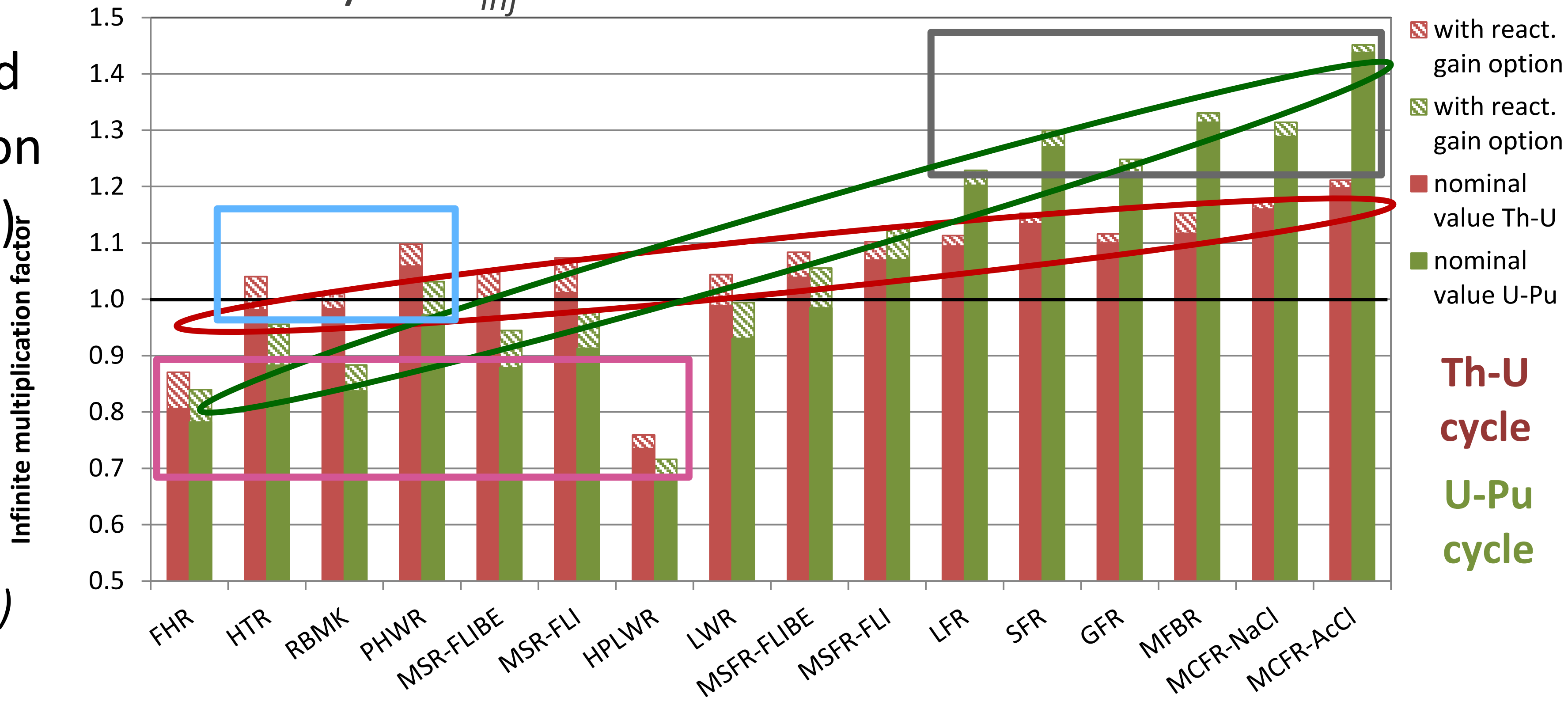
1) Not recycling of higher actinides
2) and ^{233}Pa or ^{239}Np decaying outside of the neutron flux. *(not really realistic option for solid fuel reactors as PHWR)*



Equilibrium Multiplication Factor
(solid fuel reactors)

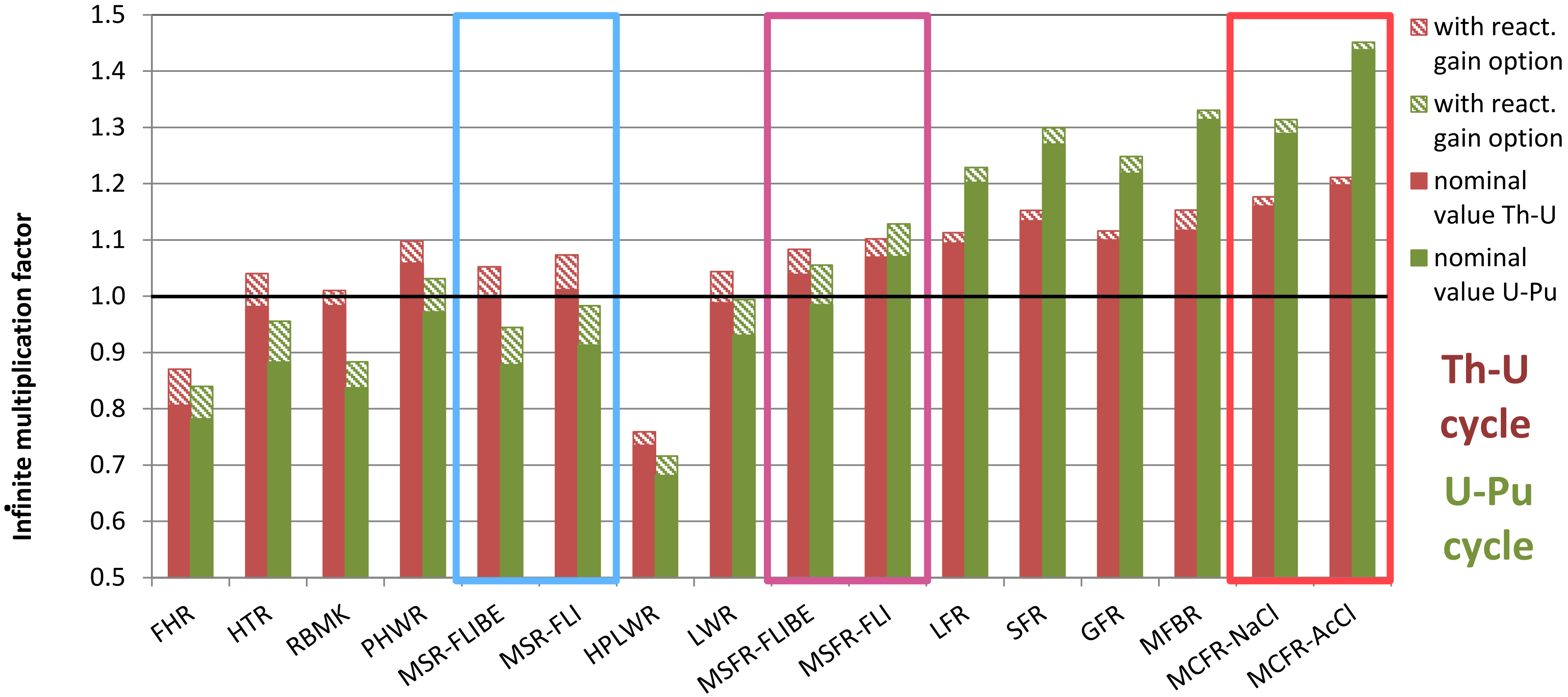
- The performance in **Th-U** cycle is less dependent on the spectrum than in **U-Pu** cycle.
- **B&B** is possible for fast reactors in U-Pu cycle. k_{inf}=1.2 is kind of threshold.
- HPLWR (steel cladding) and FHR (salt coolant absorption caused by low fuel density) have bad performance.
- HTR, RBMK and PHWR (the best thermal system) are on the breeding edge.

(leakage and FPs not accounted)



Equilibrium multiplication factor
(liquid fuel reactors)

- Graphite moderated MSR is in the Th-U cycle on the edge of breeding. *(FPs intensive separation, ^{233}Pa decay outside of core)*
- Fluorides fast MSFR can breed in both cycles *(soft fast spectra, FPs semi-intensive separation)*.
- Chlorides fast MCFR maximal reactivity from MSR cases in both cycles.



Excess reactivity break-down
(additional insight, example for ^{232}Th)

- For better understanding of the equilibrium reactivity excess, it was decomposed this way:

$$\rho \cong \frac{\bar{\nu}-2}{\bar{\nu}} + \frac{R_F^{232Th} + 2R_{n,2n}^{232Th}}{\bar{\nu}R_F^{total} + 2R_{n,2n}^{232Th}} - \frac{R_C^{other\_Ac} + R_C^{structural}}{\bar{\nu}R_F^{total} + 2R_{n,2n}^{232Th}}$$

Available neutrons | Bonus from fertile | Parasitic captures

- It was derived from neutron balance equation: $k_{\inf} = \frac{R_P^{total} + 2R_{n,2n}^{total}}{R_F^{total} + R_C^{total} + R_{n,2n}^{total}}$
- Using four assumptions: **1)** $R_P^{total} = \bar{\nu}R_F^{total}$ **2)** $R_C^{total} = R_C^{232Th} + R_C^{other\_Ac} + R_C^{structural}$

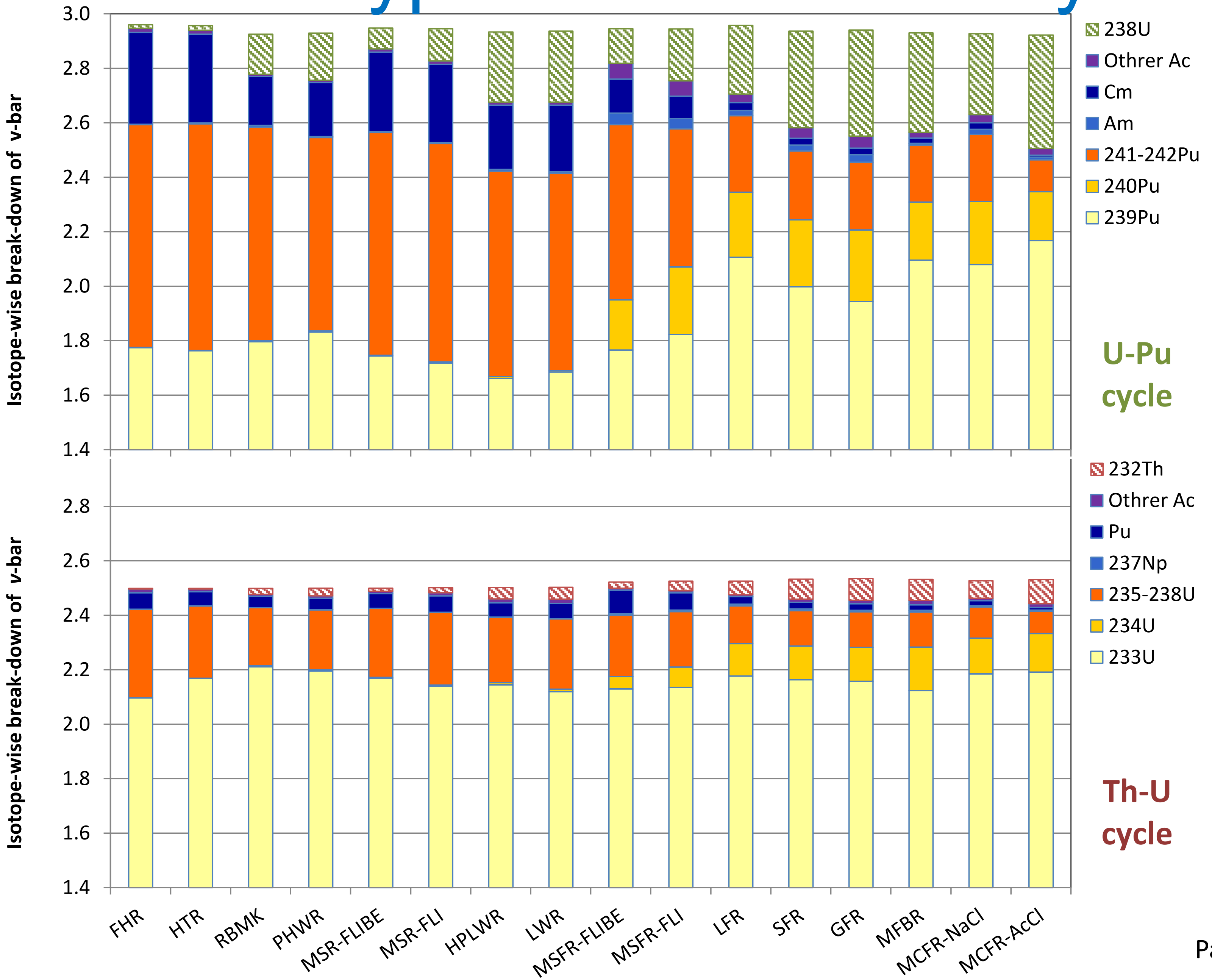
  3) $R_{n,2n}^{total} \cong R_{n,2n}^{232Th}$ (*main fertile ~ 90% of all (n,2n) reactions*)

  4) $R_C^{232Th} + R_{n,2n}^{232Th} = R_F^{total} - R_F^{232Th}$ (equilibrium *of non-Th Ac production and destruction*)

Available neutrons – hypothetical reactivity

$$\frac{\bar{\nu}-2}{\bar{\nu}}$$

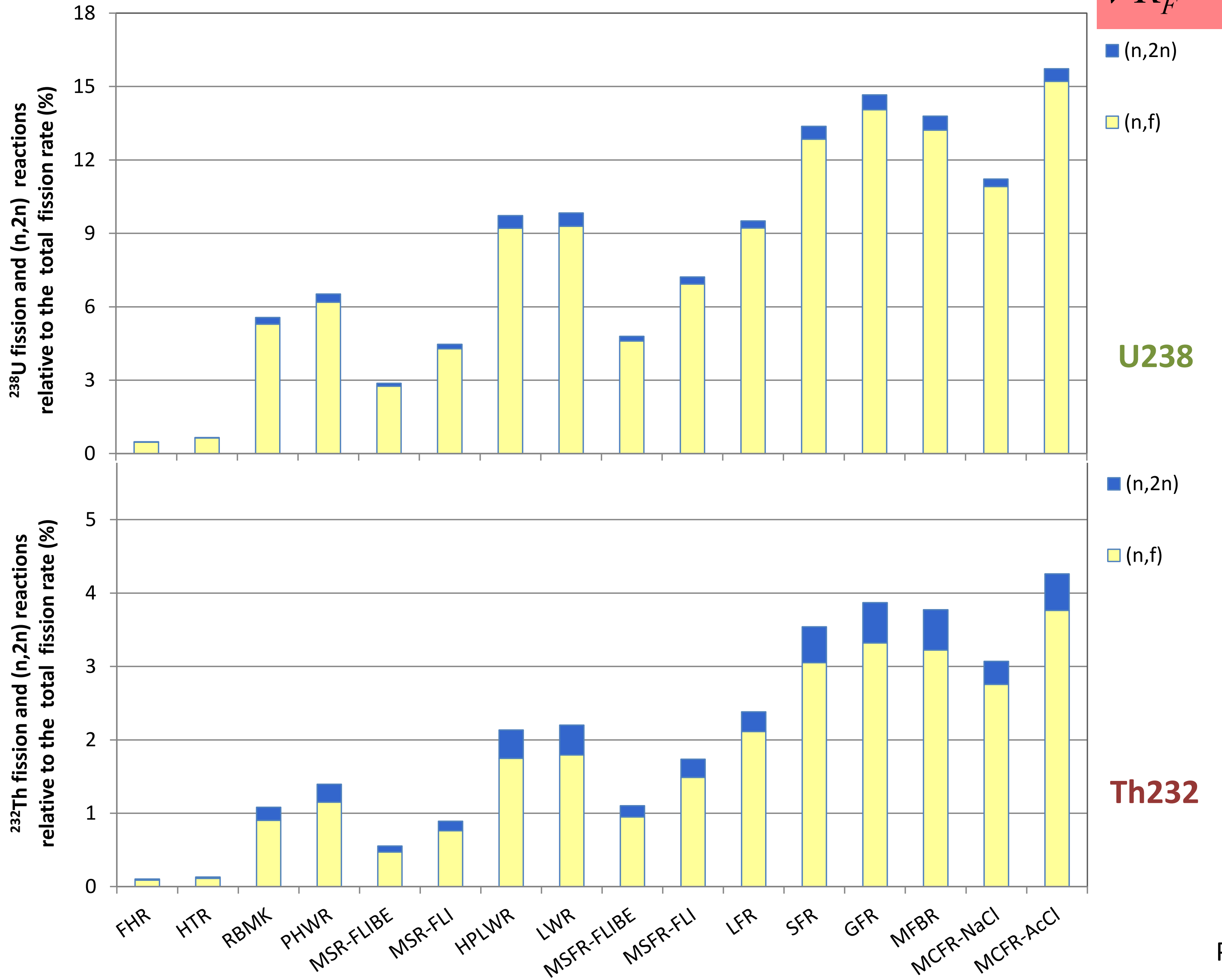
- Available neutrons **surprisingly** do not differ between reactors!
- **ν** = 2.5 in **Th-U** cycle
- **ν** = 2.9 in **U-Pu** cycle
- Hypothetical reactivity excess: **20000** pcm in Th-U **31000** pcm in U-Pu cycle (2 to 3 ratio).



Bonus from fertile material

$$\frac{R_F^{232Th} + 2R_{n,2n}^{232Th}}{\bar{\nu} R_F^{total} + 2R_{n,2n}^{232Th}}$$

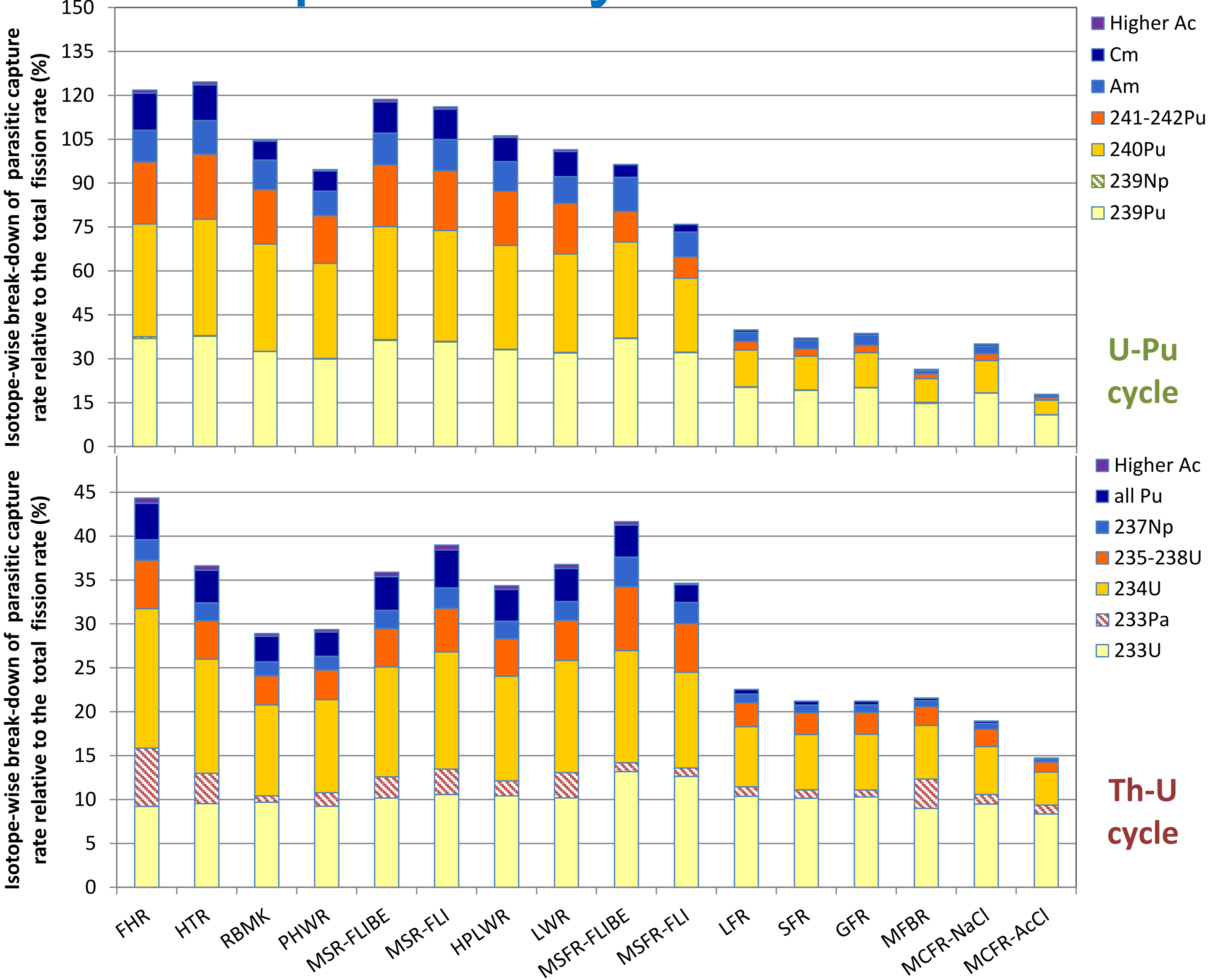
- Bonus from fertile **strongly differ** between reactors.
- It is up to **4 %** in Th-U cycle
- It is up to **15 %** in U-Pu cycle
- Bonus reactivity in fast spectrum: **1800** pcm in Th-U **5000** pcm in U-Pu cycle (2 to 5 ratio).



Parasitic neutron captures by actinides

$$\frac{R_C^{other\_Ac}}{\bar{\nu} R_F^{total} + 2R_{n,2n}^{232Th}}$$

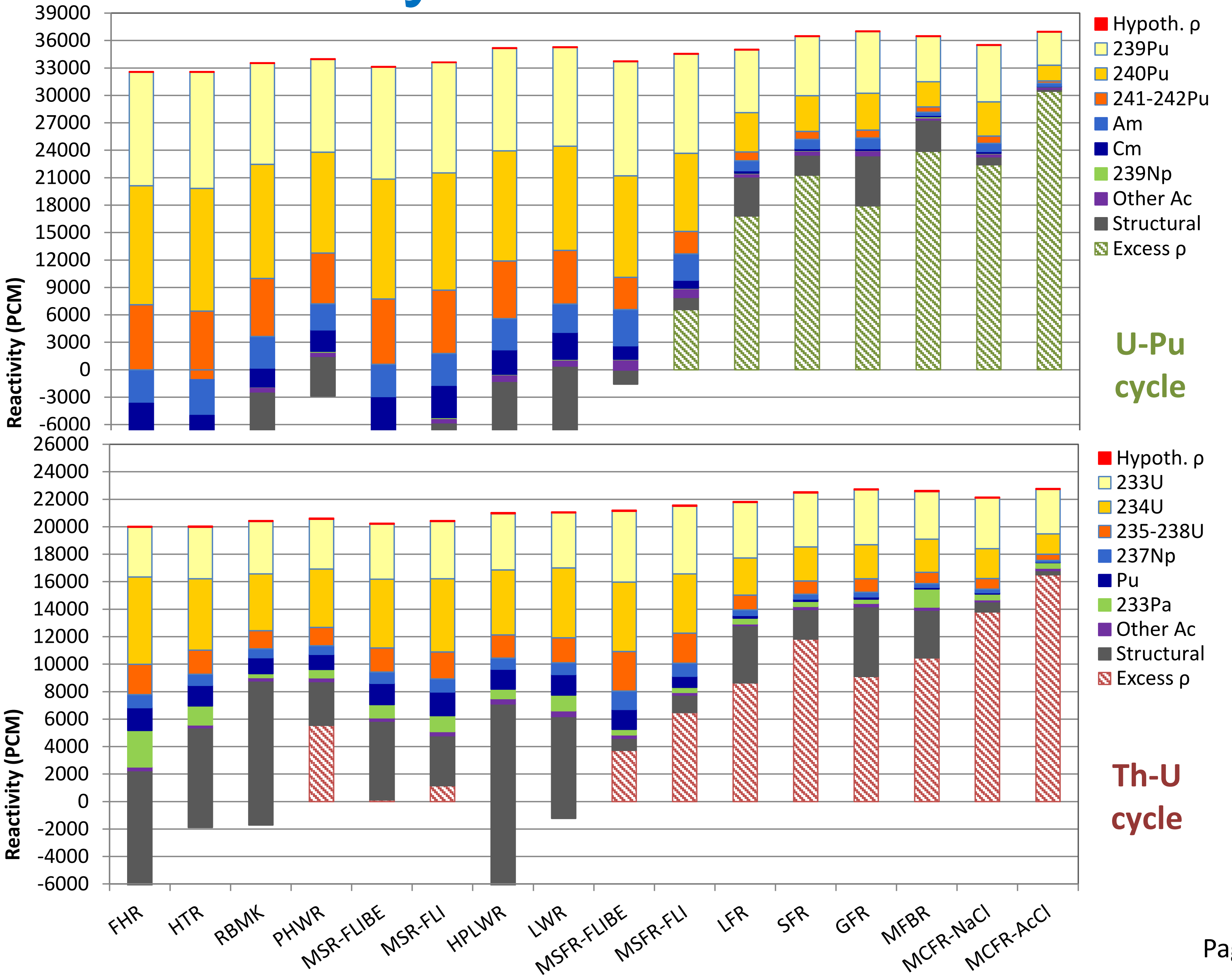
- Parasitic captures **strongly differ** between reactors.
- **20%** in fast & up to **40 %** in thermal **Th-U** cycle.
- **30%** in fast & up to **120 %** in thermal **U-Pu** cycle.
- Reactivity loss in Th-U is much lower (1/3 in thermal, (2/3 in fast case).



Overall excess reactivity

$$\rho \cong \frac{\bar{\nu}-2}{\bar{\nu}} + \frac{R_F^{232Th}+2R_{n,2n}^{232Th}}{\bar{\nu}R_F^{total}+2R_{n,2n}^{232Th}} - \frac{R_C^{other\_Ac}+R_C^{structural}}{\bar{\nu}R_F^{total}+2R_{n,2n}^{232Th}}$$

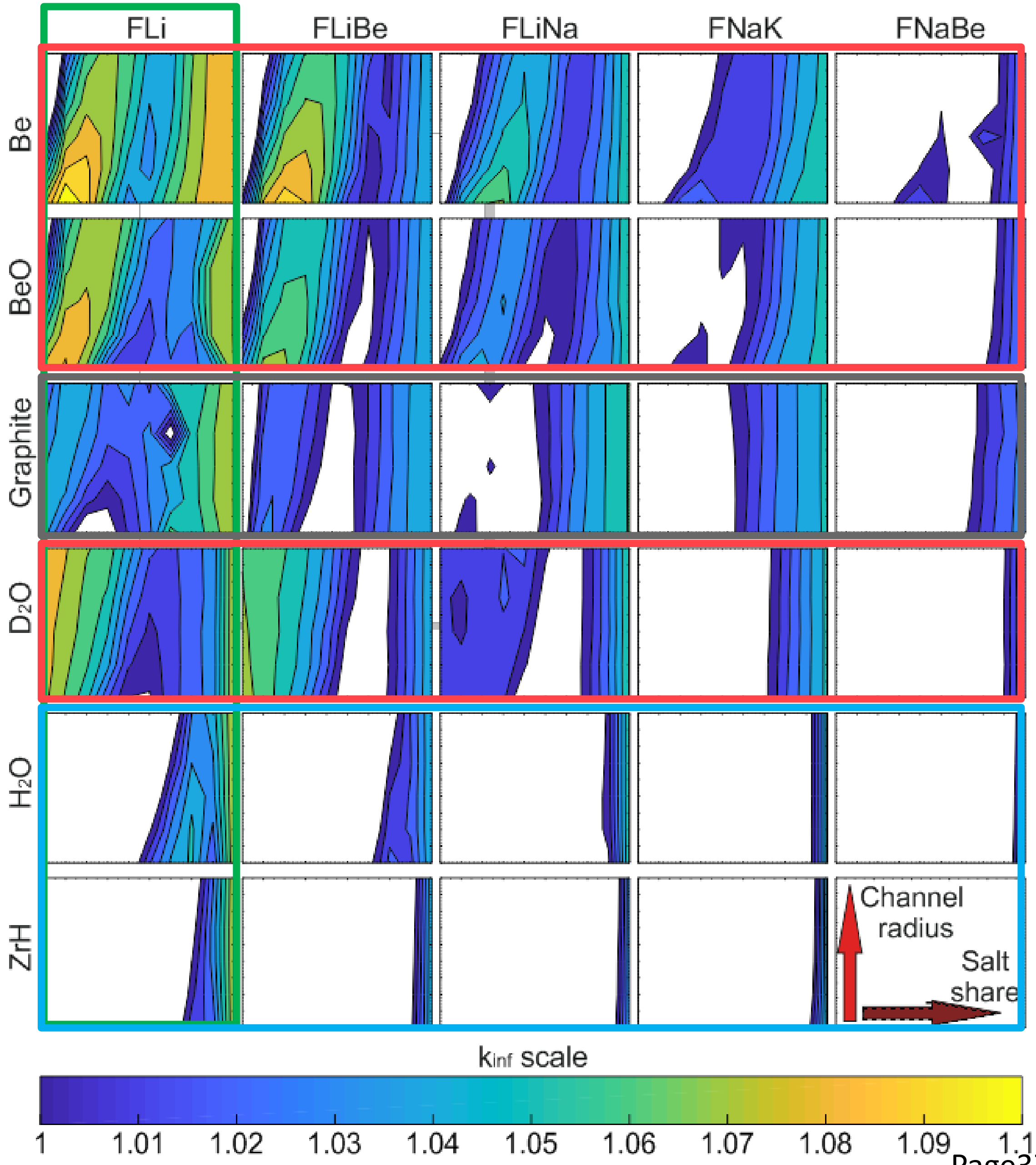
- **Th-U**: lower **ν** and lower parasitic capture of ^{233}U, breeding also in **thermal spectrum**.
- **U-Pu**: higher **ν** and higher parasitic capture of ^{239}Pu, better performance **in fast** spectrum.
- **Th-U high efficiency.**
- **U-Pu high economy.**



Th-U cycle equilibrium
additional results for MSR

- **5 fluoride salts** were analyzed with **6** selected **moderators** (inclusive FPs).
- Equilibrium k_{inf} is presented as a function of **salt share** and **channel radius**.
- **FLi** salt is neutronically the best.
- Good results for **Be, BeO, and D2O**; however, they are not compatible with the salt without cladding (SiC..?).
- Hydrogen based moderators **ZrH and H_2O** not applicable for closed cycle.
- **Graphite** is not the best moderator, but the only one directly compatible with salt.

Hombourger, B.A., 2018. Ph.D. Thesis. EPFL Lausanne, Switzerland.



Impact of cladding (FLI salt case)

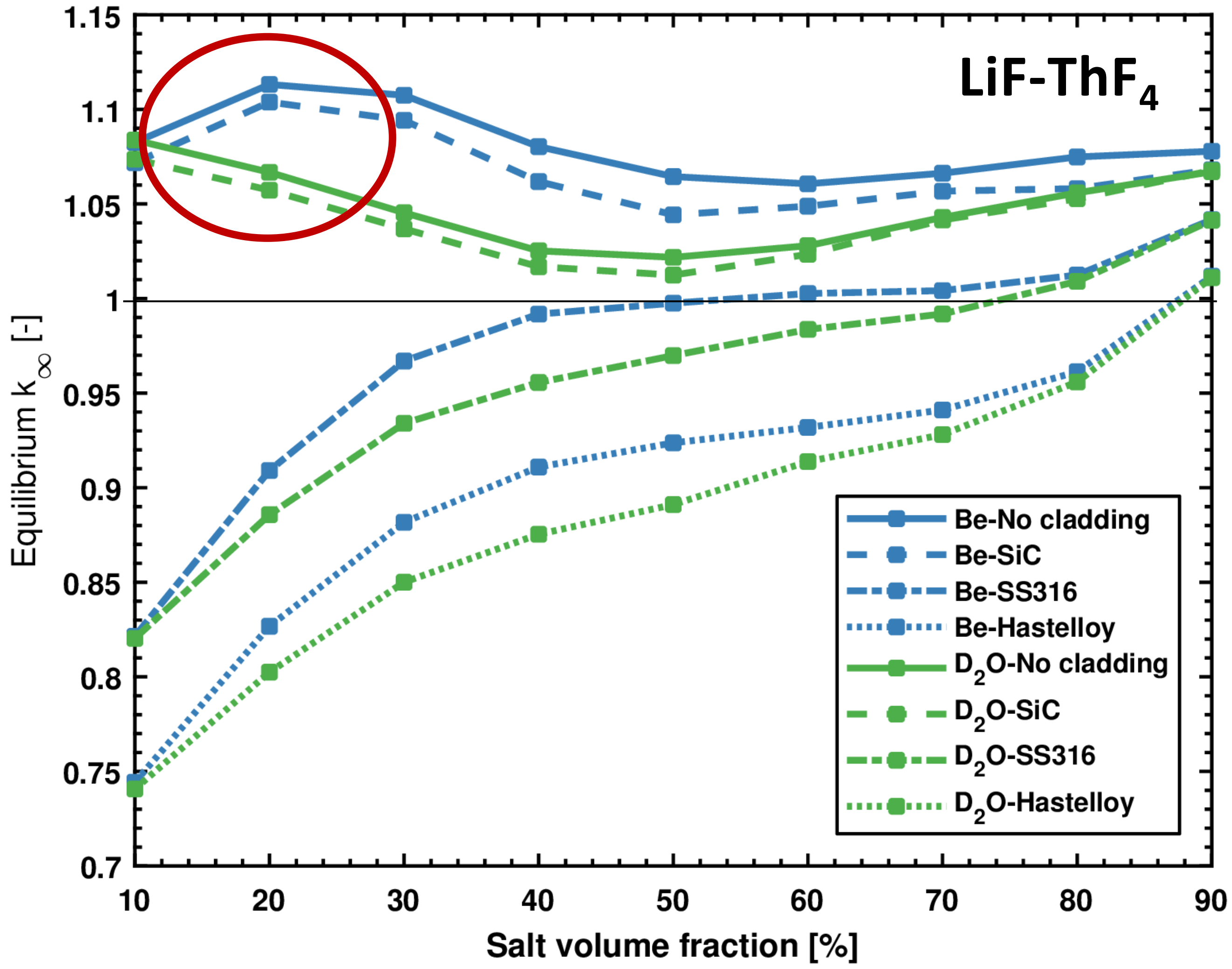
- **LiF salt** combined with **Be** and **D_2O** moderators was selected to analyze the impact of cladding:

  Hastelloy,
  SS316,
  and SiC.

- Only **SiC** seems to have acceptable low parasitic neutron capture.

- From purely neutronics perspective we can design **H**eavy **W**ater **B**oiling **T**hermal **T**horium MSR…

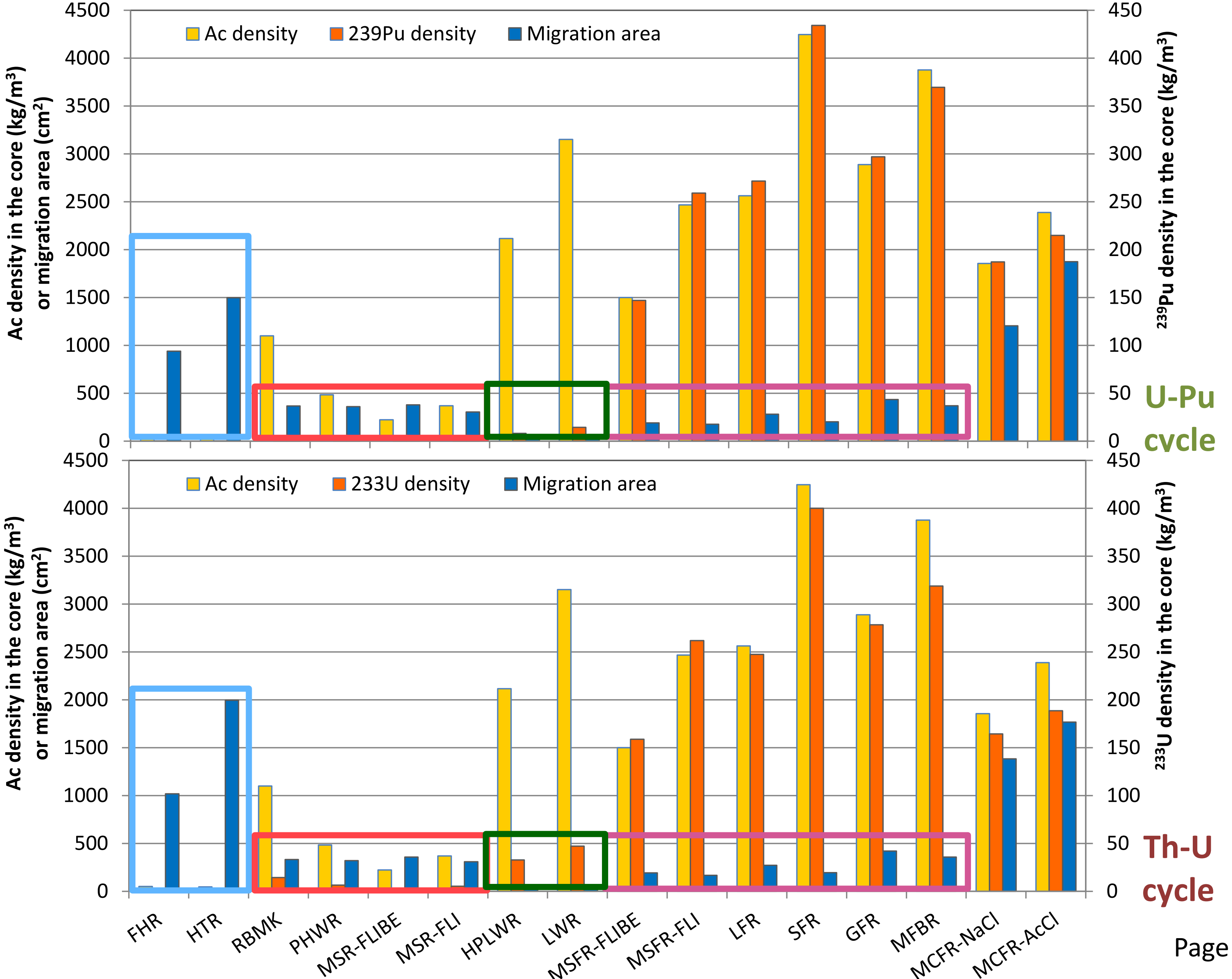
HWB-TT-MSR ☺



4b. Equilibrium core size assessment

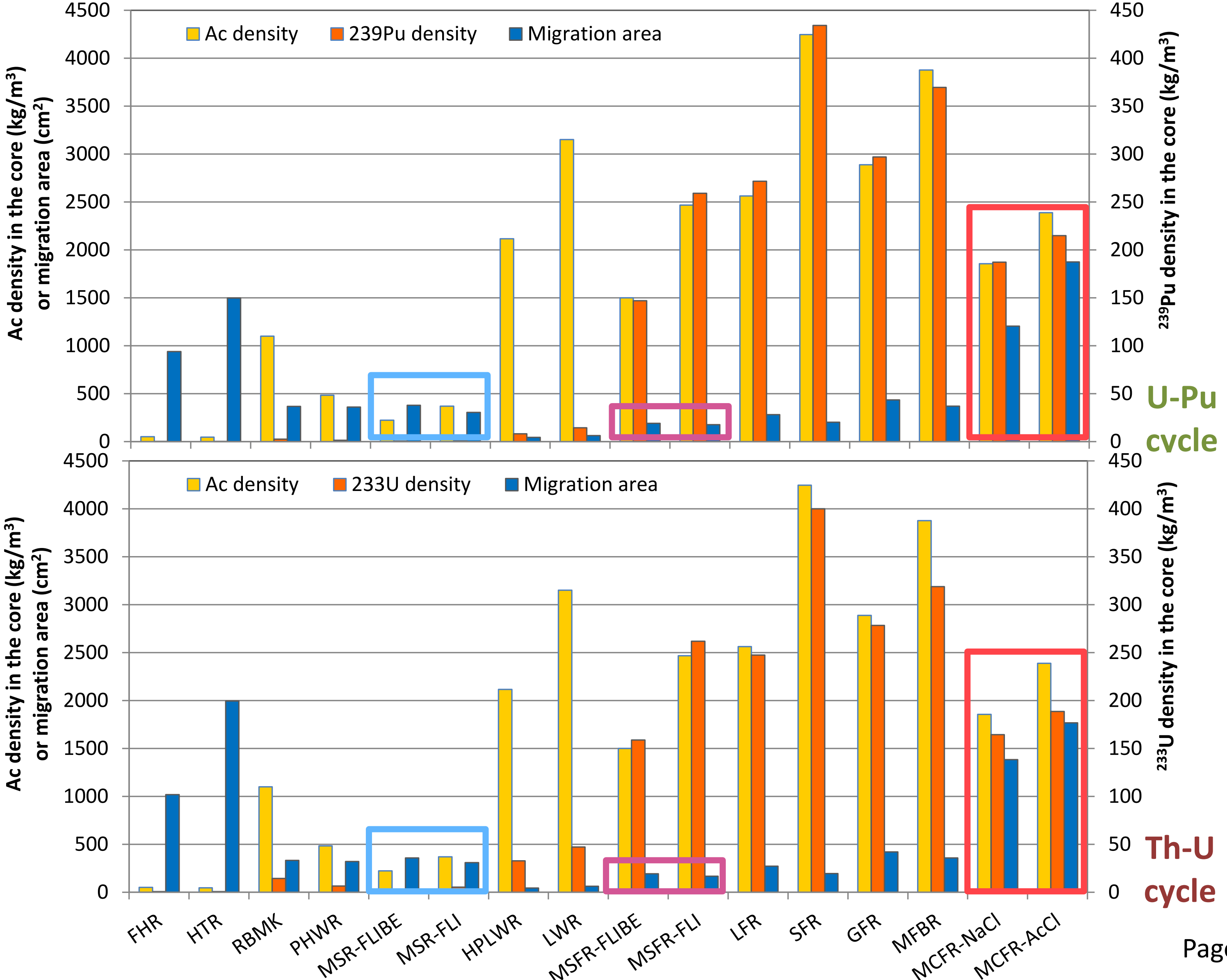
Migration area M *(determines with k_{inf} the core size)*

- **Comparable M** between the cycles; **different M** between the reactors.
- Fast reactors (except MCFR) have **small M**.
- **Graphite moderator** combined with low fuel density results in **high M**.
- **D_2O or graphite** (for higher fuel density) results in **medium M**.
- **H_2O** and high fuel density results in **minimal M**.



Migration area M *(determines with k_{inf} the core size)*

- MSFR: **small M** caused by Li and F scattering and mass.
- Graphite based MSR **higher M** caused by graphite scattering properties and lower fuel density .
- MCFR: **highest M**, absence of strong scattering XS and its resonances (^{37}Cl), lower density than MSFR-FLI.



Core radius estimate in Th-U cycle

- Bare core criticality line.

$$k_{inf} = 1 + M^2B^2$$

Derived from Fermi theory of bare "thermal" reactor:

$$k_{eff} = k_{\inf} p_1 p_2 = k_{\inf} \frac{e^{-\tau B^2}}{1+L^2B^2} \cong k_{\inf} \frac{1}{1+\left(\tau + L^2\right)B^2} = k_{\inf} \frac{1}{1+M^2B^2}$$

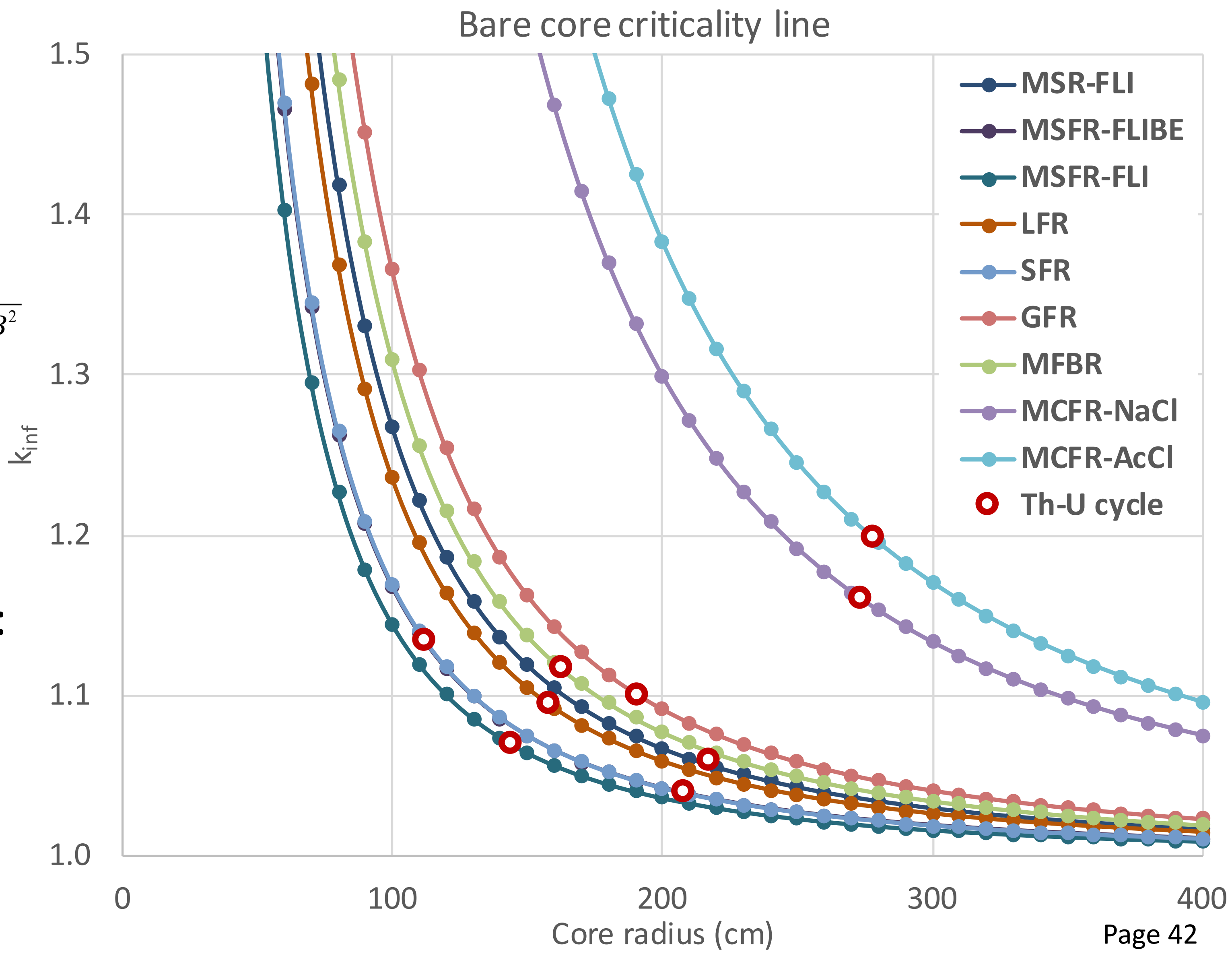
- Buckling for a cylinder:

$$B^2 = \left(\frac{\pi}{h}\right)^2 + \left(\frac{2.405}{r}\right)^2$$

- Minimal volume for given B^2:

$$\frac{h}{r} = \frac{\sqrt{2}\pi}{2.405} \cong 1.85$$

- **Core radius estimate in Th-U cycle =>**



Core radius estimate in U-Pu cycle

- Bare core criticality line.

$$k_{inf} = 1 + M^2B^2$$

Derived from Fermi theory of bare "thermal" reactor:

$$k_{eff} = k_{\inf} p_1 p_2 = k_{\inf} \frac{e^{-\tau B^2}}{1+L^2B^2} \cong k_{\inf} \frac{1}{1+\left(\tau + L^2\right)B^2} = k_{\inf} \frac{1}{1+M^2B^2}$$

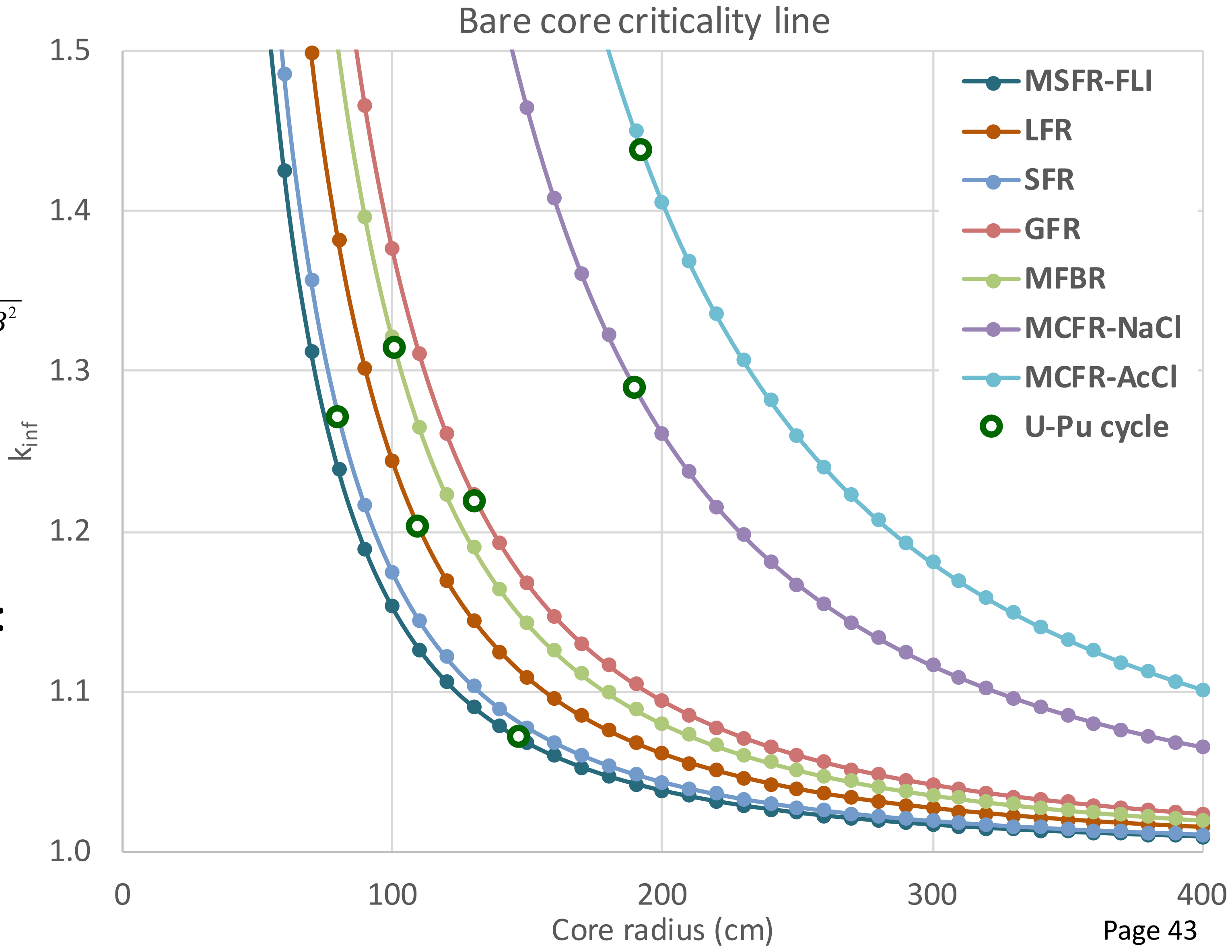
- Buckling for a cylinder:

$$B^2 = \left(\frac{\pi}{h}\right)^2 + \left(\frac{2.405}{r}\right)^2$$

- Minimal volume for given B^2:

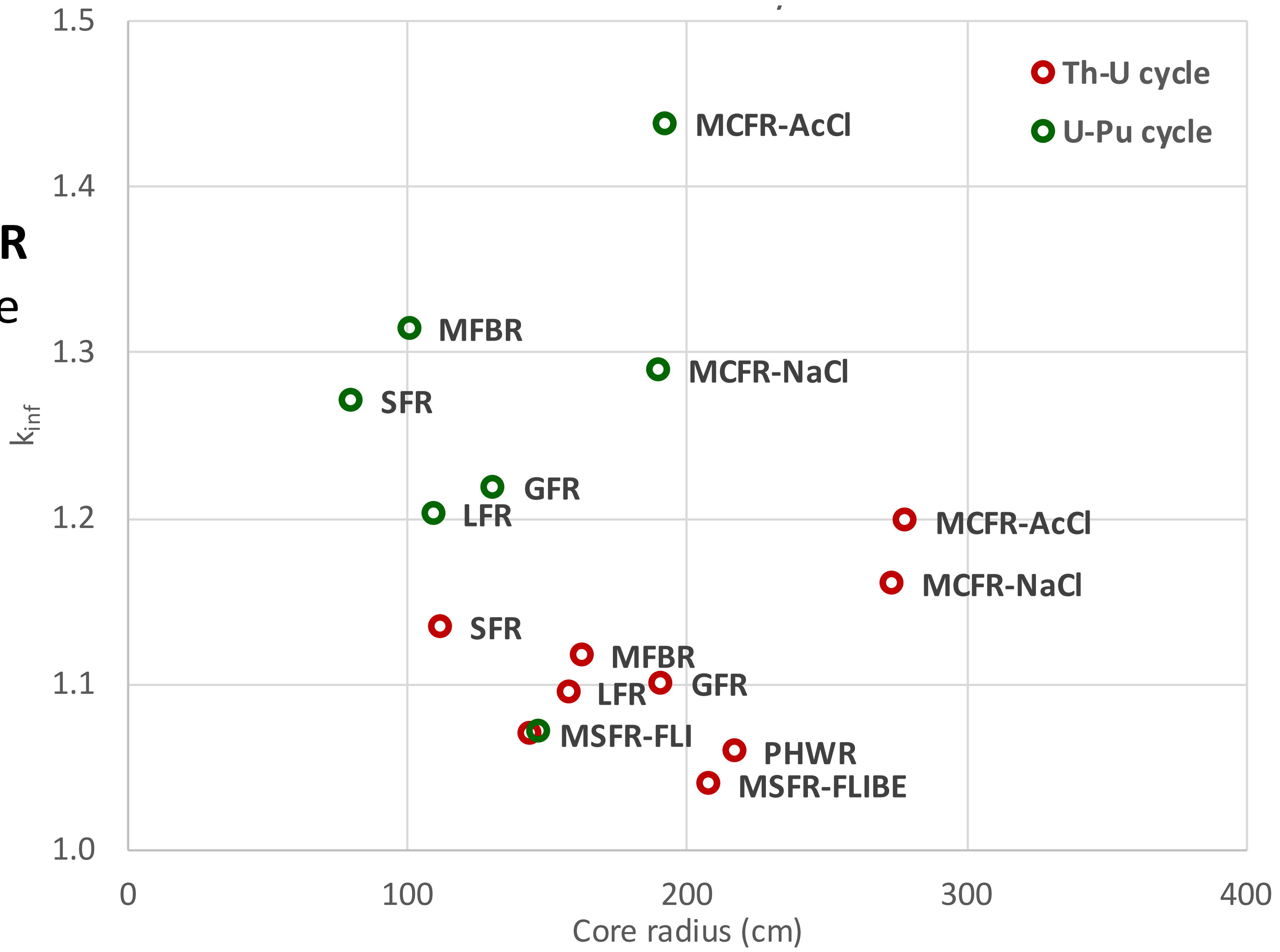
$$\frac{h}{r} = \frac{\sqrt{2}\pi}{2.405} \cong 1.85$$

- **Core radius estimate in U-Pu cycle =>**



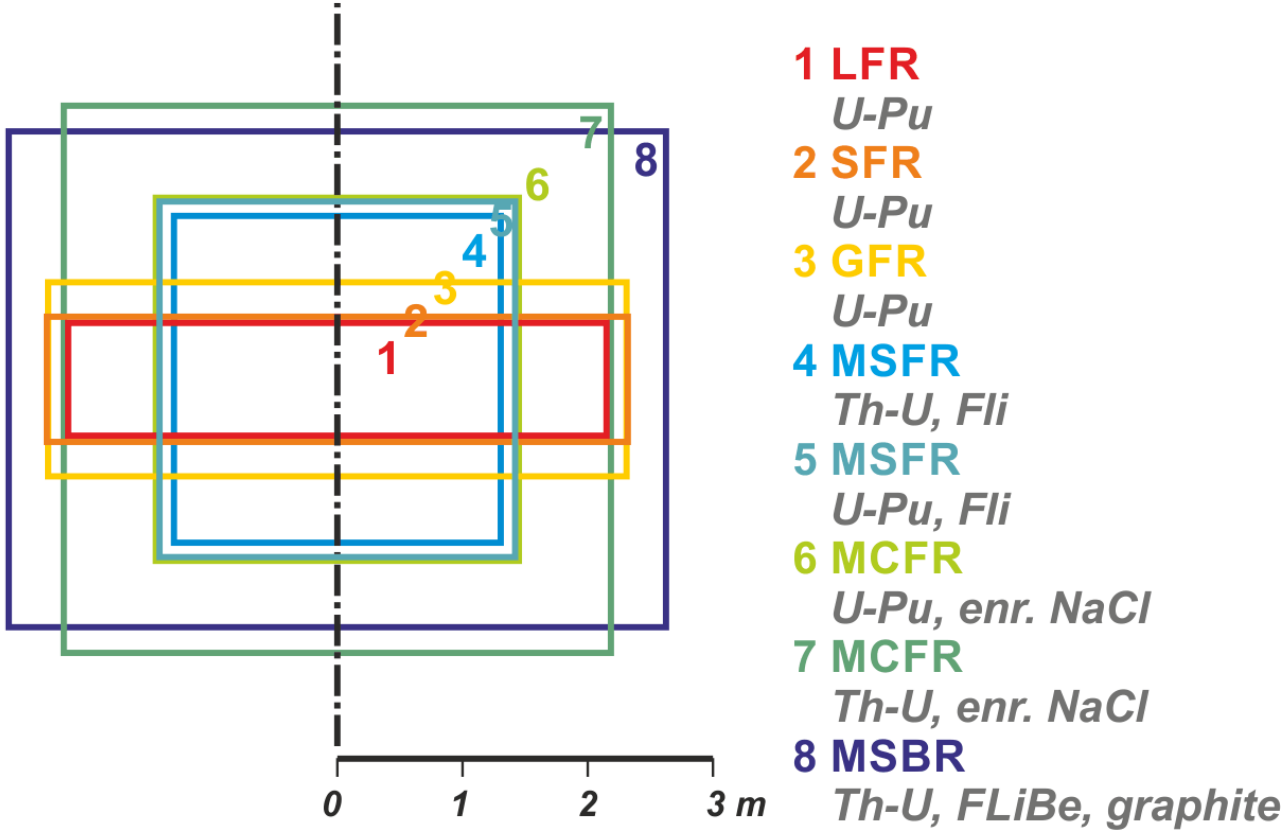
Core radius estimate: Th-U cycle X U-Pu cycle

- By all other fast reactors **U-Pu** cycle provides **smaller cores**.
- **MSFR-FLI** is the **smallest MSR** core and it has the same core size for both cycles. (**very soft fast spectrum**)
- **SFR** is the **most compact** bare iso-breeding core in both cycles.
- **MCFR** is the **biggest** bare iso-breeding core in both cycles.



Reflected core size in equilibrium

- Using 1m **Hastelloy reflector** core size was estimated for **single-fluid MSFR and MCFR**.
- It was compared with classical pan-cake fast reactors (1,2,3)
- MSFR in Th-U (4) is compact.
- MSFR in U-Pu (5) is slightly bigger.
- MCFR in U-Pu (6) is comparable to MSFR in U-Pu (5).
- MCFR in Th-U (7) is quite big.
- MSBR (ORNL design, 13% salt).

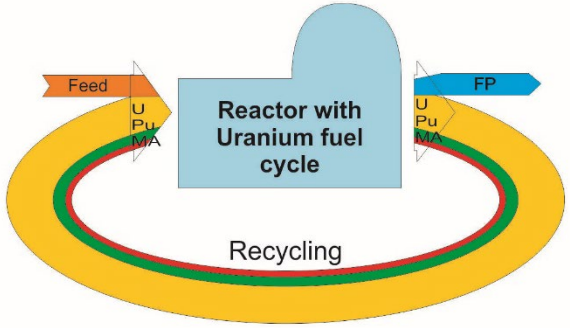


Hombourger, B.A., 2018. Ph.D. Thesis. EPFL Lausanne, Switzerland.

4c. Equilibrium radiotoxicity assessment

Actinides losses by recycling

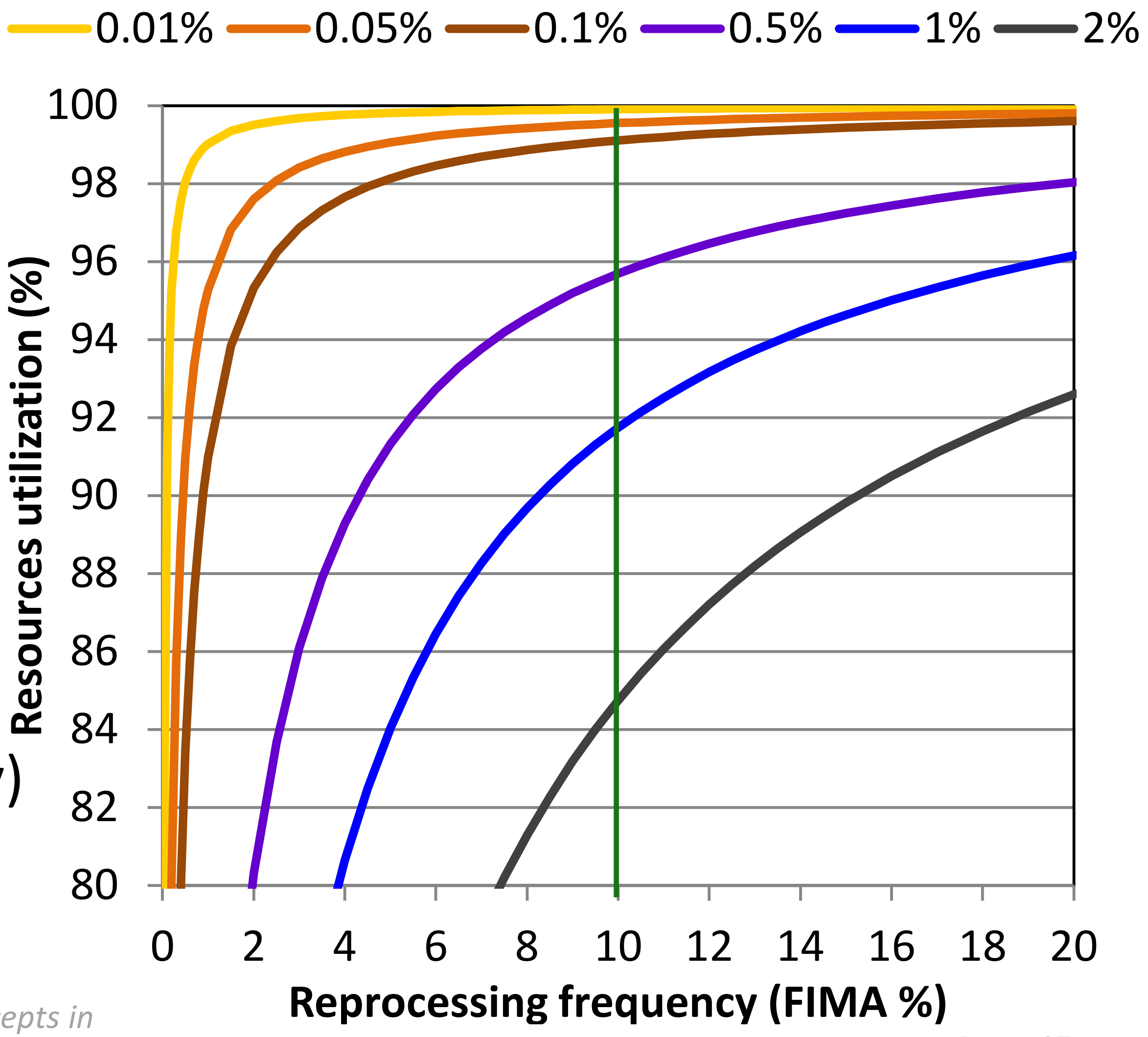
- Resources utilization in closed cycle is high; however, it is never 100%.



- There are always **reprocessing losses - L**.
- Utilization depends on **L** (in %) and on **reprocessed fuel burnup - B** (in FIMA %):

$$Utilization = 1 - losses = 1 - \frac{L(1-B)}{1-(1-L)(1-B)}$$

- Typical fuel burnup (= reprocessing frequency) in solid fuel fast reactor is **10% FIMA**. (Utilization **~90%** when MA are not recycled)



J. Krepel, B. Hombourger, E. Losa, Fuel cycle sustainability of Molten Salt Reactor concepts in comparison with other selected reactors, PHYTRA4, Marrakech, Morocco, September 17-19, 2018.

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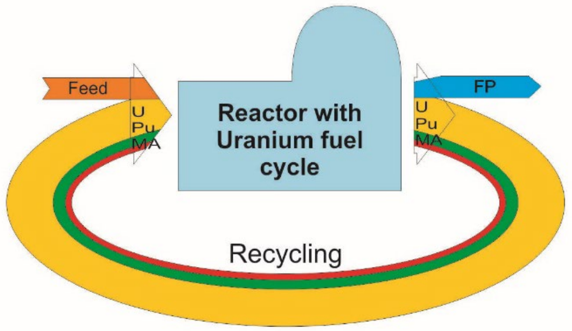
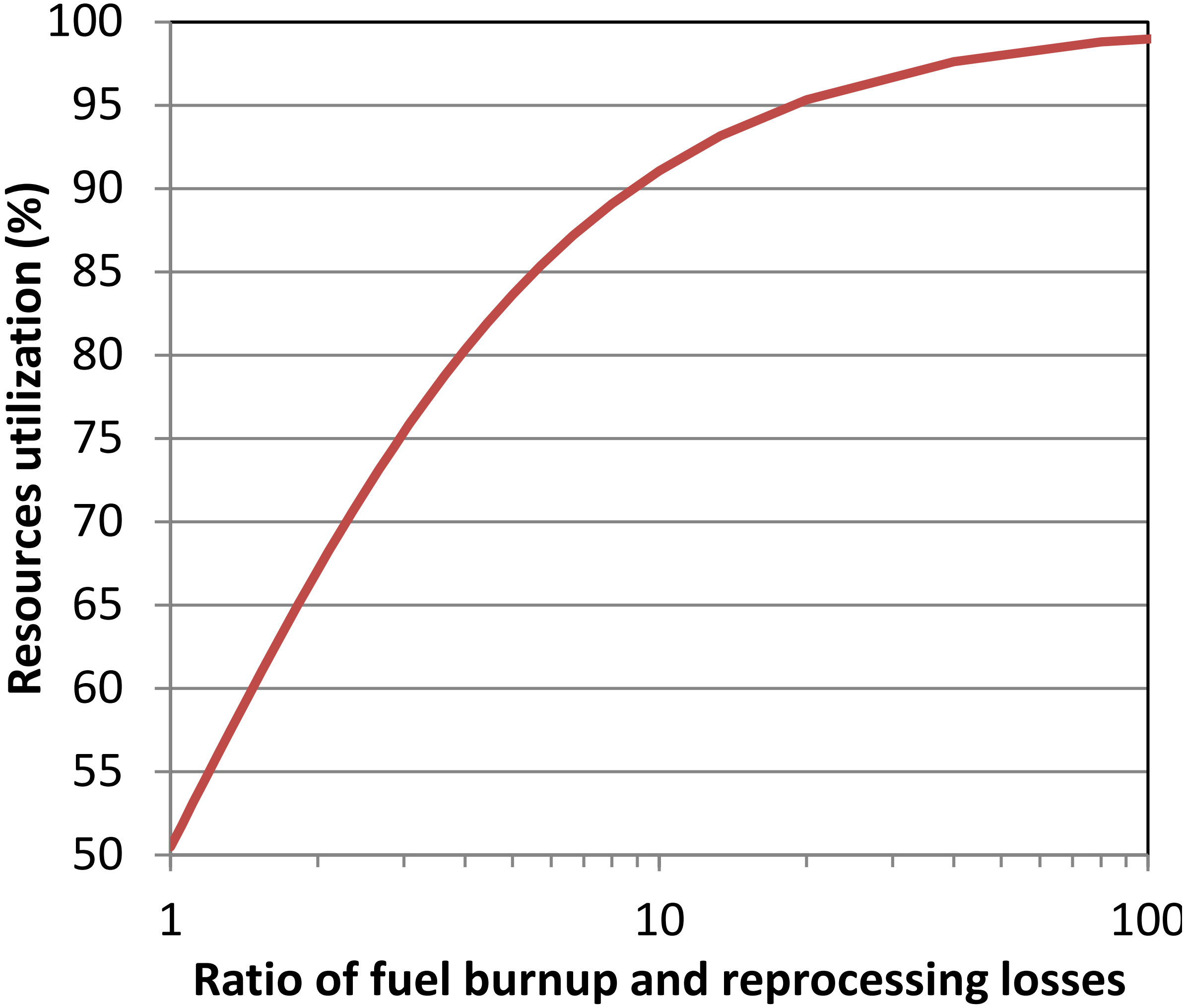


- There are always **reprocessing losses - L**.
- Utilization **above 90%** requires burnup **B** to be **10x** higher than reprocessing losses **L**.

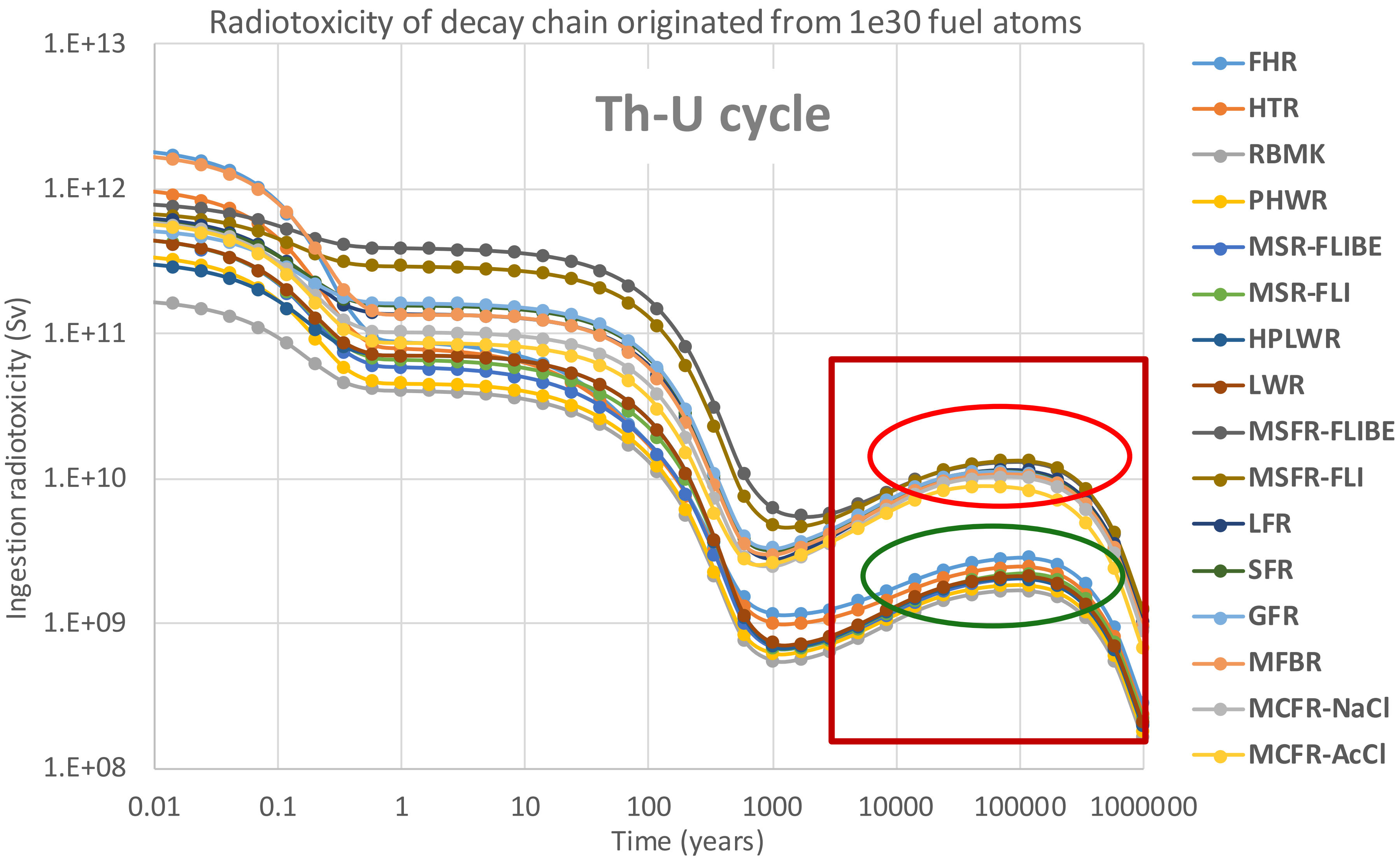
$$Utilization \cong \frac{x}{1+x} \qquad x = B/L$$



- **MSR can be sensitive to the losses**, because the reprocessed **fuel has often low burnup**.

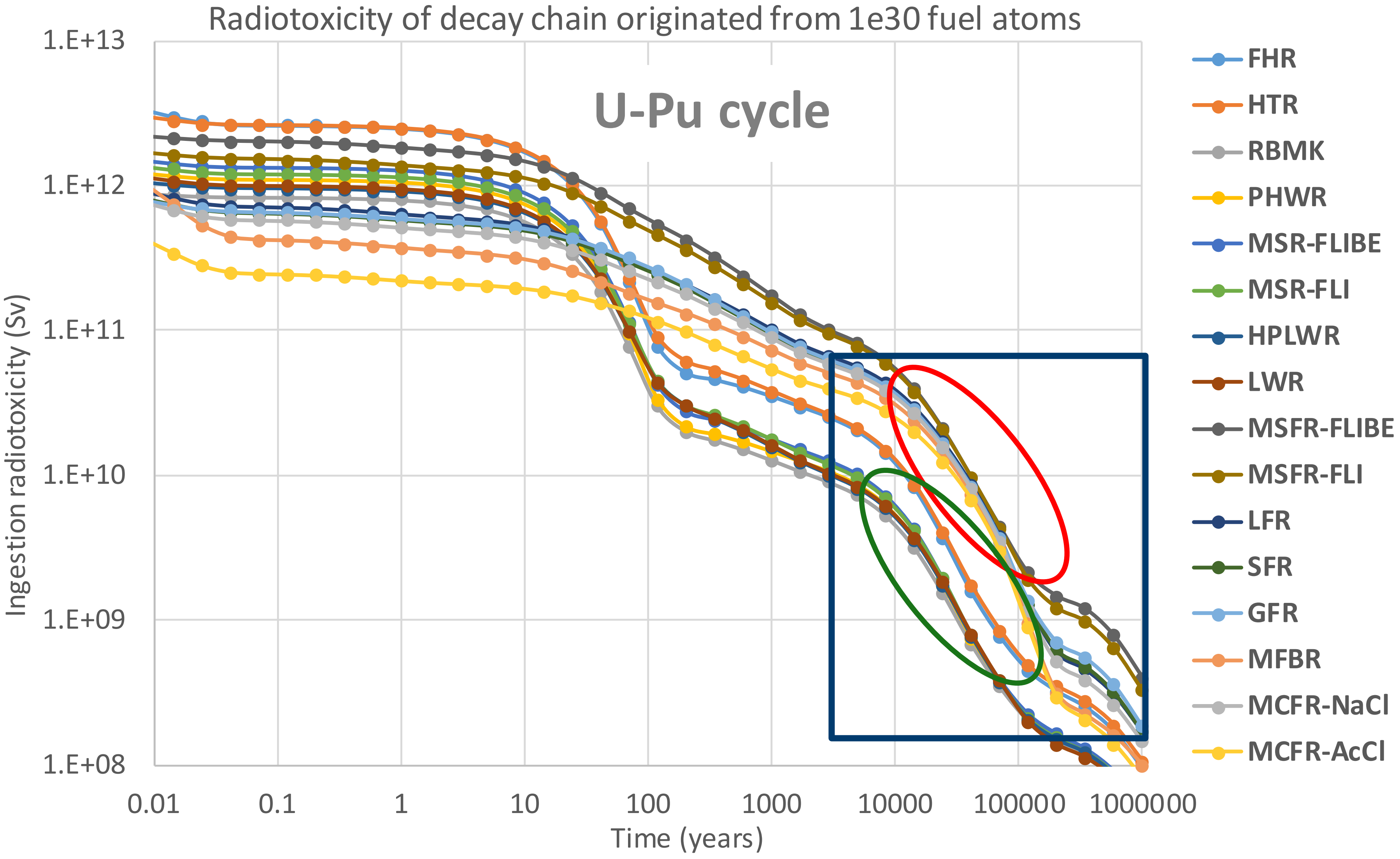
Relative fuel radiotoxicity of Th-U cycle

- **10^{30} fuel atoms** radiotoxicity.
- **Thermal reactors** are better than **fast reactors**.
- Some of them **cannot breed** and the chart does not account for reprocessing **frequency and losses**.
- **There is a secondary peak.**



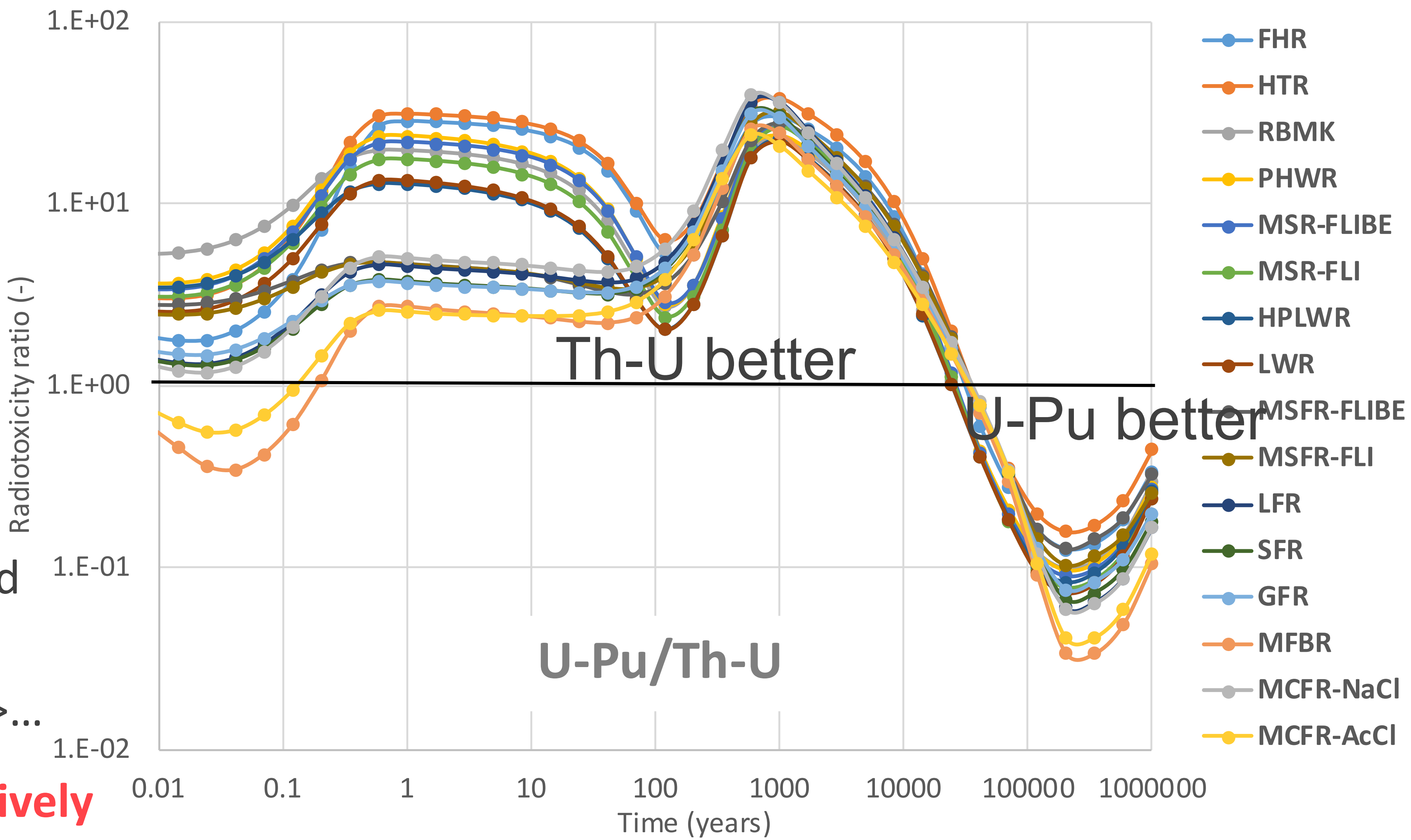
Relative fuel radiotoxicity of U-Pu cycle

- **10^{30} fuel atoms** radiotoxicity.
- **Thermal reactors** are better than **fast reactors**.
- Some of them **cannot breed** and the chart does not account for reprocessing **frequency and losses**.
- **There is not a secondary peak.**



Relative fuel radiotoxicity: Th-U X U-Pu cycle

- Th-U closed cycle provides in general lower radiotoxicity.
- Nonetheless, Th-U has secondary radiotoxicity peak but U-Pu not.
- It is predominantly caused by ^{238}Pu (and ^{237}Np) decay chain: ^{238}Pu->^{234}U->^{230}Th->…



- **This result is exclusively valid for cores with equal amount, burnup and treatment of the fuel!**

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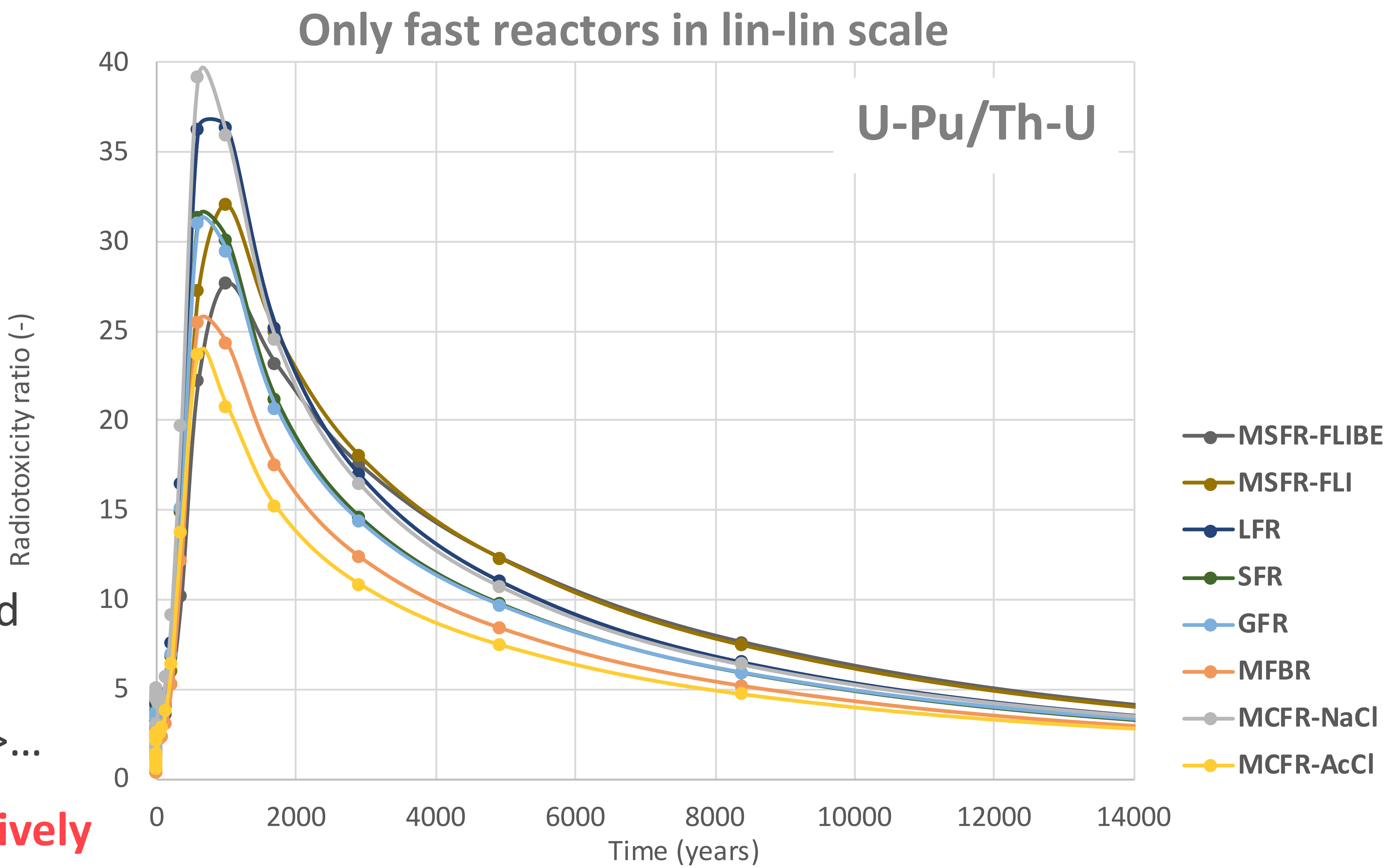
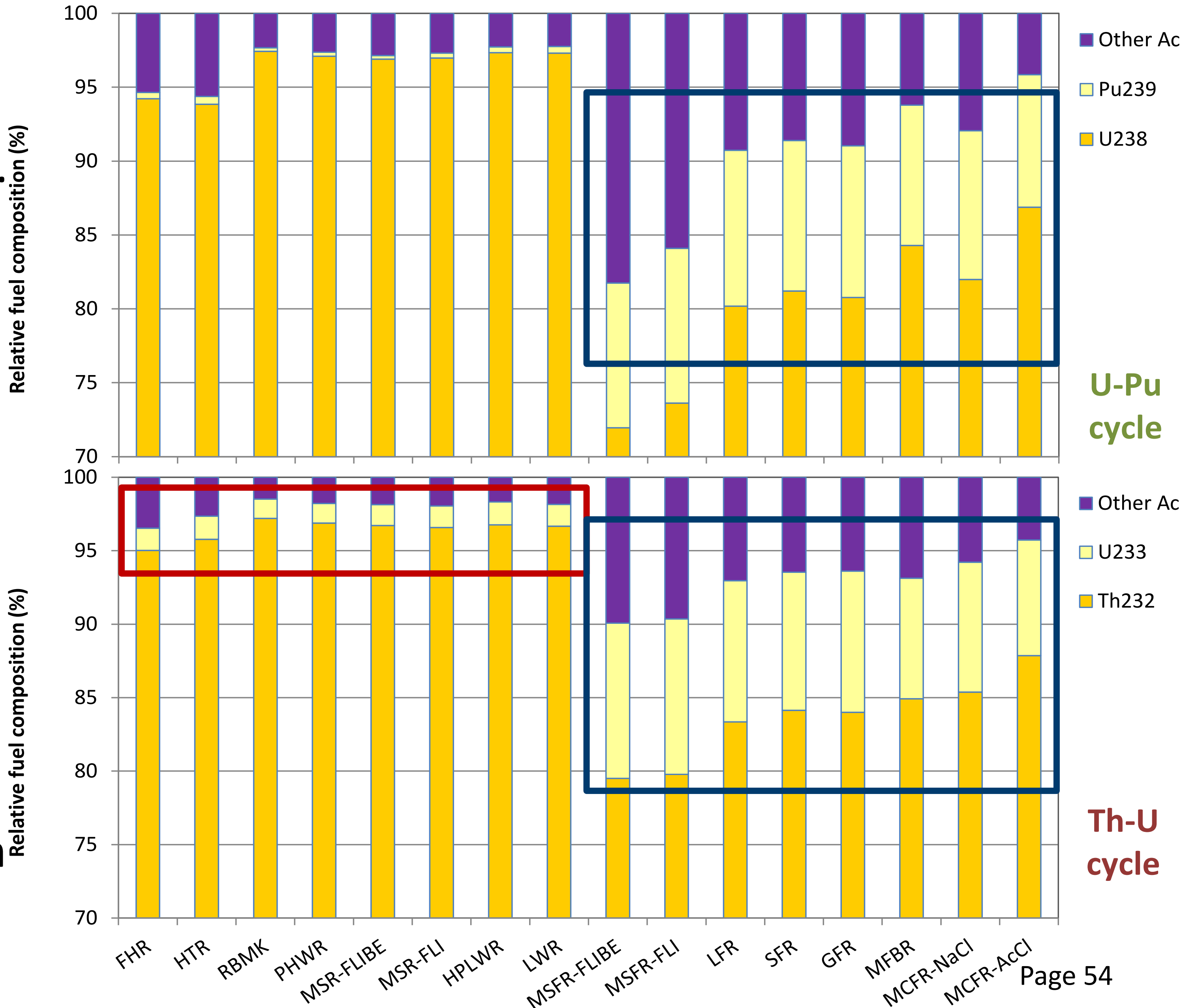


- **This result is exclusively valid for cores with equal amount, burnup and treatment of the fuel!**

5.Miscellaneous
a) Fission products importance

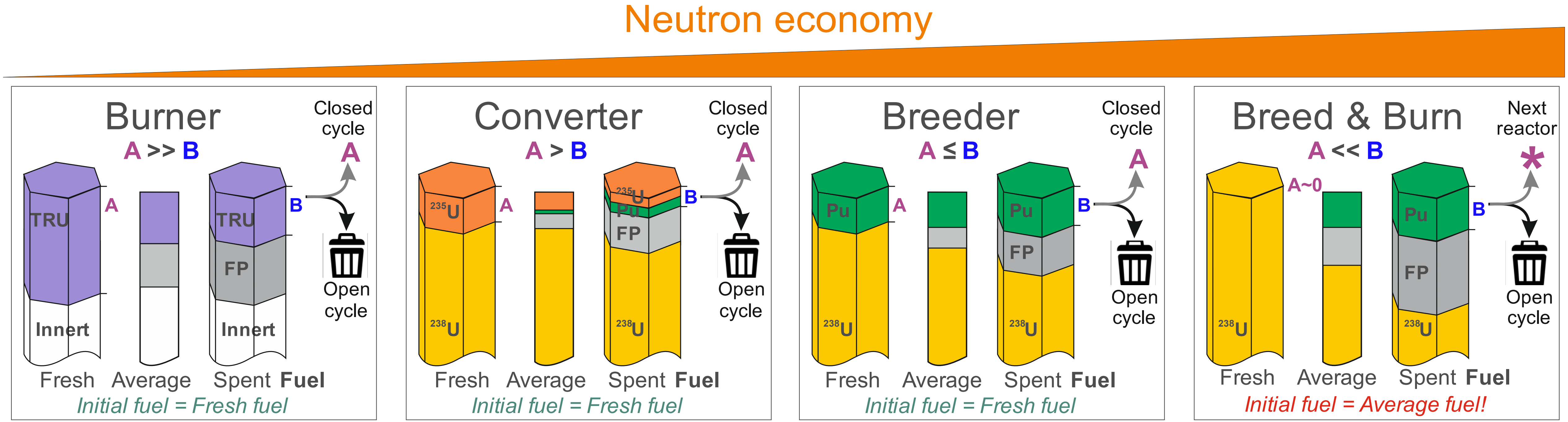
FPs importance

- Usual claim: **Fission products** (FPs) have **higher XSs** in thermal spectrum.
- Sure, but ^{233}U, ^{235}U, ^{239}Pu also.
- Fissile share in equilibrium:
  <2% for thermal **Th-U**
  ~10% in fast **Th-U** and **U-Pu** cycle
- Accordingly, **5% of FPs** relative to fissile share represent:
  250% in thermal Th-U case
  50% in fast Th-U and U-Pu cases.
- The **tolerance to FPs** in **fast** spectrum is strongly supported by **this feature**.



5.Miscellaneous
b) Closed cycle ≠ breeding

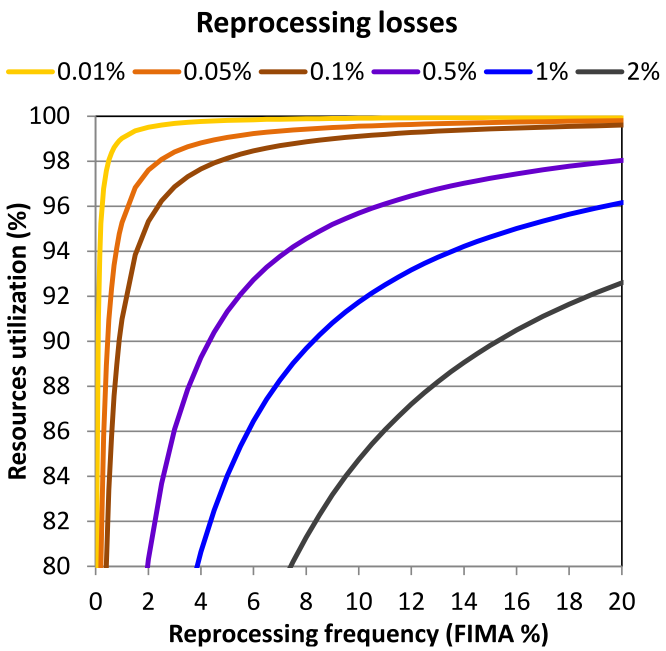
Reactor classification by neutron economy

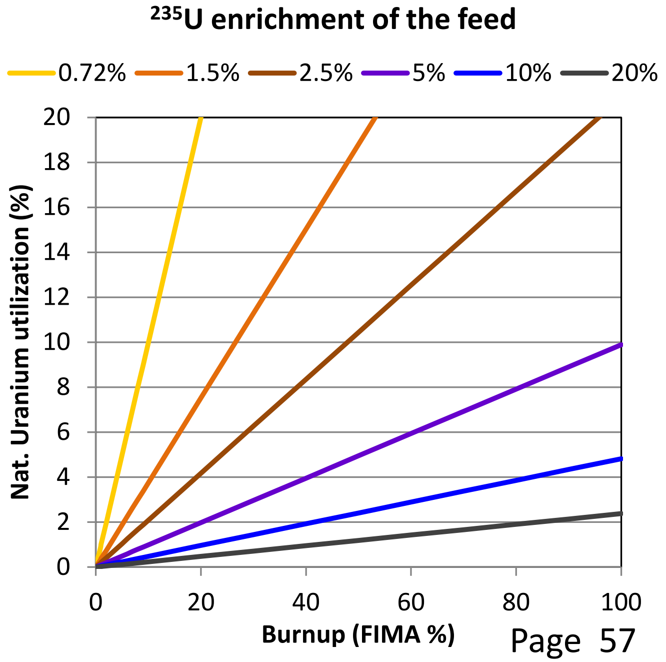


- Burner is typically used for waste burning and excludes fertile isotopes as ^{238}U or ^{232}Th.
- Convertor, e. g. LWR or DMSR, is usually operates in open fuel cycle and burns ^{235}U.
- Breeder profit from neutronics advantages only in the closed cycle.
  For Iso-breeding (EU) or Break-even (US) reactor => A=B.
- Extreme breeder can be operated in Breed & Burn mode.
  It can have high fuel utilization even without reprocessing.

Recycling X breeding

- Fuel cycle can be closed for: **Burner, Convertor, and Breeder**.
- Recycling does **not make sense** for **B&B** reactor.
  However, the fuel can be recycled and used in other reactor.
- **Recycling** is the ultimate **waste reducing** option.
- **Recycling in a breeder** => **highest** resources **utilization.**
  It is limited by reprocessing losses.
- **Recycling in a convertor** => **medium** resources **utilization.**
  It is limited by enrichment process and reprocessing losses.
- **Recycling in a burner** => mainly **waste minimization.**





5.Miscellaneous
c) Open cycle ≠ burning

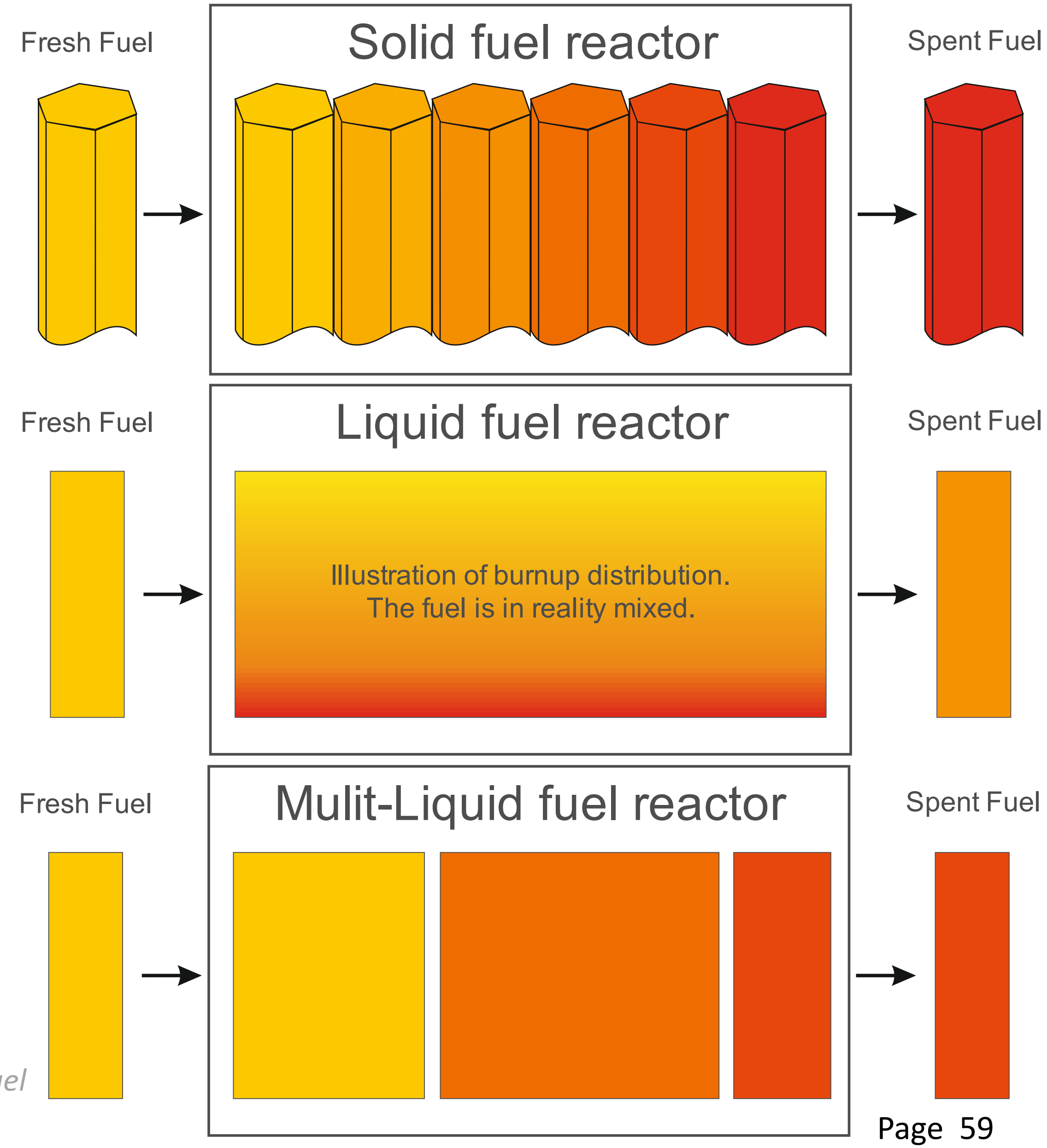
Breed & Burn (B&B)

special open cycle mode

- In B&B, initially the fissile fuel will be **bred** and firstly later it will be **burned**.
- The B&B cycle in **liquid fuel** reactor substantially differs from **solid fuel.**

  Discharged fuel:
  Most burned in solid fuel case
  Average burned in liquid fuel case.

- To increase the burnup and reduce the core size (**single-fluid** layout can be bulky), **multi-fluid** layout can be used.

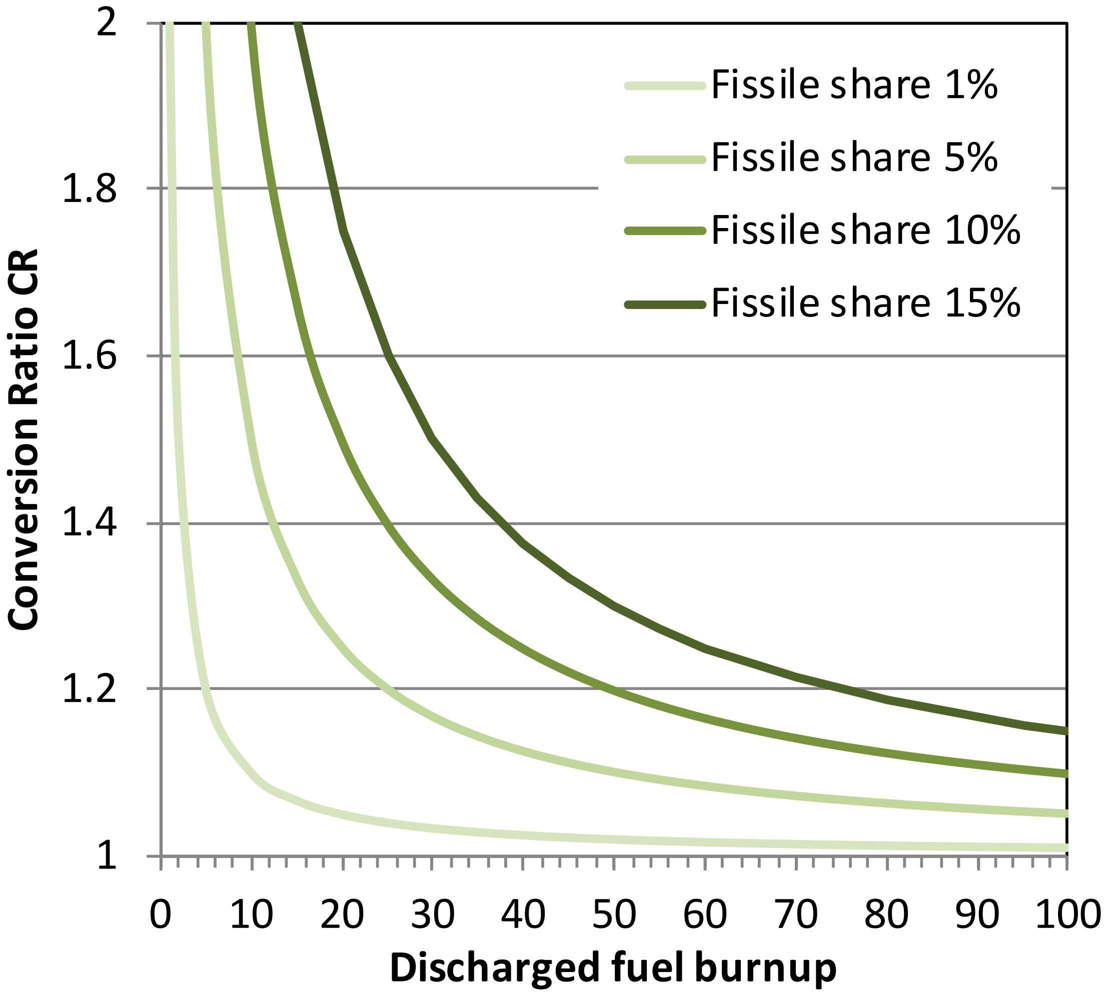


Hombourger, B., Křepel, J., Mikityuk, K., Pautz, A., 2017. On the Feasibility of Breed-and-Burn Fuel Cycles in Molten Salt Reactors, in: Proceedings of FR17. Yekaterinburg, Russian Federation.

B&B: trivial fuel cycle criteria

- In B&B cycle conditions:
  1) fresh fuel is only fertile material
  2) spent fuel is not recycled.
- B&B trivial criterion (tautology): **I = II**
  I: Fissile Fuel $\mathbf{F_F}$ share in the discharged fuel.
  II: New fissile fuel bred in the discharged fuel.
- $F_F = B(CR-1)$

where CR is conversion ratio and B is the fuel burnup.



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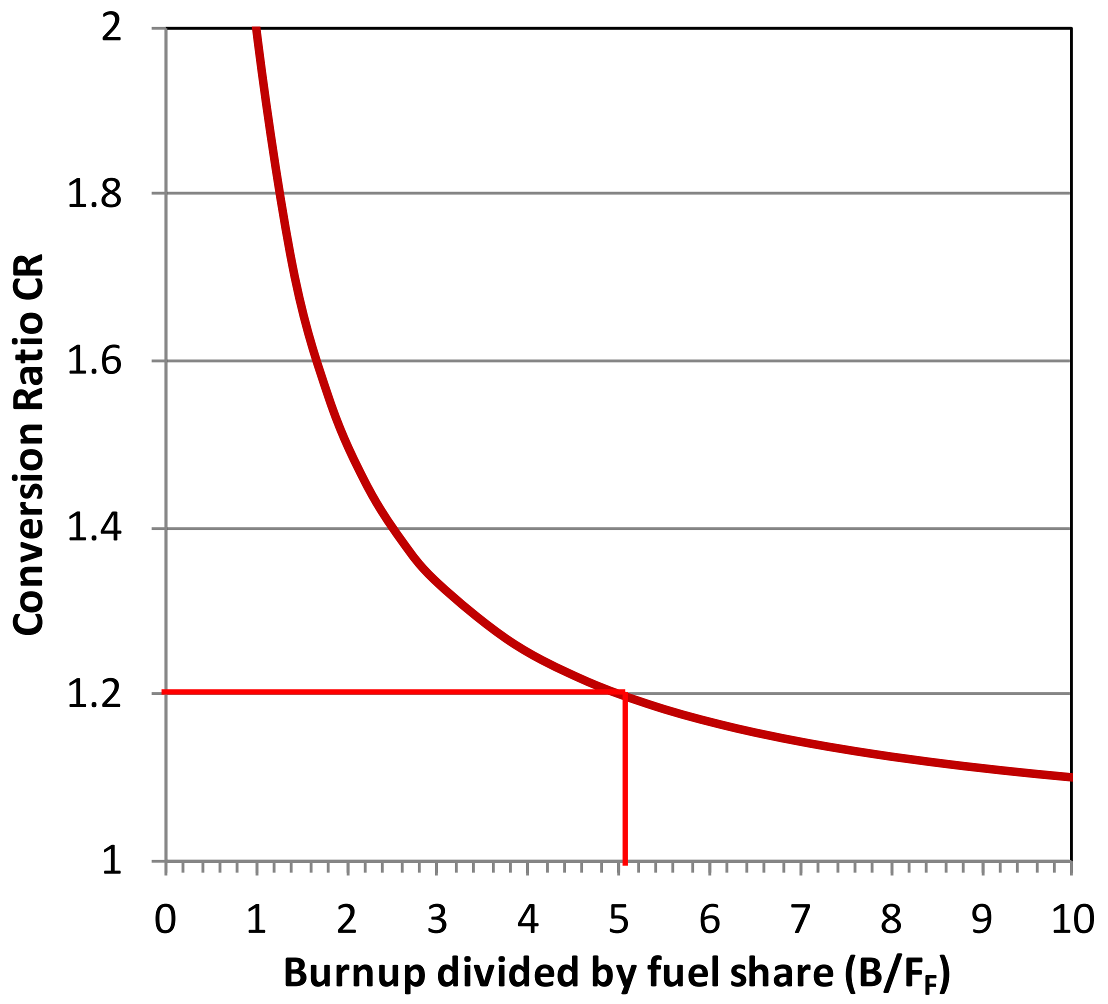
  I: Fissile Fuel $\mathbf{F_F}$ share in the discharged fuel.
  II: New fissile fuel bred in the discharged fuel.
- $$F_F = B(CR-1) \Rightarrow \frac{1}{CR-1} = \frac{B}{F_F}$$

  where CR is conversion ratio and B is the fuel burnup.
- Reactor must be critical for CR, F_F, and B,
  e.g. for CR=1.2: F_F=10% ⇔ B=50% (1% ⇔ 5%)
- Fuel utilization in B&B cycle?
  It is equal to the burnup.

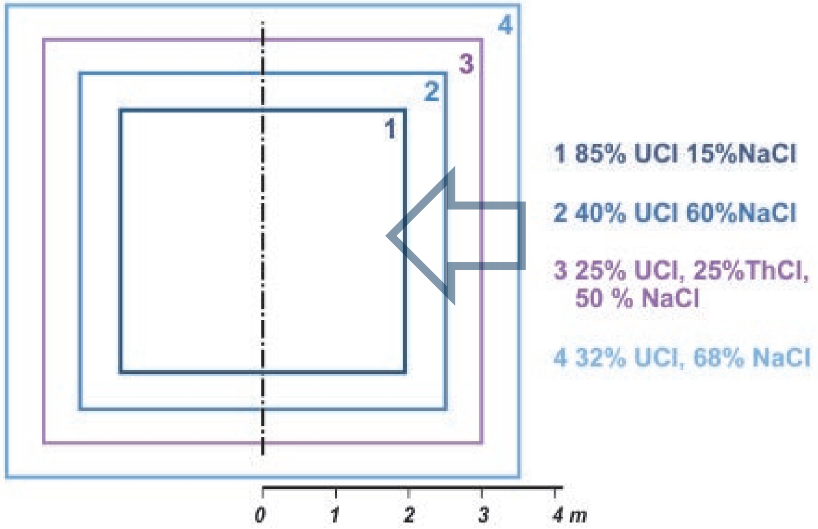


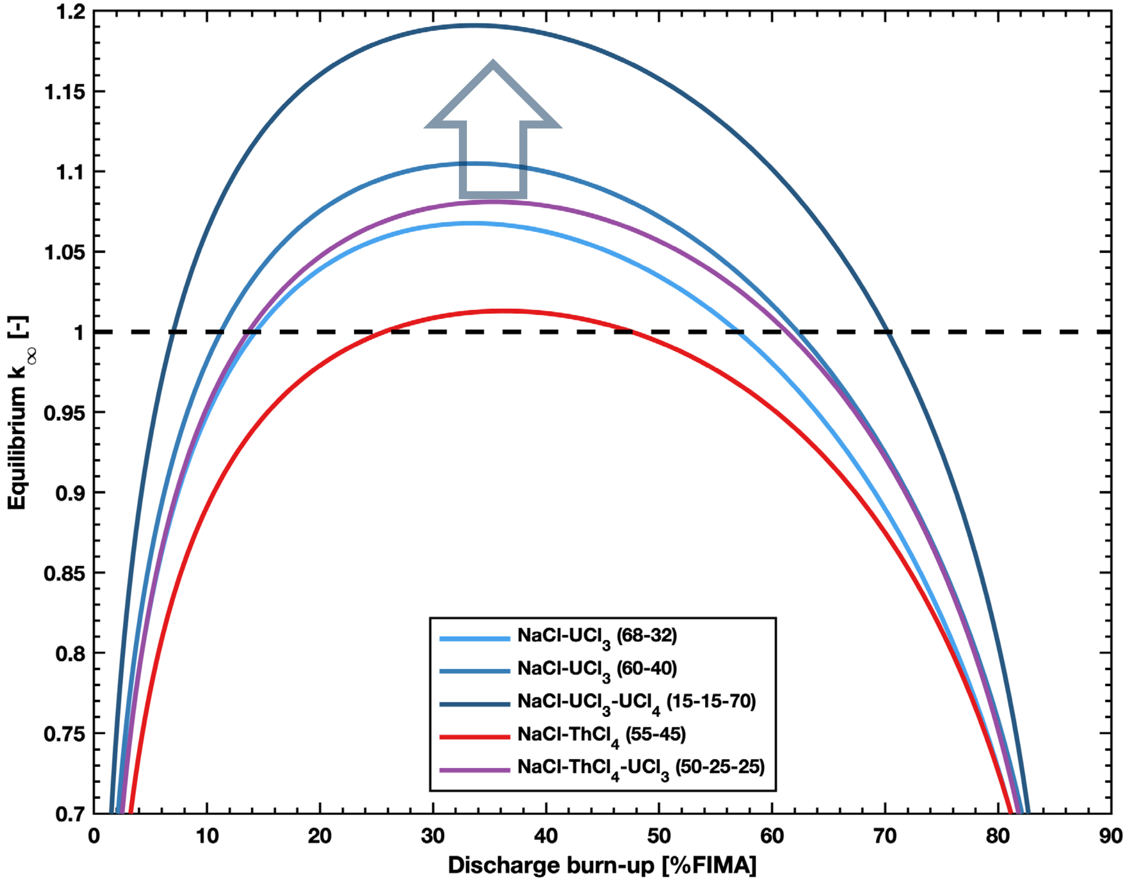
J. Krepel, B. Hombourger, E. Losa, Fuel cycle sustainability of Molten Salt Reactor concepts in comparison with other selected reactors, PHYTRA4, Marrakech, Morocco, September 17-19, 2018.

Breed and Burn in MCFR:

Th-U X U-Pu cycle

- B&B is practically not possible in Th-U cycle.
- It is only possible in mixed U-Pu & Th-U cycle.
- B&B cores are bulky (chlorides = hard spectrum, but also high Migration area).
- The performance increases in U-Pu cycle with growing actinides share in the core.





Hombourger, B. et al., 2019. Breed-and-Burn Fuel Cycle in Molten Salt Reactors. Submitted to special MSR edition of The European Physical Journal

5.Miscellaneous
d) Transition to equilibrium

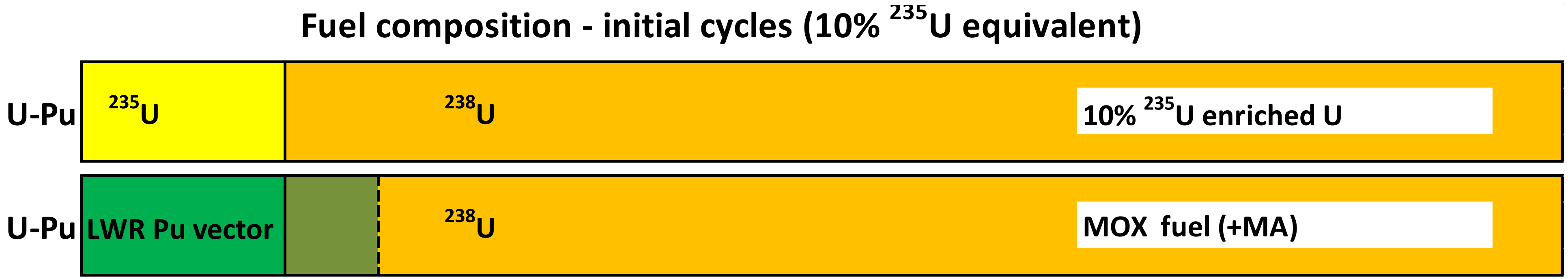
Transition to equilibrium

5 major fissile materials to approach the equilibrium

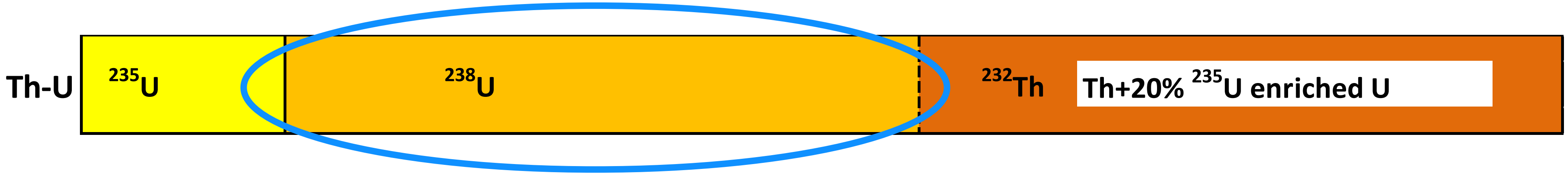
Material	RG_Pu	LEU	HEU	U233	WG_Pu
Fissile isotope(s)	^{239}Pu, ^{241}Pu	^{235}U	^{235}U	^{233}U	^{239}Pu
Fissile isotope share	~60%	1-20%	21-95%	60-100%	>93%
"Availability"	medium	high	high	low	medium
Proliferation risk	medium	medium	high	high	high

RG_Pu and LEU as initial fuel load

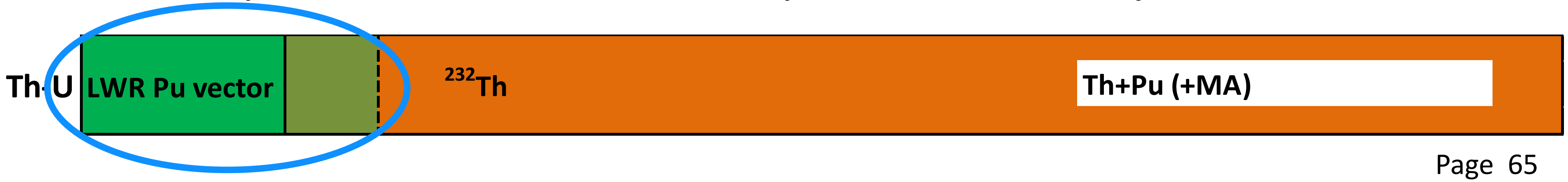
- Both **RG_Pu** and **LEU** are very natural option to start the **U-Pu** cycle.



- Starting **Th-U** cycle with **LEU** induces **^{238}U presence** in the core.



- Starting **Th-U** cycle with **RG_Pu, LEU** or their mixture introduces strong **perturbation**.
- **Pu and $^{235 \& 238}U$** are not presented in the salt at equilibrium Th-U cycle.



Summary of neutronics comparison

	U-Pu cycle	Th-U cycle
Reserves of ^{238}U and ^{232}Th:	no argument for preference, we are lucky to have both.	
Features of ^{238}U and ^{232}Th:	slightly better *(direct fission, etc.)*	
Features of ^{239}Pu and ^{233}U:	higher ν, higher capture	lower ν, lower capture
Thermal spectrum capability:	no	yes
Fast spectrum capability:	yes	yes
Breed and burn capability:	yes	no
Radiotoxicity at equal conditions:	initially higher	lower
Core size for fast reactors:	smaller	bigger
Core size in fluoride MSFR:	slightly bigger	smaller
Initial fuel for transition to eql.:	LEU or RG_Pu	RG_Pu or LEU in mixed cycle

GEN IV International Forum[SM]

Upcoming Webinars

29 July 2020	Overview of Small Modular Reactor Technology Development	Dr. Frederik Reitsma, IAEA
26 August 2020	MSR Safety Evaluation in the US	Dr. David Holcomb, ORNL, USA
22 September 2020	Integrated Energy Systems Laboratory Initiative	Dr. Shannon Bragg-Sitton, INL, USA