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Estimation of minimal critical size of bare iso-breeding core for 8 selected fast reactors in Th-U and U-Pu cycles

Technical Meeting on the Benefits and Challenges of Fast Reactors of the SMR Type

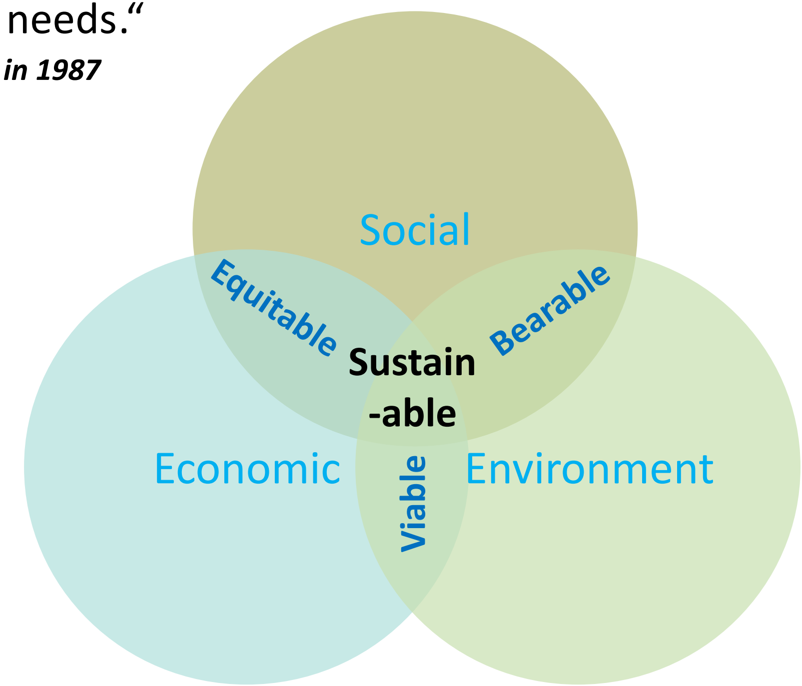
24–27 September 2019 Milan, Italy

Introduction 1: General sustainability

- "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.“
  Brundtland Commission in 1987

- The three pillars / factors of sustainability:

  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.

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

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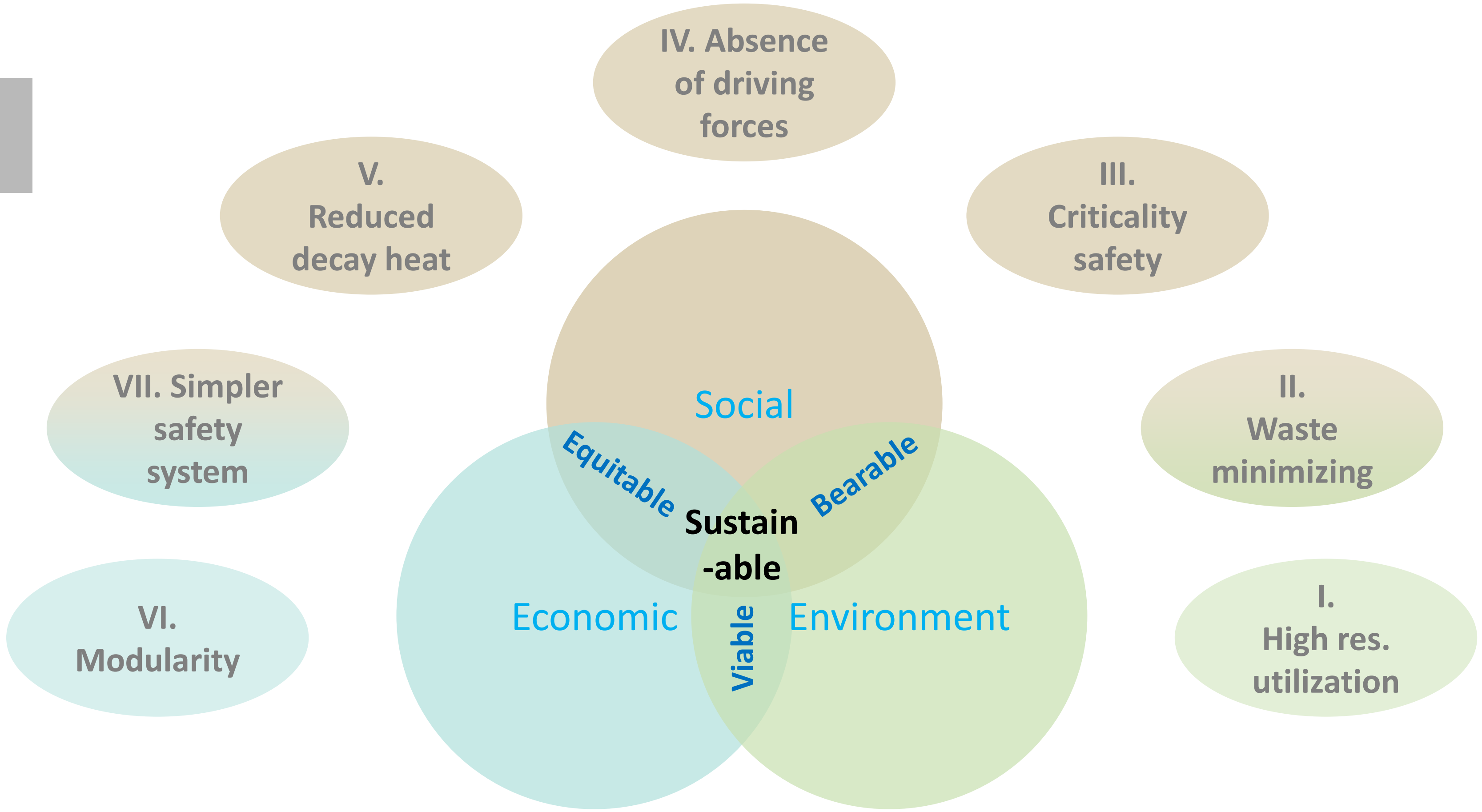
Introduction 2: Issues with current reactors

1. **Safety** (social sustainability)
   of GenIII / GenIII+ reactors is very high. Nonetheless, due to the **driving forces** presence (pressure, exothermic reactions, etc.), robust barrier system is needed to isolate the source term from environment in case of accident. There is still **residual risk** of failure.

2. **Waste and fuel scarcity** (social and environmental sustainability)
   current reactors are predominantly relaying on **low enriched uranium** (^{235}U < 5 %) and **spent fuel** is often not recycled (long term stewardship burden). Even when recycled, the low enriched uranium is needed. LWR's can **not breed** enough own fuel and cannot thus use solely ^{238}U or ^{232}Th.

3. **Capital cost** (social and economical sustainability)
   the biggest issue of current reactors is probably the capital cost. **Pressurized components** and robust, redundant and diversified **complex safety system** are a burden.
   Many of currently constructed reactors are **first-of-a-kind** and this fact, together with safety / **local regulation**, often increases the capital cost (cause delays).

Potential advantages/features of fast SMRs



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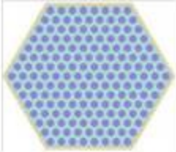
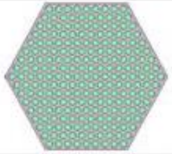
Content of this study

- For environmental and social sustainability it is important to maximize energy production from natural resources. In nuclear cycle it typically means fuel recycling.
- Repetitive recycling with fixed fuel cycle parameters leads to an equilibrium closed cycle. The equilibrium represents Eigen-state of the Bateman equation.
- In broader study the Eigen-state was simulated for 8 fast reactors.
- Several strongly simplifying assumptions were used.
- In this study the minimal size of bare iso-breeding critical core was estimated and compared between 8 fast reactors and two fuel cycles: Th-U and U-Pu.

Equilibrium cycle comparison for 8 fast reactors

- **Assumptions:**
  1) infinite lattice.
  2) bare core for critical size estimation.
  3) neglected fission products.
  4) design as is, no additional optimization.
  5) ENDF/B-VII.0.
- **8 fast reactors:**
  4x MSR, LFR, GFR, SFR, and MFBR
  were compared in both
  U-Pu and Th-U cycles.
- It is a sub-set of bigger study where 16 reactors (8 thermal and 8 fast were compared)

Solid fuel fast reactors			
Reactor name (and label)	**Lattice geometry**	**Name and short name**	**Lattice geometry**
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.

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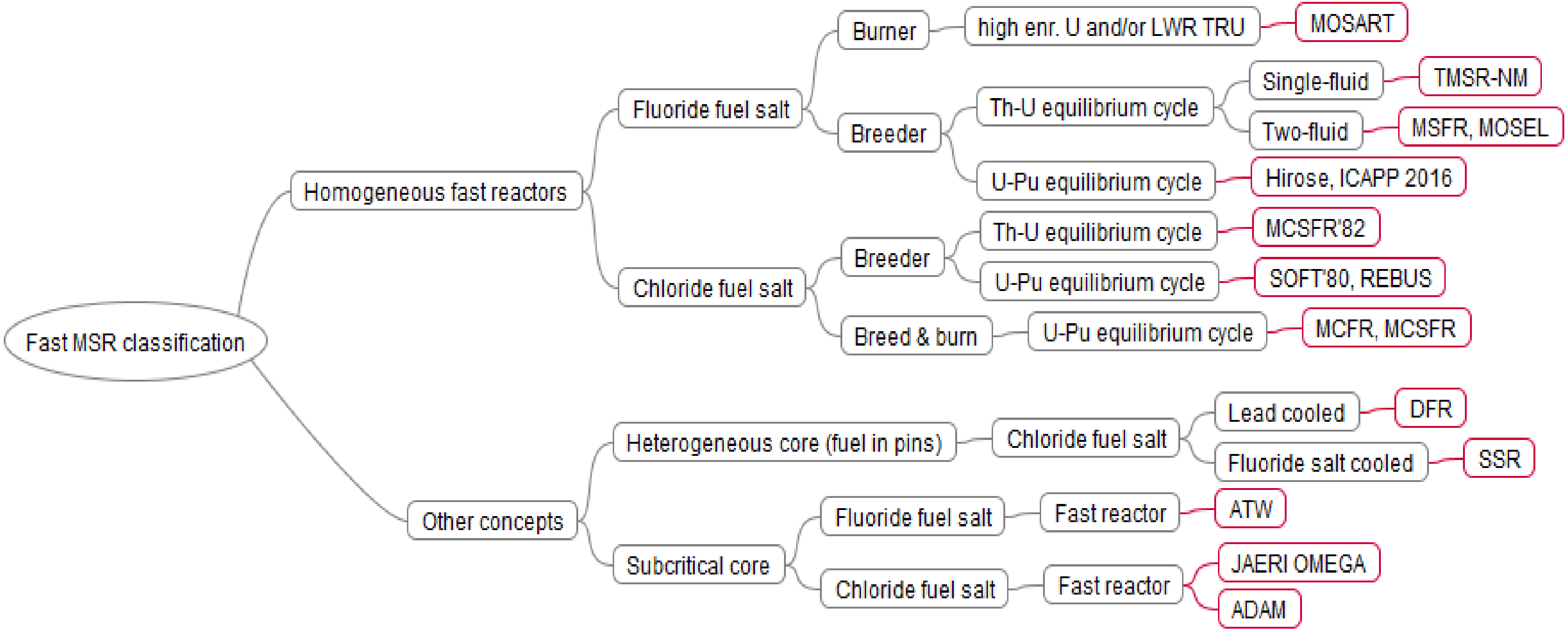
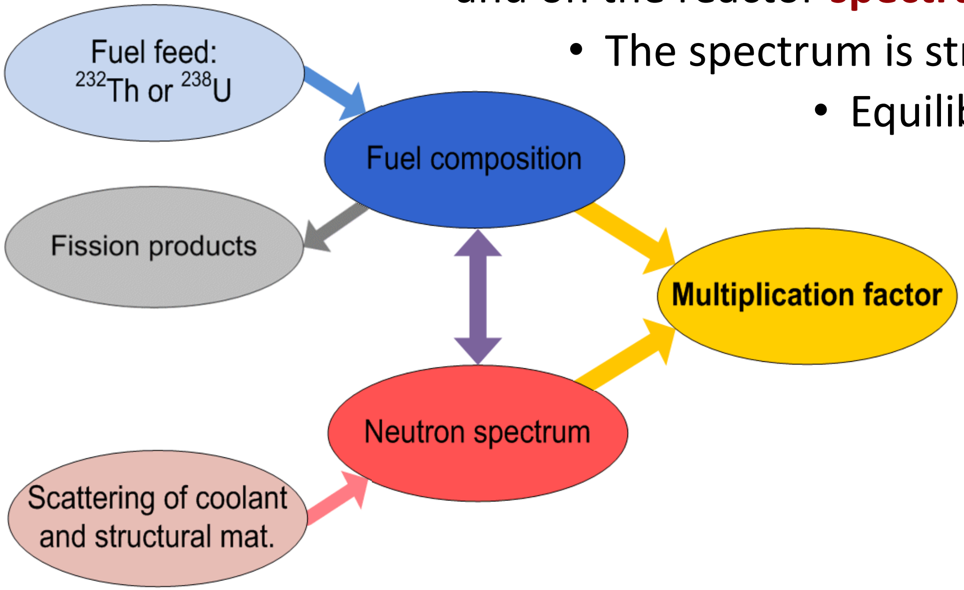


Repetitive recycling = equilibrium cycle

- 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
    - and on the reactor **spectrum**.
      - The spectrum is strongly determined by **scattering materials**.
        - Equilibrium composition and spectrum determine the **multiplication factor**.

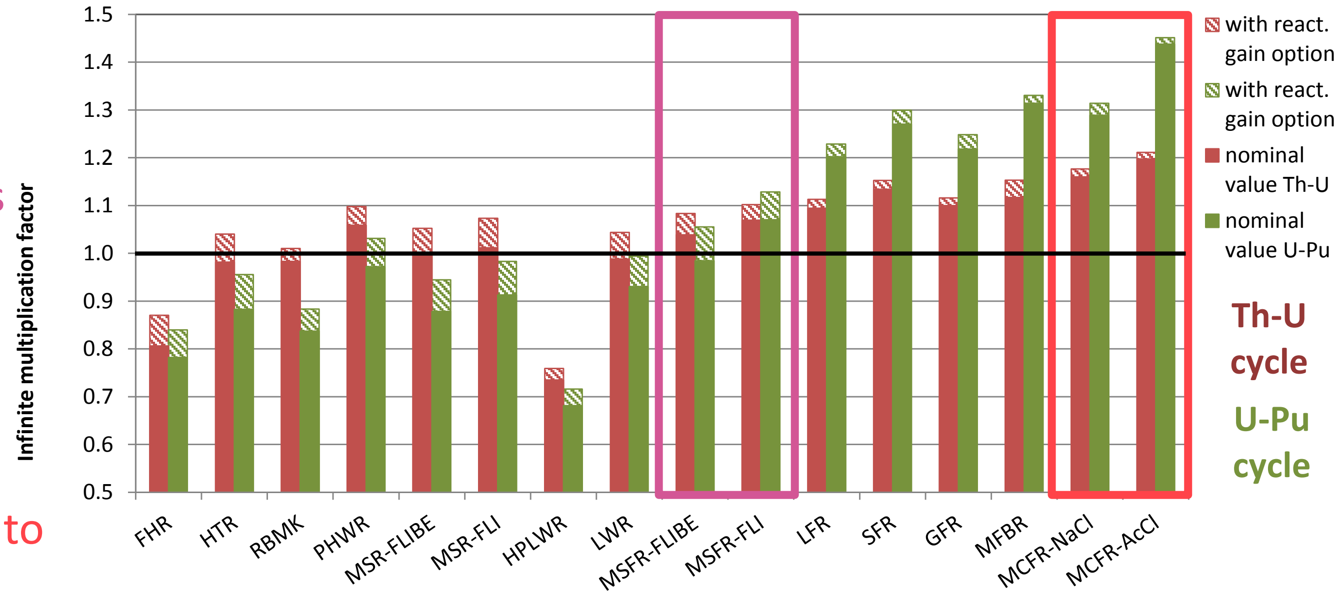


- Equilibrium is **inherent core state.** *(Bateman's matrix eigenstate: composition, spectrum, reactivity)*
- Equilibrium **reactivity** indicates neutron **efficiency** of the core and its **capability for breeding**.

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

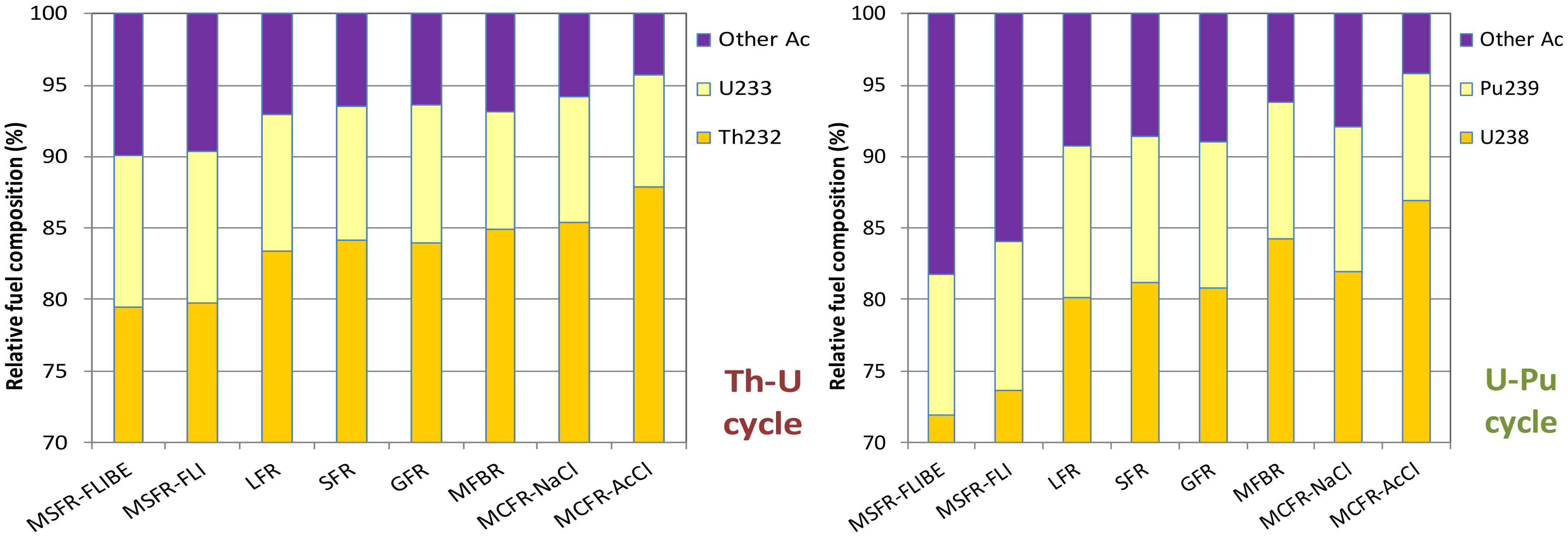
Equilibrium multiplication factor (reactivity)

- Better performance: **Th-U in thermal** and **U-Pu in fast** spectra.
- Fluorides fast MSFR possible in both cycles (equal performance but very soft fast spectrum).
- Chlorides fast MCFR comparable reactivity to solid fuel fast reactors.



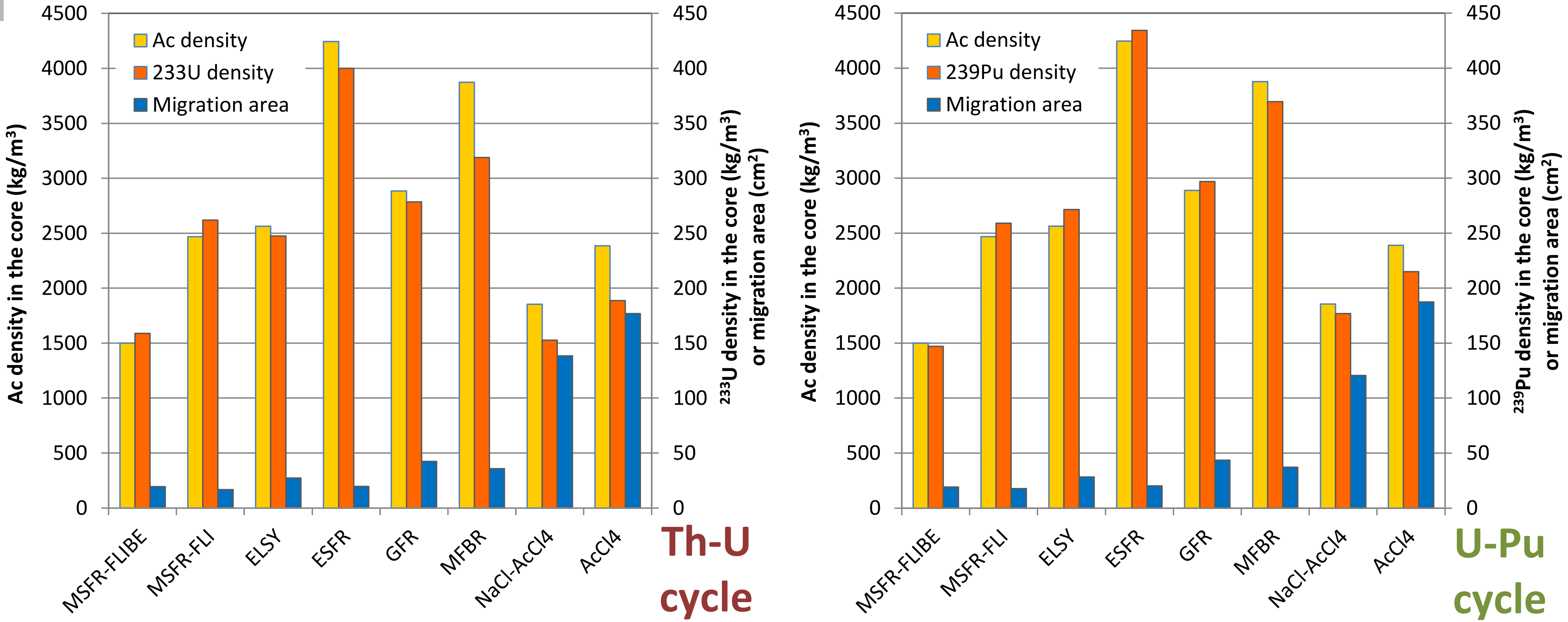
Relative equilibrium fuel composition

- All studied fast reactors have roughly the same fuel composition.
- Only MSFR with very soft fast spectrum produce more of higher actinides.



Actinides specific density and migration area

- All studied fast reactors have roughly the same fuel composition.
- Only MSFR with very soft fast spectrum produce more of higher actinides.



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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:

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

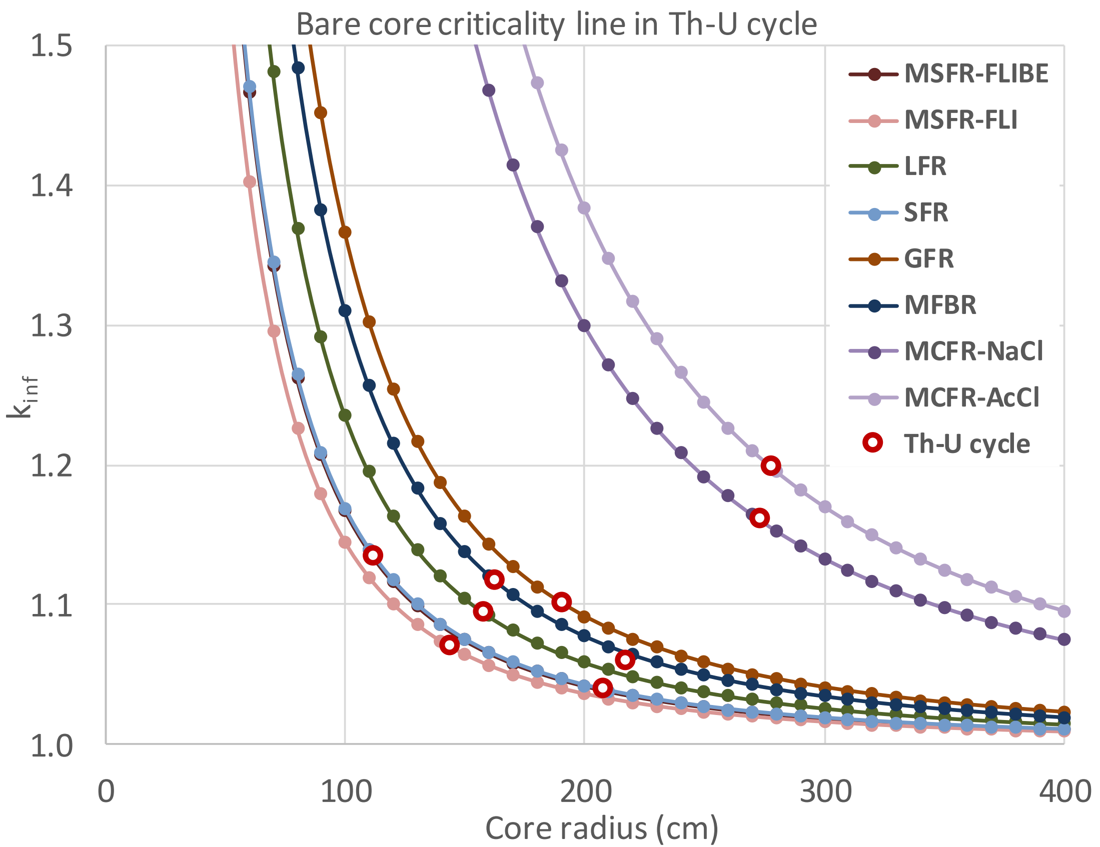
- Buckling for a cylinder:

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

- 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 =>**



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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:

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

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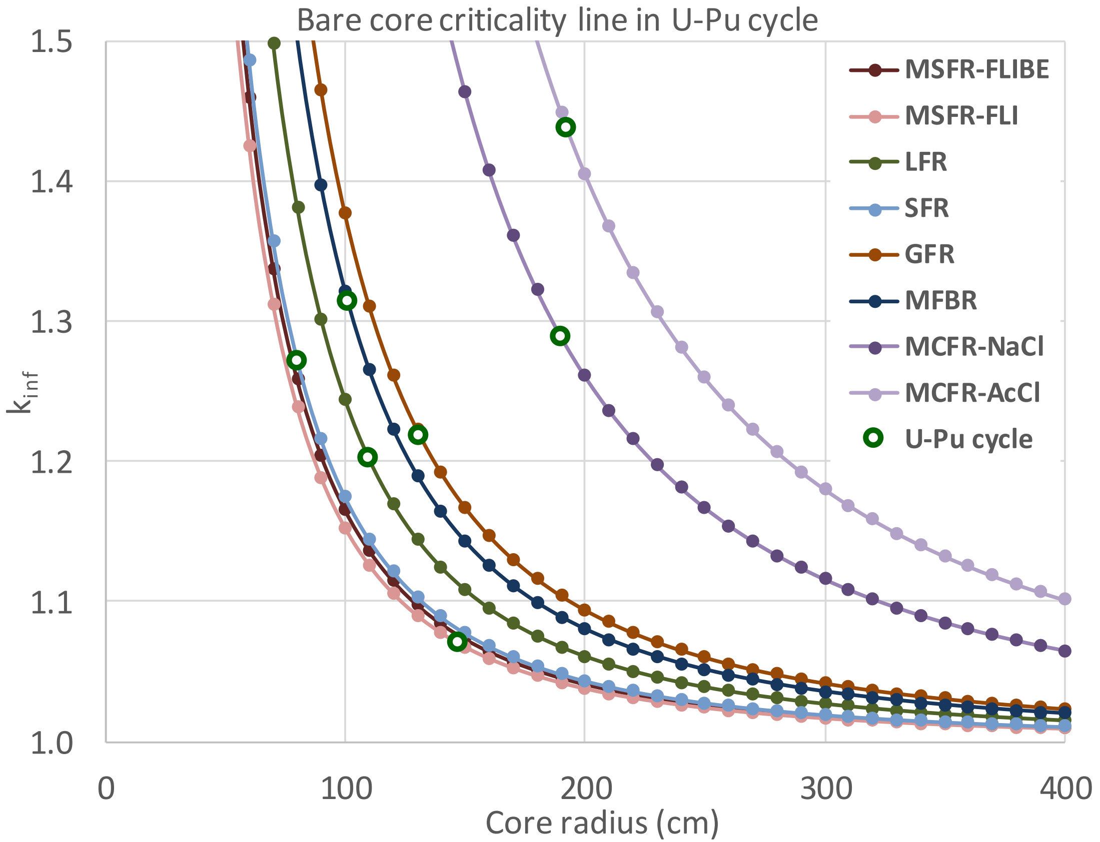

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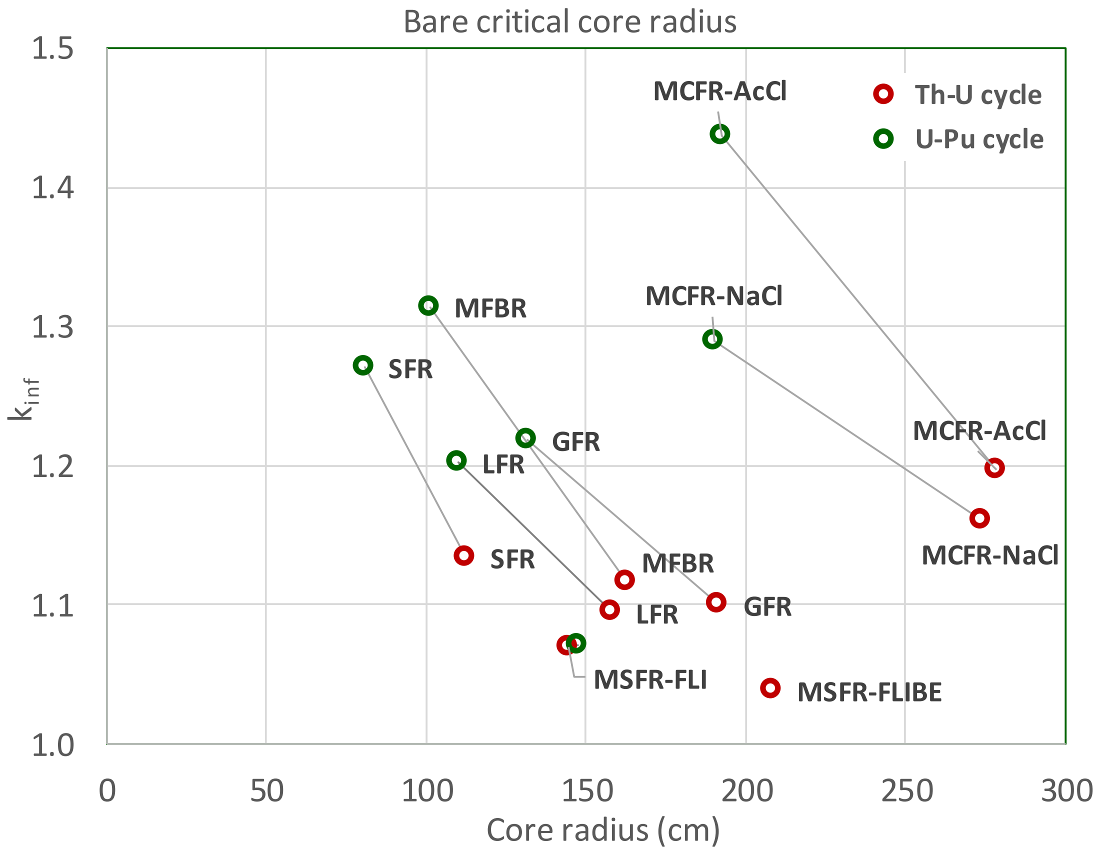
Core radius estimate: Th-U cycle X U-Pu cycle

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



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Equilibrium state: k_{eff} and BG relation

- In equilibrium (Bateman matrix eigenstate) 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 of fertile material so that k_{eff} = 1 and BG ≠ 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.

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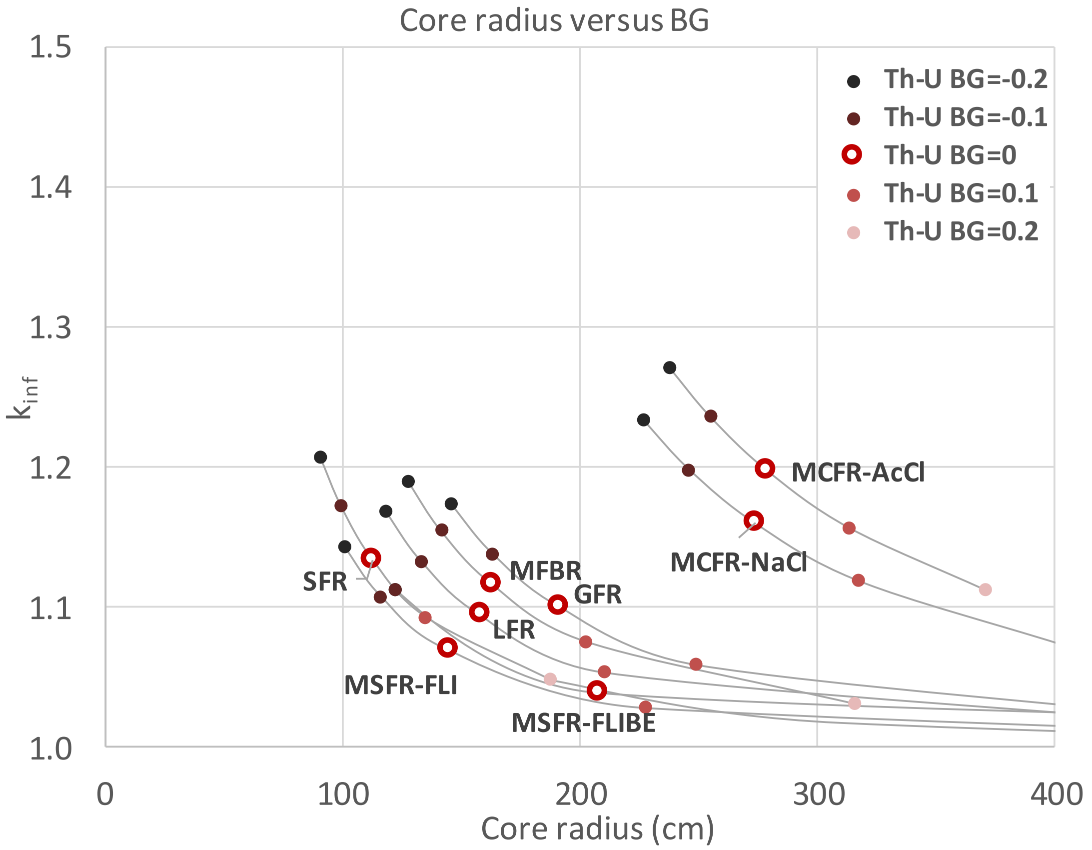
Core radius estimate in Th-U cycle

- Combining these two equations:

$$k_{eff} \cong k_{\inf} \frac{1}{1+M^2B^2}$$

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

- Bare core size can be estimated for several BG values.
  Th-U cycle =>



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Core radius estimate in U-Pu cycle

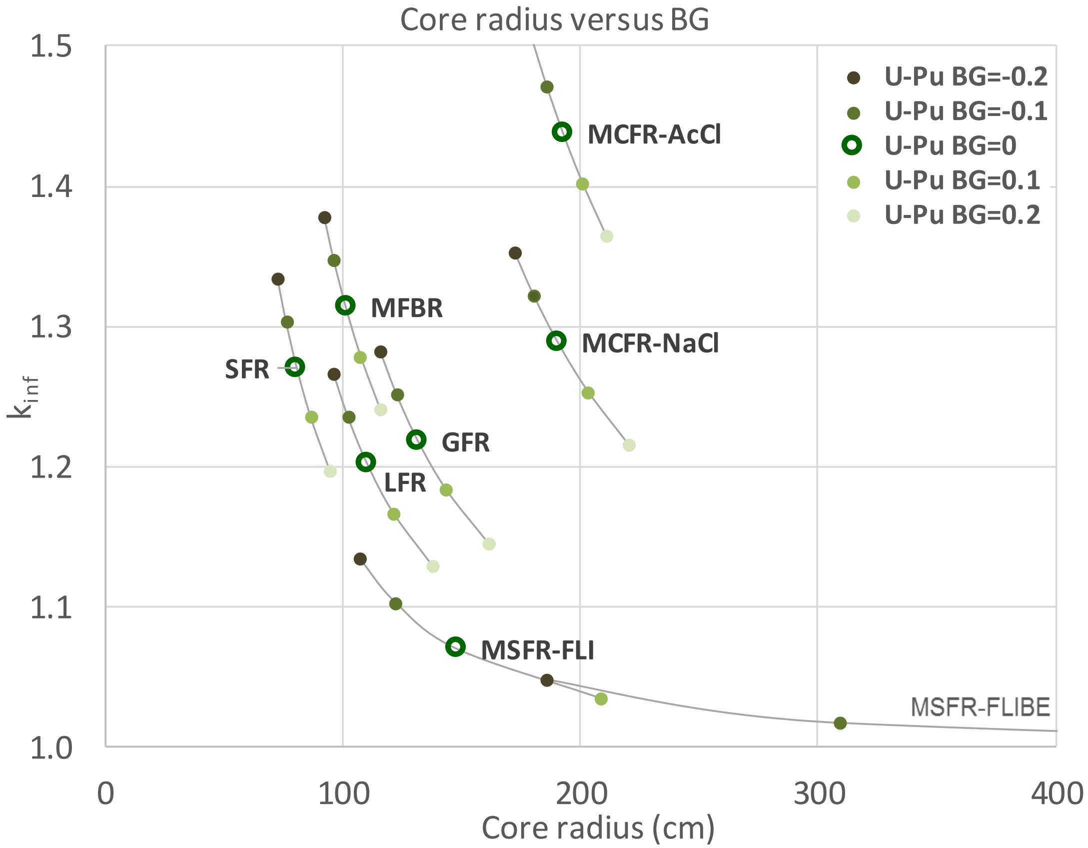
- Combining these two equations:

$$k_{eff} \cong k_{\inf} \frac{1}{1+M^2B^2}$$

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

- Bare core size can be estimated for several BG values.

U-Pu cycle =>



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Summary and conclusions

- **8** selected fast reactors 4 with **liquid** and 4 with **solid** fuel were compared at **equilibrium** closed **Th-U and U-Pu** fuel **cycles**.
- **U-Pu cycle** stronger profits from **spectrum hardening** and in all cases provide higher k_{inf} and smaller critical iso-breeding core than Th-U cycle (except MSFR).
- **Metal cooled reactors** in U-Pu (SFR, LFR, and MFBR) provide the **most compact core**.
- Nonetheless, the **actual SMR design** will strongly depend on: core shape (**pan cake**), reflector or **blanket** application, and foreseen fuel **burnup**.

Wir schaffen Wissen – heute für morgen

Thank you for your attention.