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Molten Salt Reactor: sustainable and safe reactor for the future?

NES colloquium 14.09.2016

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INTRODUCTION

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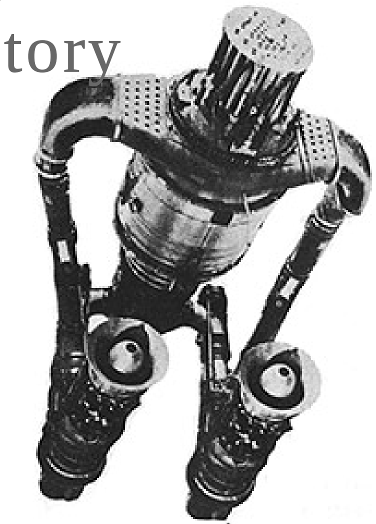
History of Molten Salt Reactor (MSR) started at Oak Ridge National Laboratory

Illustration, not MSR

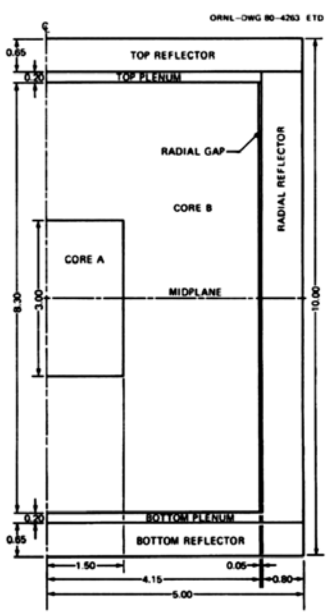


- **1950s** • **Aircraft Reactor Experiment (ARE)***
- **1960s** • **Molten Salt Reactor Experiment (MSRE)***
- **1970s** • **Molten Salt Breeder Reactor (MSBR)***
- **1970s** • **EIR (PSI) study (report nr. 411, 1975)**

  fast spectrum, chlorides

- **1980s** • **Denatured Molten Salt Reactor (DMSR)***

*** ORNL**



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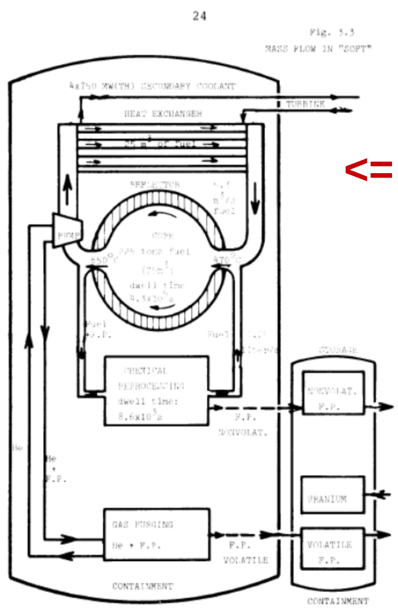

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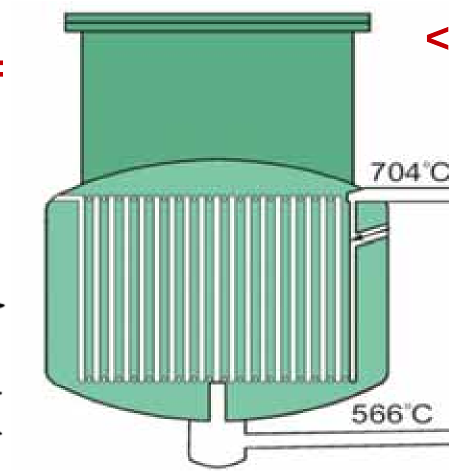

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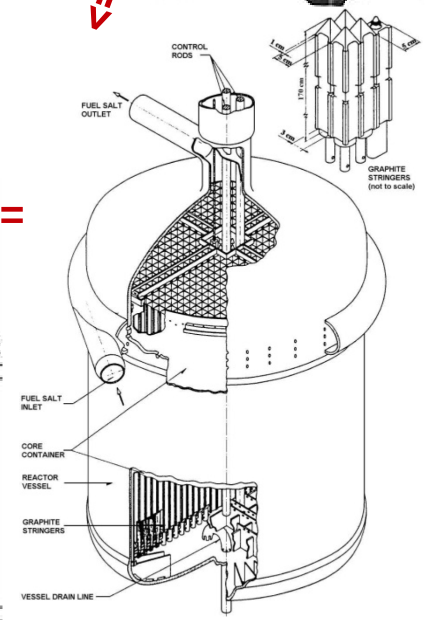


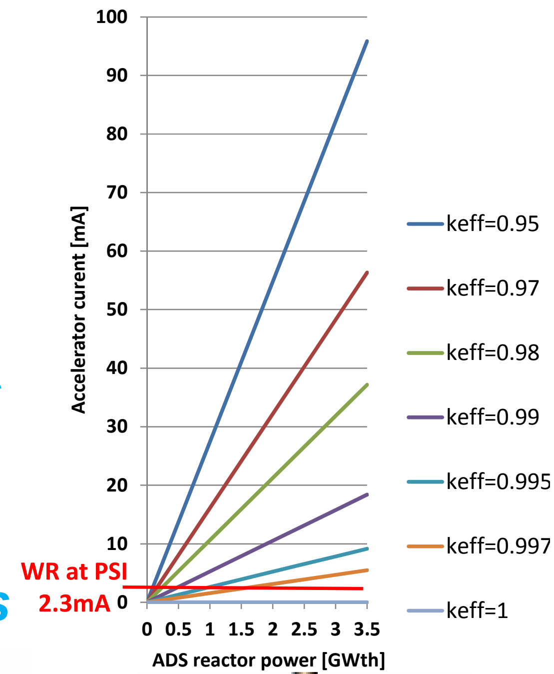
History of MSR: revival

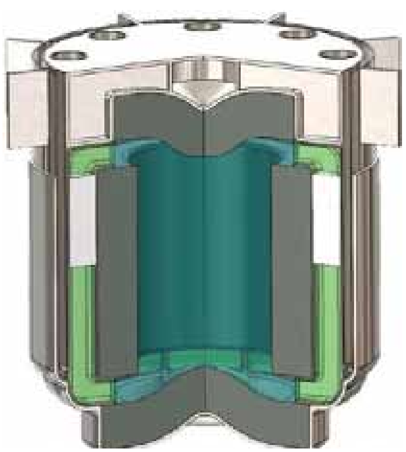
1990s • Accelerator-driven transmutation of Nuclear Waste - ATW (LANL)

2000s • Generation IV, Amster, Sphinx, …

2010s • MSFR, Mosart, … *fast spectrum, fluorides*
FHR (fluorides cooled HTR)

2015+ • MCFR, Breed & Burn (TerraPower, PSI, …)
fast spectrum, chlorides





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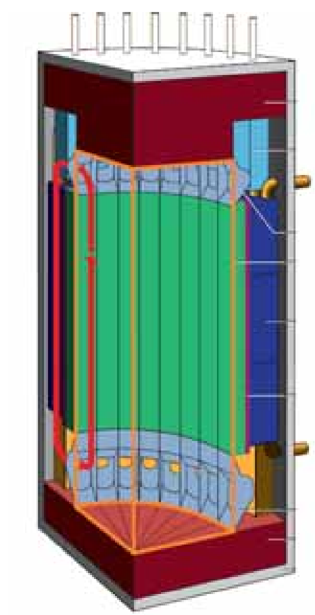

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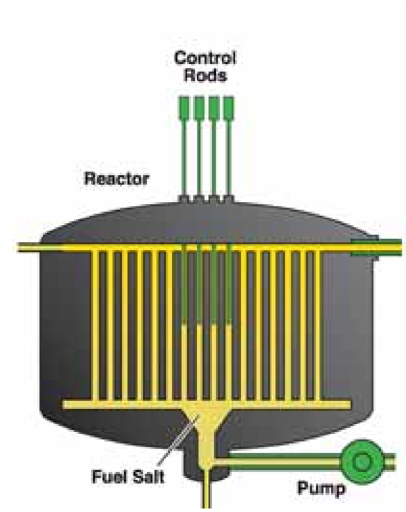

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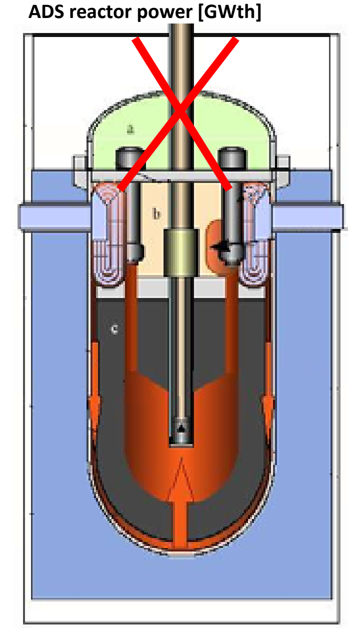
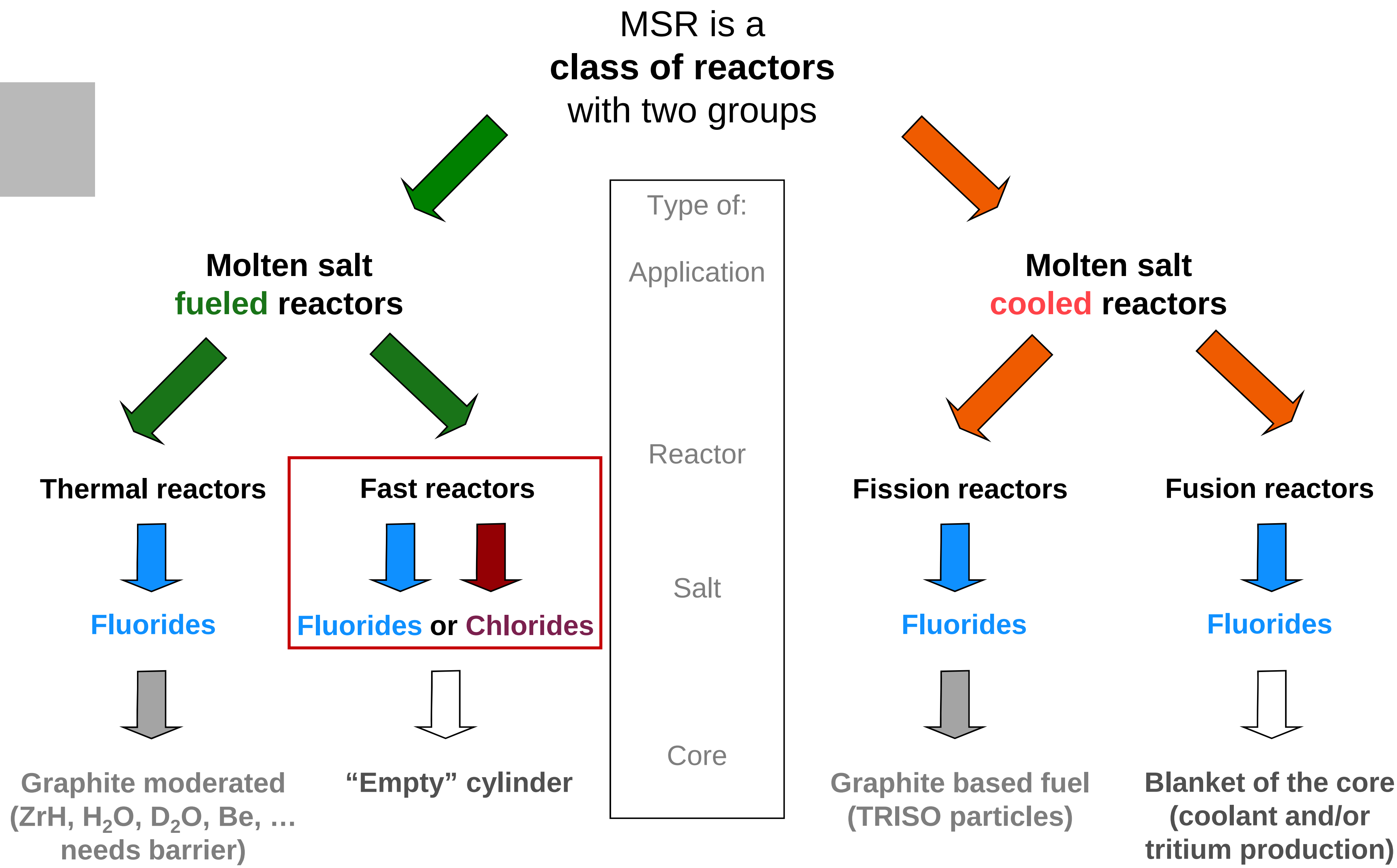


Classification of MSR

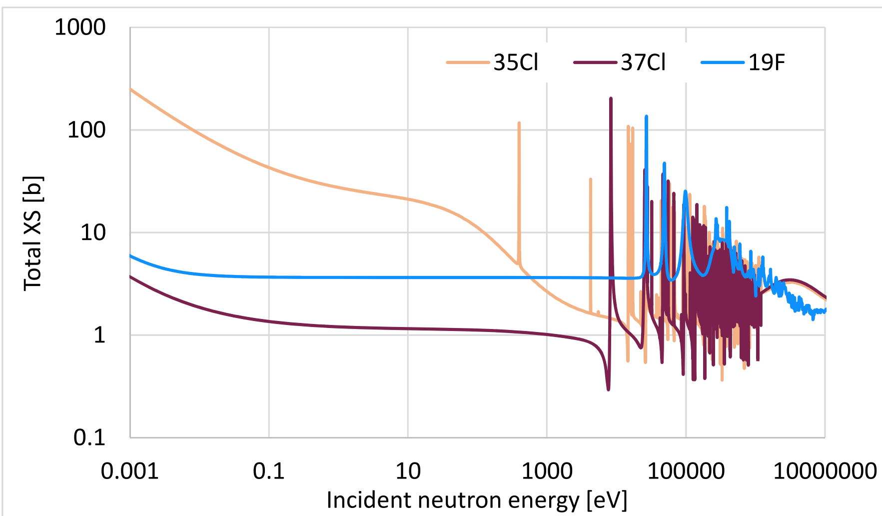


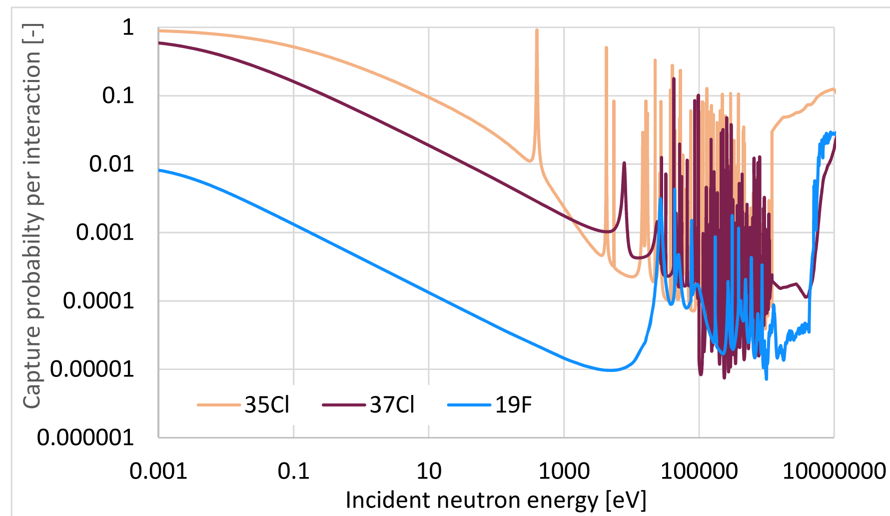
Anions in the salts

Fluorides | **Chlorides**

100% ^{19}F

76% ^{35}Cl + 24% ^{37}Cl





Number of collision to slow-down fast neutron (2MeV->1eV)

^{19}F	^{35}Cl	^{37}Cl
142 (+big inelastic XS)	**258**	**273**

For instance: Iodine as the fission product is the next possible anion.

Cations in the salts

Lithium

5% ^{6}Li + 95% ^{7}Li

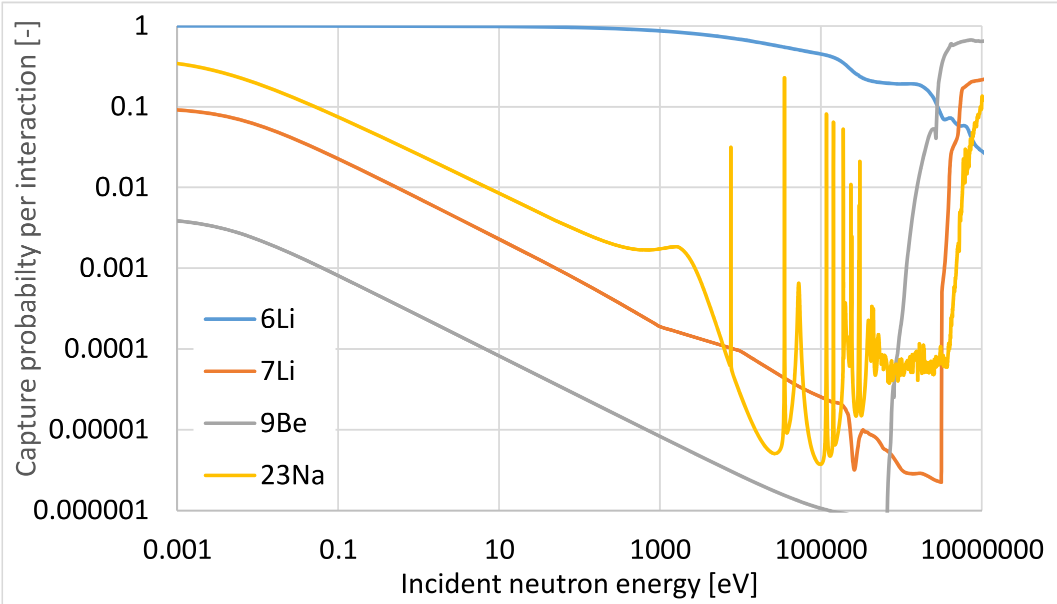
Beryllium

100% ^{9}Be

Sodium

100% ^{23}Na

Potassium, Rubidium, …



Number of collision to slow-down fast neutron (2MeV->1eV)

^{6}Li	^{7}Li	^{9}Be	^{23}Na
49	56	70	172

For instance: Cesium as the fission product is the next possible cation.

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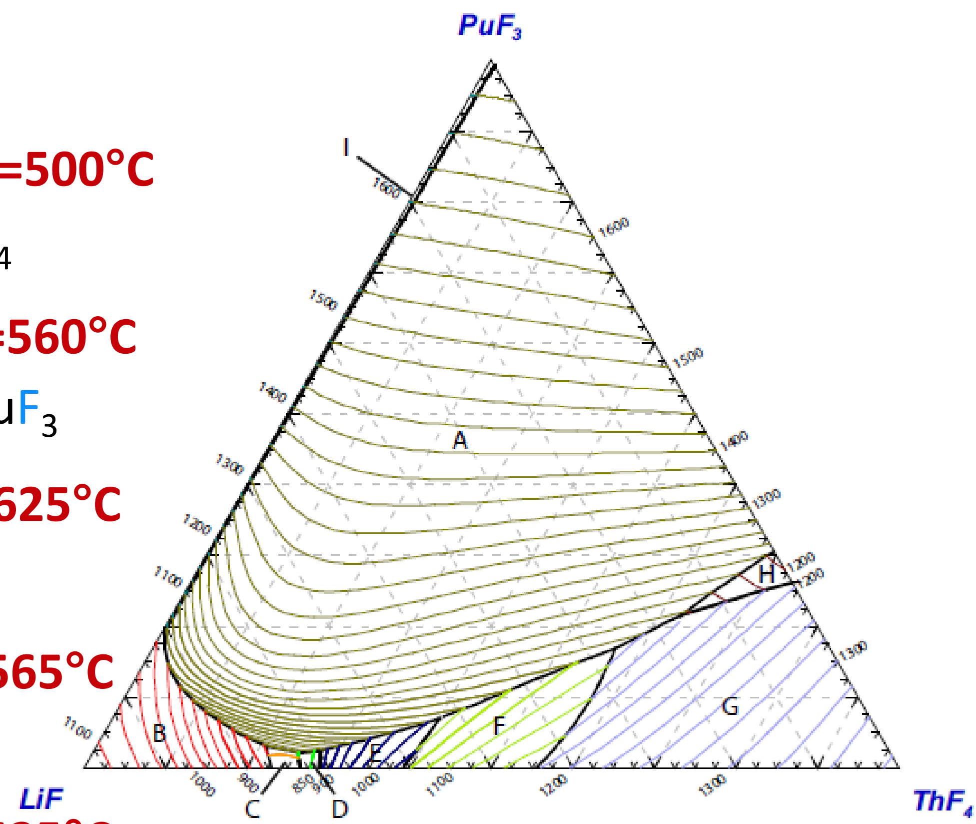
What are the salt mixtures

- Typically eutectic mixture of carrier salts (LiF, BeF_2, NaF, $LiCl$, $NaCl$, …) and actinides salts (ThF_4, UF_4, PuF_3, $PuCl_3$, $ThCl_4$, …)
- **MSRE** salt, **$T_{melt.}$=432°C**
  65%LiF-29.1BeF_2-5%ZrF_4-0.9%UF_4
- **MSBR** , Th-U equilibrium cycle, **$T_{melt.}$=500°C**
  71.7%LiF-16%BeF_2-12%ThF_{4-}0.3%UF_4
- **MSFR**, Th-U equilibrium cycle, **$T_{melt.}$=560°C**
  78%LiF - 17.6%ThF_4 - 4%UF_4 - 0.2%PuF_3
- **MSFR**, ~~Pu started Th-U cycle~~, **$T_{melt.}$=625°C**
  78%LiF - 16%ThF_4 - 6%PuF_3
- **MCFR**, Pu started U-Pu cycle, **$T_{melt.}$=565°C**
  60%$NaCl$ - 35%UCl_3 - 5%$PuCl_3$
- **MCFR**, Pu started Th-U cycle, **$T_{melt.}$=425°C**
  55%$NaCl$ - 39%$ThCl_4$ - 6%$PuCl_3$



LiF-ThF_4-PuF_3 ternary phase diagram
w/ fixed 1% mol UF_4 concentration
*E. CAPELLI et al., "Thermodynamic Assessment of the LiF–ThF4–PuF3–UF4 System," J. Nucl. Mater., **462**, 43 (2015).*

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Why MSR? Motivation & appealing features

I. ***Neutronics advantages, excellent neutron efficiency.***
(parasitic absorptions of carrier salt (and graphite) are small; in U-Th cycle also the capture of ^{233}U is low)

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

III. ***MSR can be operated with flexible fuel cycle.***
(as thermal, epithermal, or fast breeder and/or burner in Th-U cycle and as fast breeder (breed & burn) and/or burner in U-Pu cycle)

IV. ***MSR can be designed as an inherently safe reactor with reduced risk.***
(low inventory of gaseous and volatile fission products, negative temperature feedbacks, possibility to "reshape" the liquid fuel for decay heat removal - passive fuel drainage)

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Key MSR challenges

I. *Structural materials temperature, corrosion, and embrittlement.*
(redox potential must be controlled to prevent corrosion, nickel alloys suffer from irradiation embrittlement.)

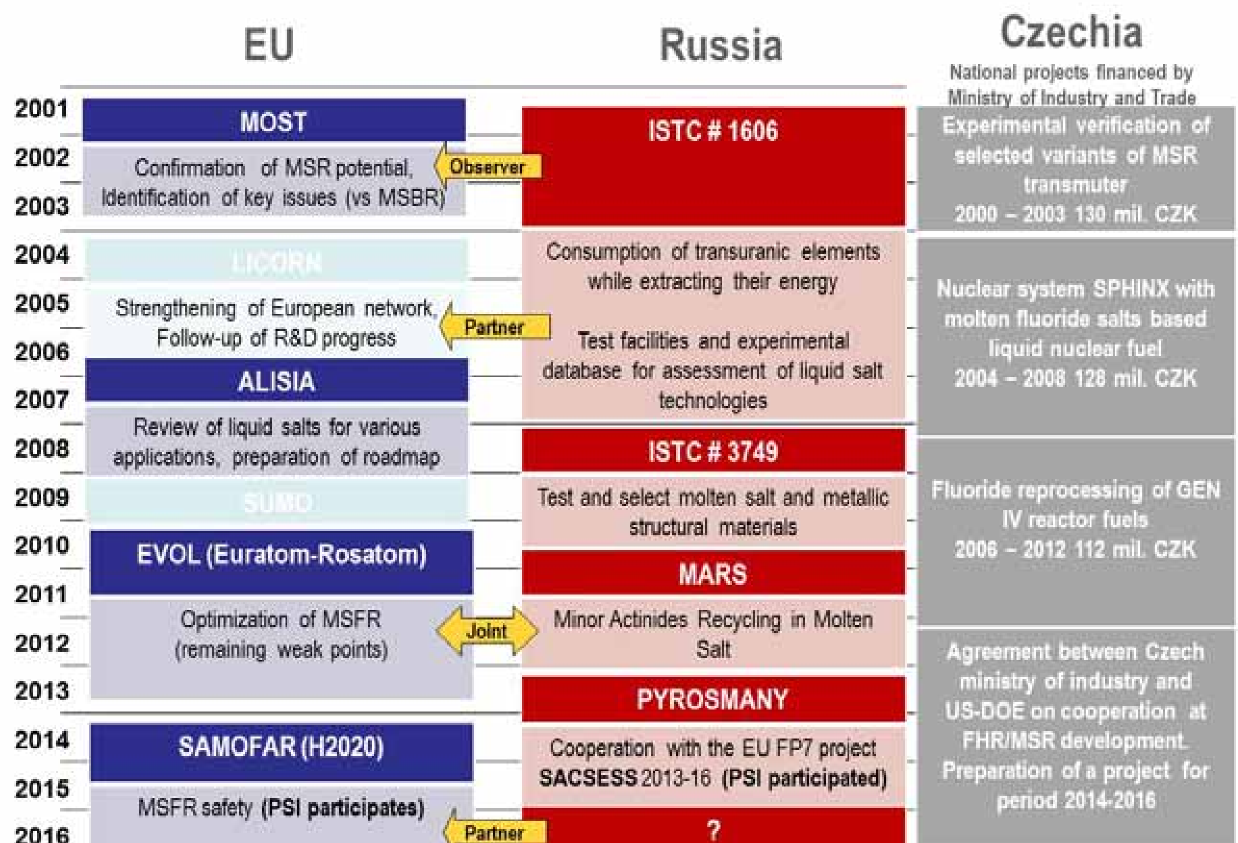
II. *Thermal-Hydraulics, dynamics, and limited graphite lifespan.*
(molten salt is specific volumetrically heated medium, delayed neutrons are drifted out of the core, and if applied, graphite mechanical stability suffers by irradiation)

III. *Missing safety guidelines, complicated reprocessing techniques.*
(combined regulations for reprocessing plants and reactors?, fluoride volatilization techniques, Electro-separation processes, Molten salt / liquid metal reductive extraction)

IV. *Fuel salt selection, chemical treatment, and proliferation risk.*
(melting temp., tritium production, solubility of PuF_3, on-line refueling, He bubbling to remove gaseous and volatile fission products, proliferation risk related to ^{233}Pa or ^{233}U relatively easy separation)

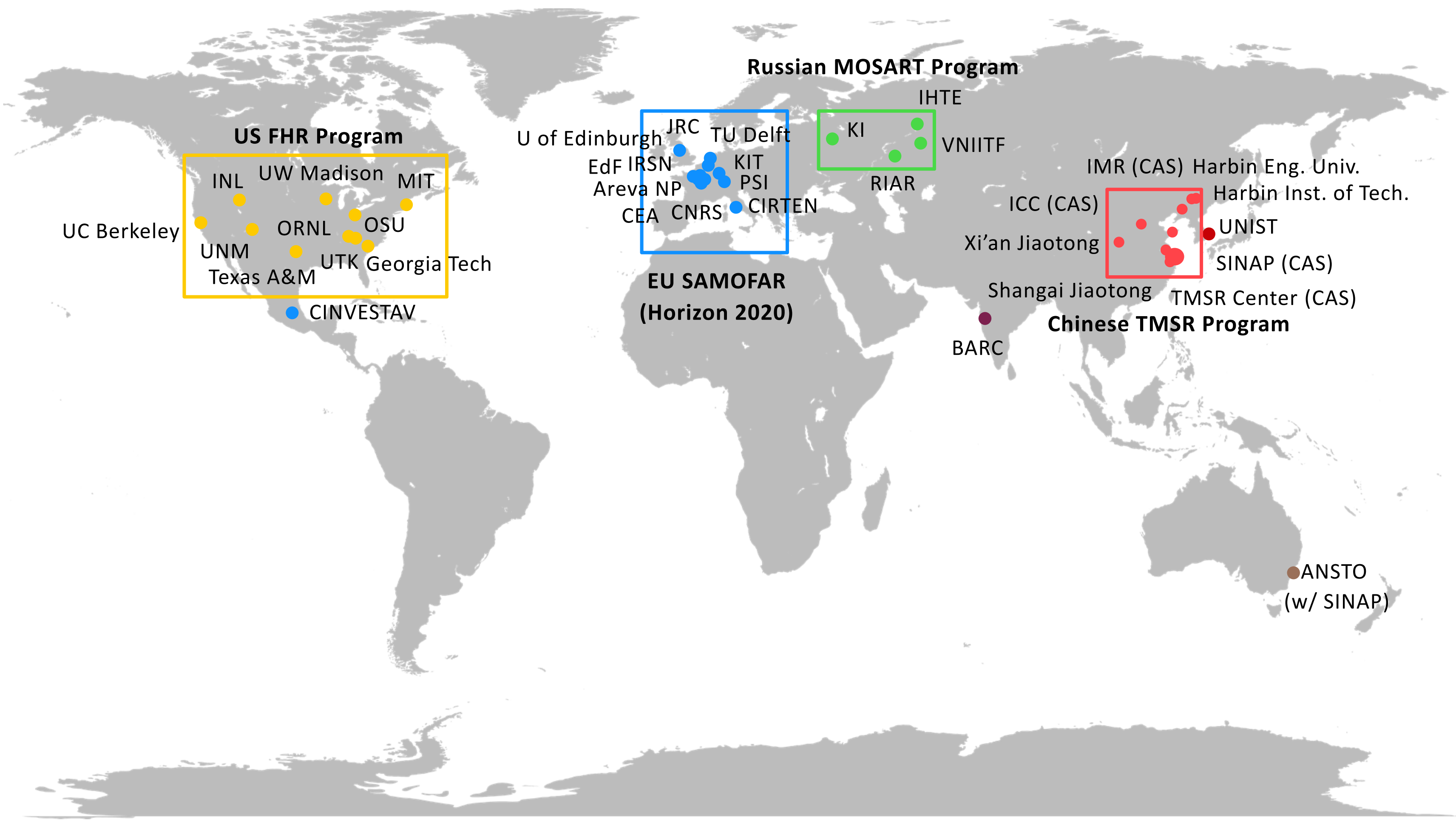
Who is interested in MSR

- **Russia** (LWR->SFR->MSR strategy, fluorides MA burner but also breeder),
- **USA** (coolant for **FHR, graphite** moderated or **chlorides** fast **MSR**),
- **China** (**TMSR** program with a plan to rebuild MSRE like demonstrator),
- **India** is considering MSR Th breeder, but the program is at initial stage,
- The **EU** research is coordinated by a **Horizon 2020** project **SAMOFAR (MSFR** safety)
- Evolution in Europe in last few years **=>** (Russia, France, and even Czechia had national programs.)



Adopted partly from: C. Renault, FISA 2010, The Molten Salt Reactor: R&D Status and Perspectives in Europe

MSR national programs today



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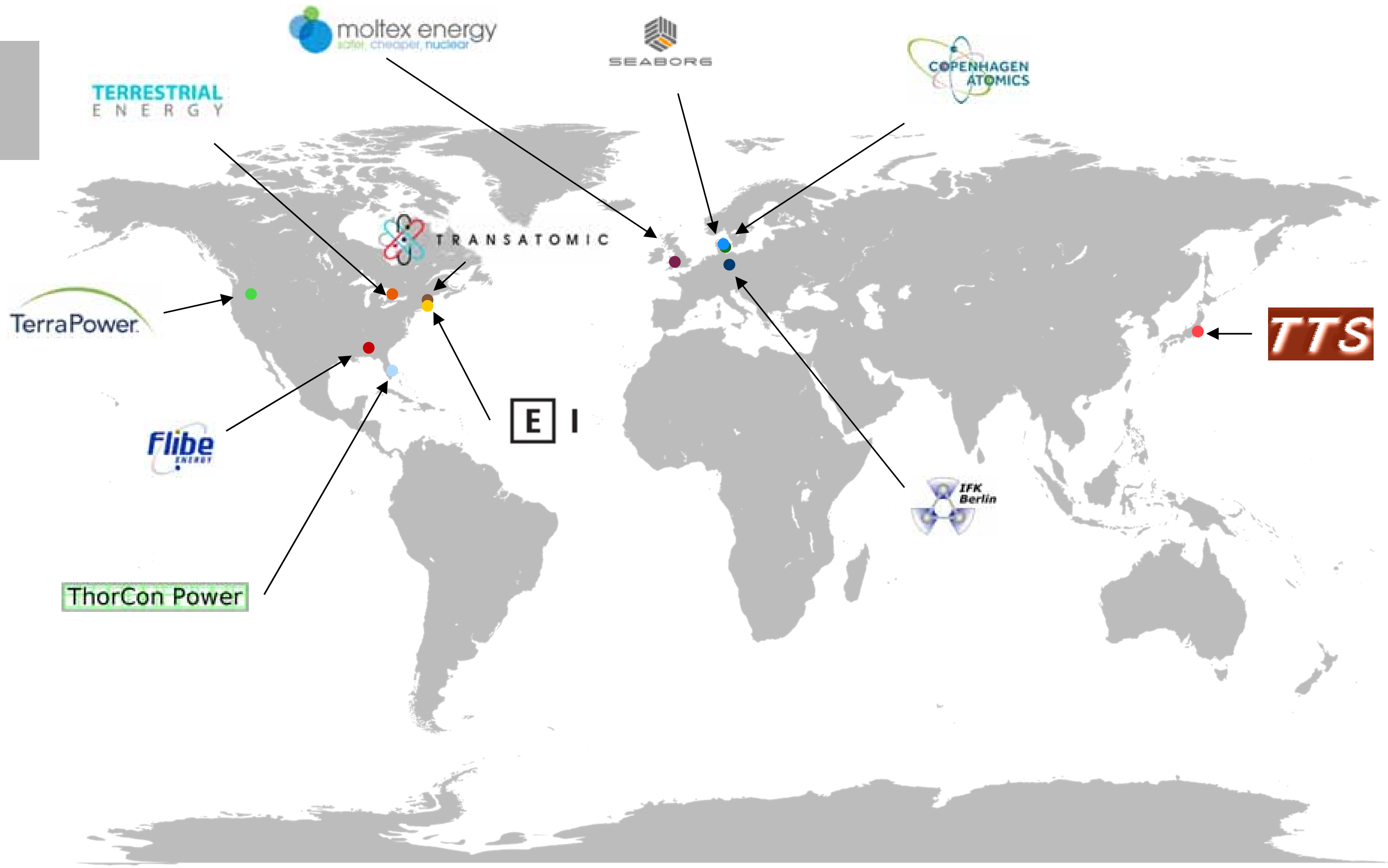
MSR start-ups field illustration



MSR start-ups field illustration

Company name	Location	Reactor name	Description of design
Transatomic Power	Boston, USA	Waste-Annihilating Molten Salt Reactor (WAMSR)	ZrH-moderated SNF/LEU burner
Terrestrial Energy	Toronto, Canada	Integral Molten Salt Reactor (IMSR)	Graphite-moderated integral LEU burner
TerraPower	Washington, USA	Molten Chloride Fast Reactor (MCFR)	Chloride-based fast U-Pu cycle reactor
FLiBe Energy	Alabama, USA	Liquid Fluoride Thorium Reactor (LFTR)	Graphite-moderated two-fluid Th breeder
ThorCon Power	Florida, USA	ThorCon	Graphite-moderated Th+LEU burner, deployed by ship
Elysium Industries	Boston, USA	TBA	TBA
Copenhagen Atomics	Copenhagen, Denmark	Copenhagen Atomics Waste Burner	Graphite-moderated Pu+MA+Th burner
Seaborg Technologies	Copenhagen, Denmark	Seaborg Technologies Wasteburner (SWaB)	Graphite-moderated Pu+MA+Th burner
Moltex Energy	London, UK	Stable Salt Reactor (SSR)	Chloride-fuelled Pu breeder, internal fluoride salt cooling
IFK Berlin	Berlin, Germany	Dual Fluid Reactor (DFR)	Chloride or metallic-fuelled Pu breeder, internal lead cooling
Thorium Tech Solutions	Tokyo, Japan	FUJI, miniFUJI	Graphite-moderated single-fluid Thorium breeder

Summary: Predominance of graphite-moderated burners (simple!)

Justification of the MSR research at PSI

- **MSR** technology bears many innovative and **multidisciplinary features** that could be used in the frame of the division-level project and provide **framework** for **PhDs** and **PostDocs** projects and for funding from alternative financial sources, e.g. **SNF, KTI**, and attract the students.
- MSR may be **acceptable for public**: high resources utilization, low waste production, and risk reduction and/or exclusion of severe accidents. In long term it can have a **potential to be cheaper** that current technology.
- **MSR** allows for cooperation with **international partners**:
  - In 2015, Switzerland joined the **GIF Molten Salt Reactor Project.**
  - Bilateral cooperation with ITU, POLIMI, CTU Prague, Terrestrial Energy, …
  - **NES Division Project** on Gen-IV MSR (umbrella for several project).
  - There are already **5 financed** national and international **projects** related to MSR at NES.

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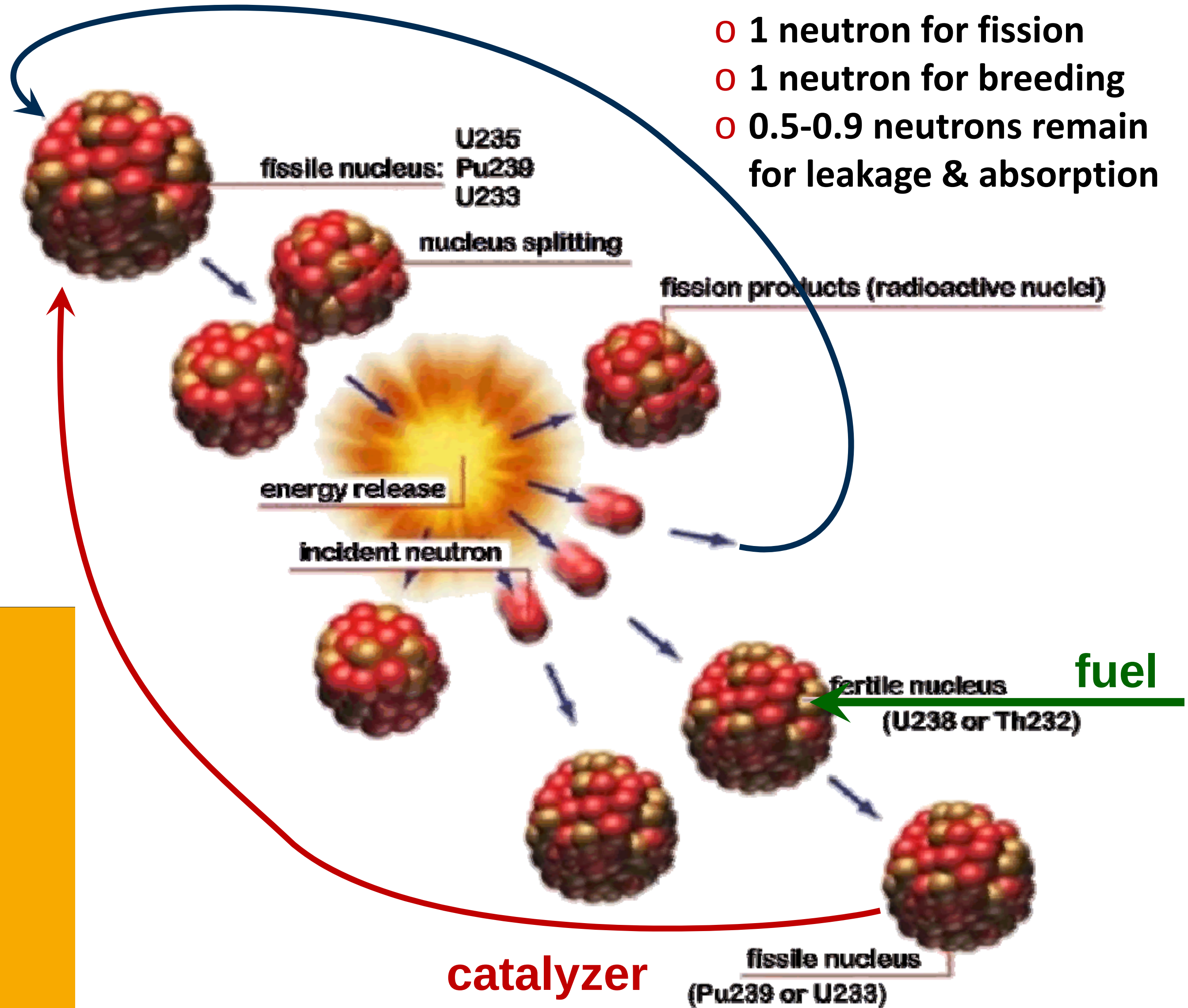
SUSTAINABILITY

Sustainability = natural resources utilization

- 1 neutron for fission
- 1 neutron for breeding
- 0.5-0.9 neutrons remain for leakage & absorption

- Illustrative size of actinides reserves:
- ^{235}U
- ^{238}U
- ^{232}Th

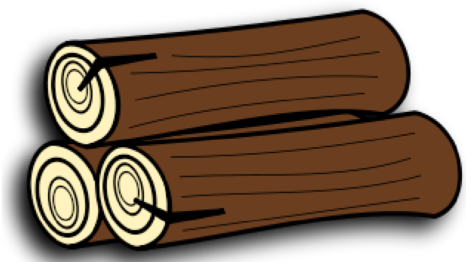


Ideal reactor burns ^{238}U or ^{232}Th

Works only if emissions (FPs) are (continuously) removed

- Catalyzer is not in nature
- Initial fuel only ^{235}U..?
- FPs removal
  = fuel reprocessing outside of the core

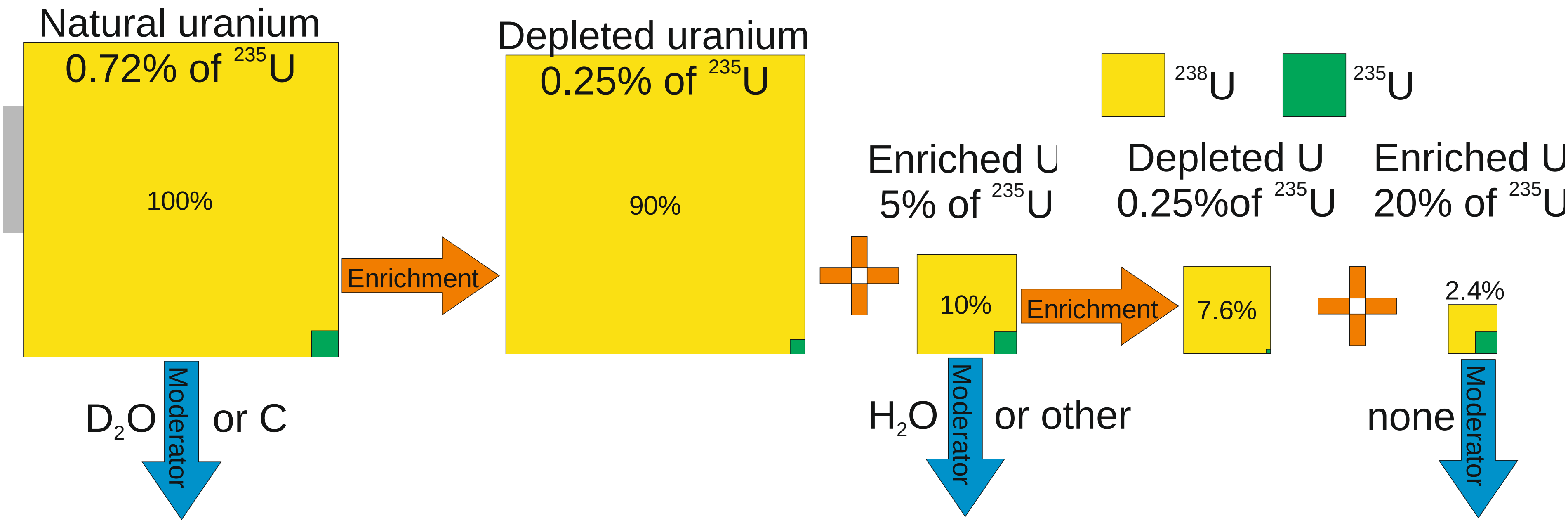
Fuel: ^{238}U or ^{232}Th



Efficient reactor
("catalyzed" by ^{239}Pu or ^{233}U)

Energy

Any ^{235}U fueled reactor has low sustainability



CANDU	PWR, BWR	SFR, LFR, GFR

Burn-up of the fuel in **FIMA %** (GWd/t_{hm}):

0.65-0.75 (6.5-7.5)	**3.3-7.0** (33-70)	**10-15** (100-150)

Burn-up in % of the original mass of natural uranium:

0.65-0.75	**0.33-0.7**	**0.24-0.36**

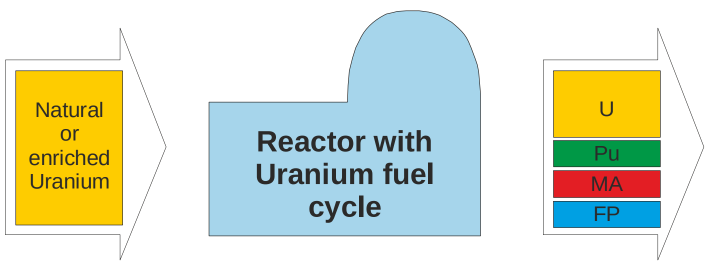
Sustainability:

Any ^{235}U fueled reactor has low fuel utilization.

Initial fuel & open versus closed cycle

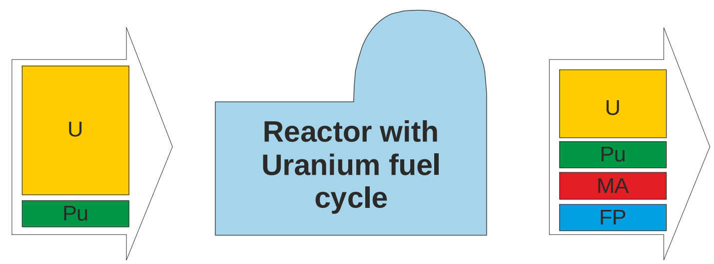
Uranium-Plutonium cycle

Initial stage: 235U based



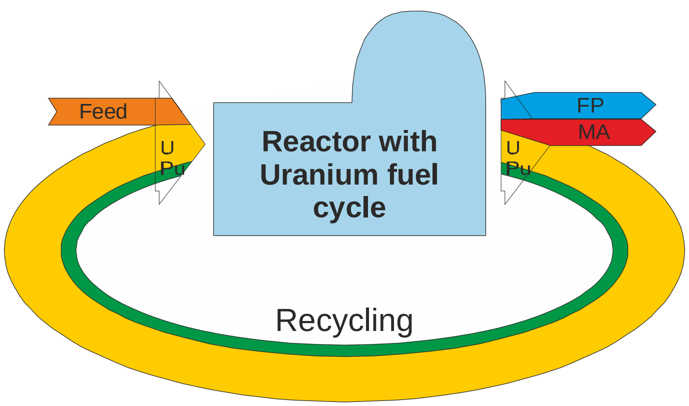
Nat. U utilization: **~0.75%**

Secondary stage: MOX based



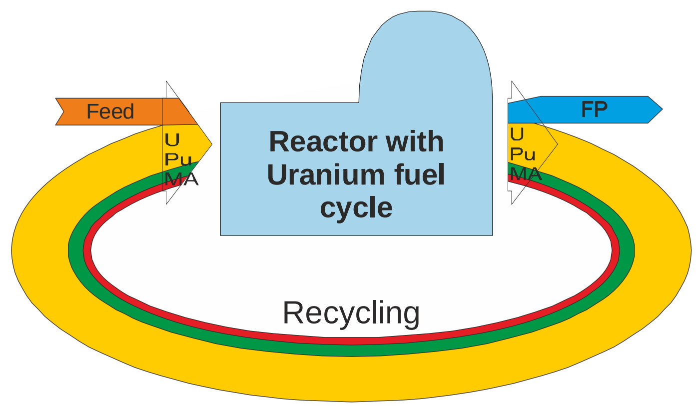
Nat. U utilization: **~1.5%**

Partly closed cycle / Pu multi-recycling



Nat. U utilization: **80+%**

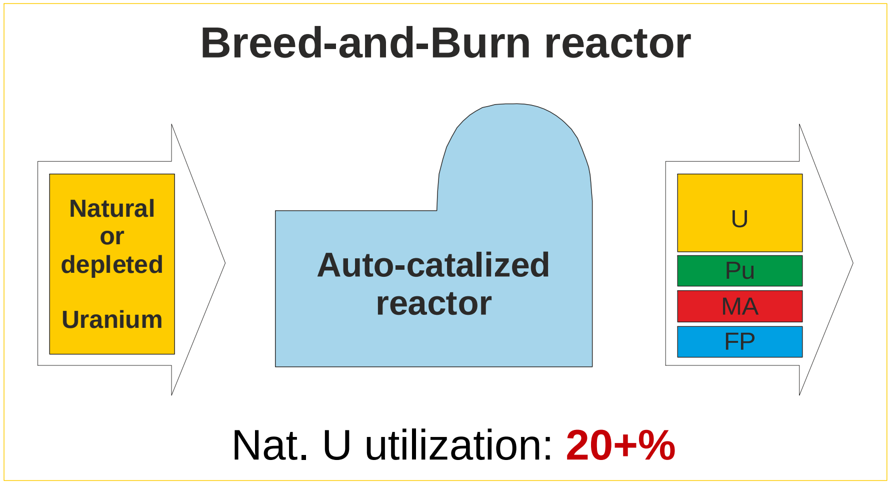
Fully closed cycle



Nat. U utilization: **90+%**

Higher utilization without reprocessing?

- Higher ^{235}U enrichment and deeper burn-up in current reactors does not really improve natural uranium utilization.
- Only in **Breed-and-Burn** (**B&B**) cycle up to 20+% of natural uranium utilization can be achieved without reprocessing.
- It requires supreme neutron economy: in open breeding cycle the discharged fuel is not recycled.
- Mass of discharged fissile fuel should be equal to the mass of discharged fission products multiplied by breeding gain.



Closed fuel cycle => equilibrium state

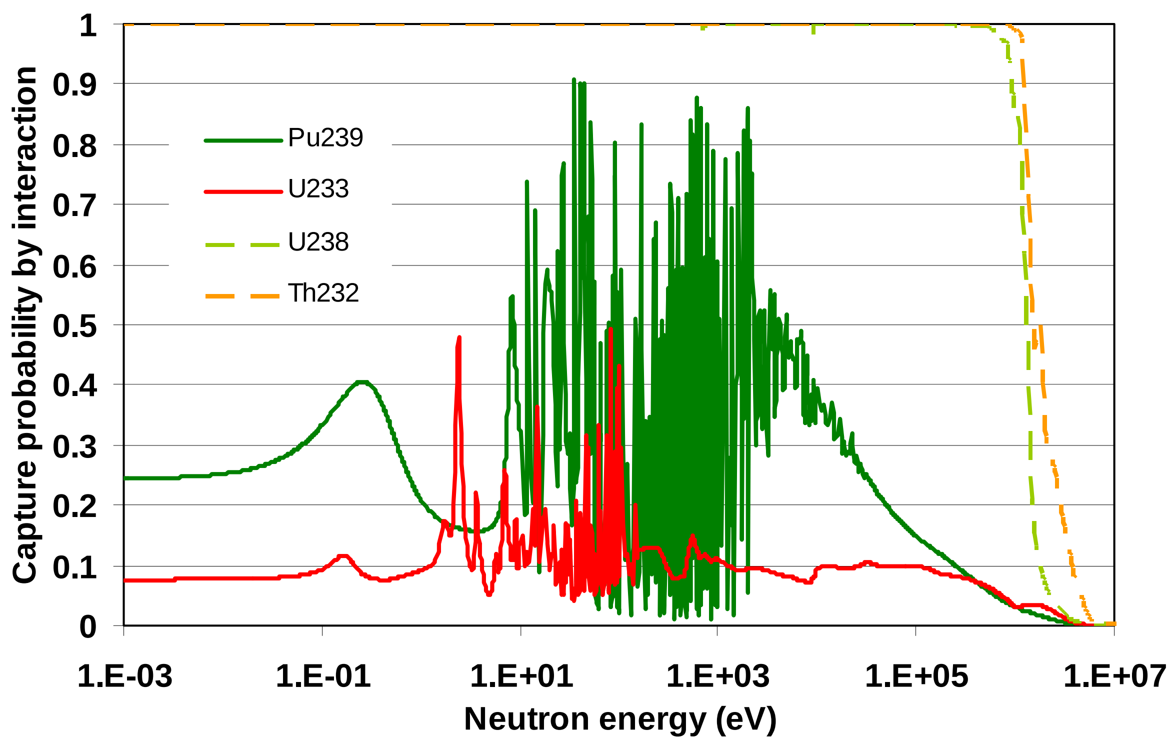
Repetitive fuel recycling
(90+% fuel utilization)

Minor actinides build-up
(Ac waste = reprocessing losses)

Equilibrium fuel composition
(depends on spectrum)

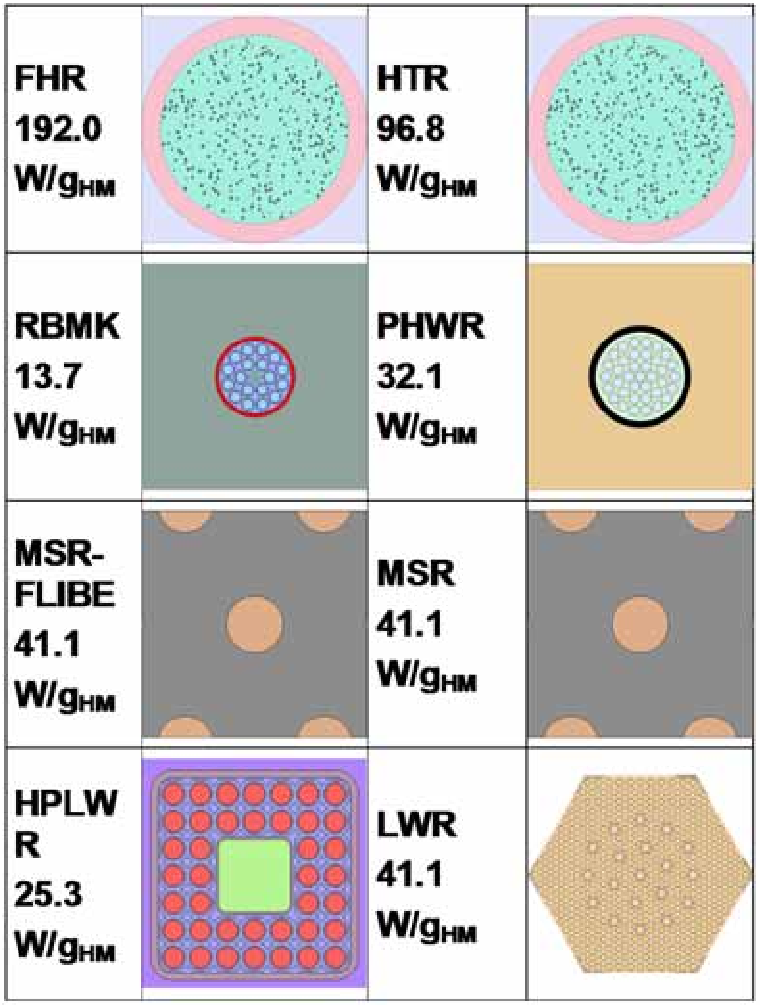
Eql. fuel parasitic neutron capture
(determines reactivity)

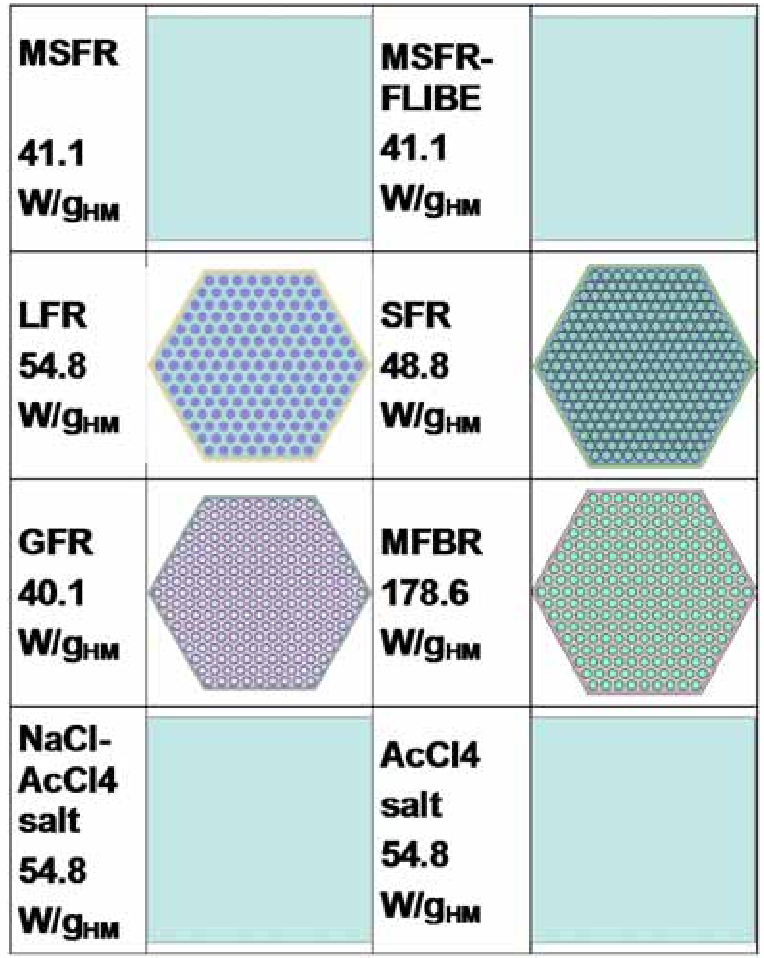
Equilibrium reactivity
(determines closed fuel cycle capability)



Capture on ^{233}U and ^{239}Pu is the main source of secondary fertile elements ^{234}U and ^{240}Pu and later also of Minor Actinides (MA) build-up.

Closed cycle evaluation for 16 reactors

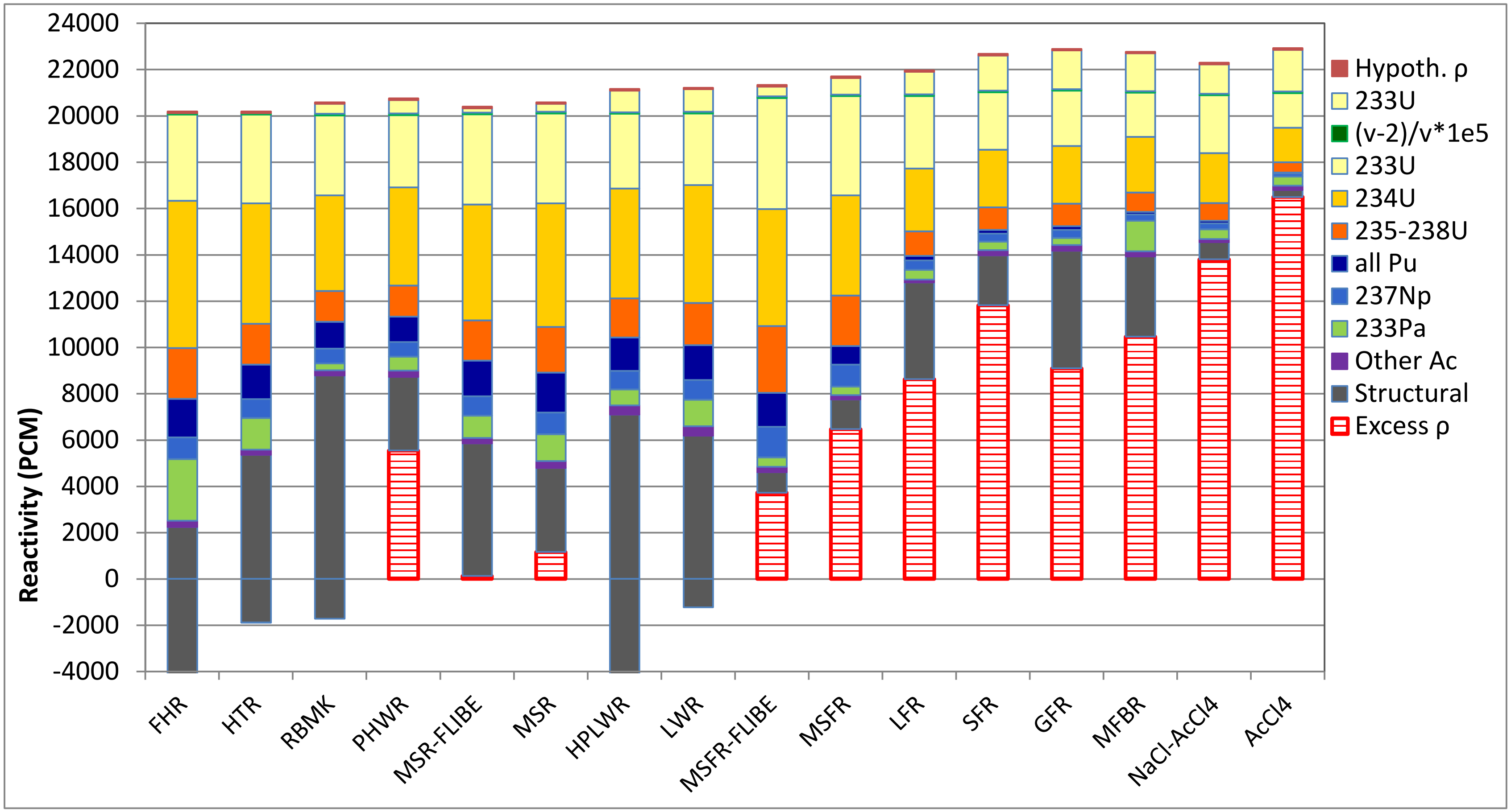




- The simplified designs were adopted as is without optimization.
- If the core consists of assemblies with identical geometry but different fuel composition only assembly was simulated.
- If the geometry differs, only one selected case is presented.

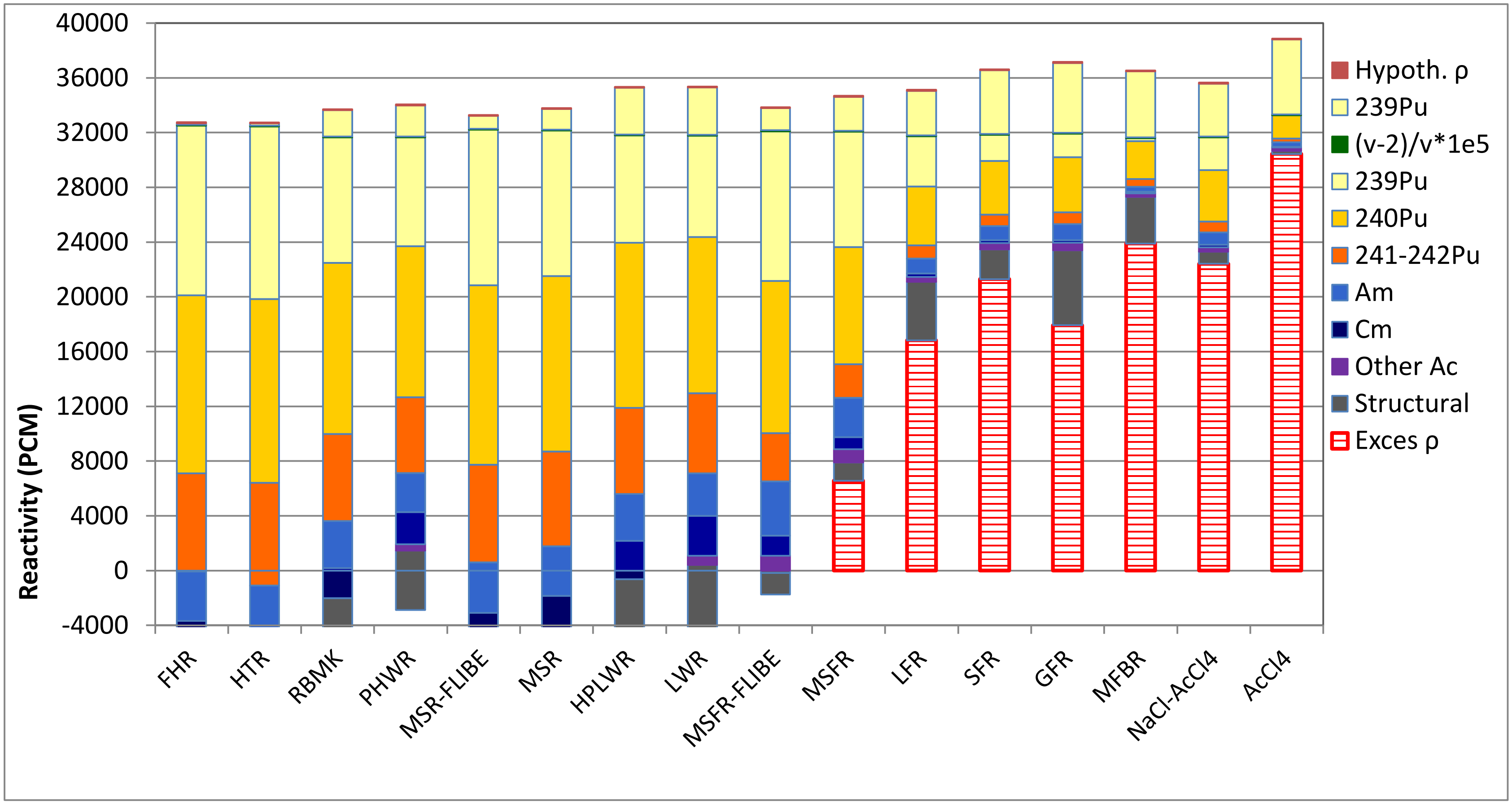
Excess reactivity for **Th-U** cycle

- **Excess reactivity** of the equilibrium fuel quantifies the **closed cycle capability**.
- Comparison of **16 reactors** on the basis of eql. reactivity for infinite lattice (no FPs).
- It includes also **isotope-wise** break-down of the **parasitic captures**.



Excess reactivity for **U-Pu** cycle

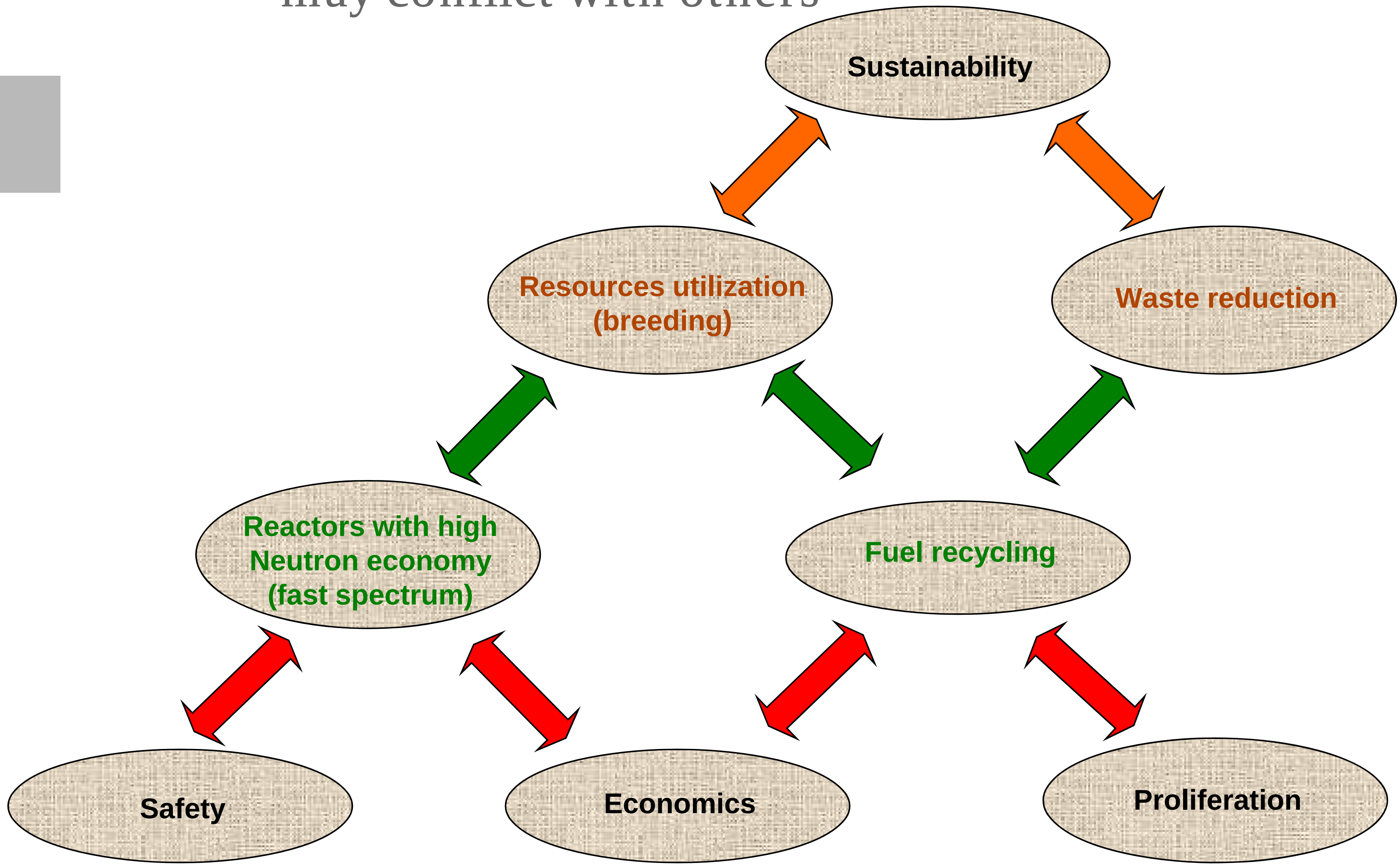
- Only fast spectrum system capable to close the U-Pu cycle.
- Low ^{239}Pu fission probability: ^{239}Pu: 65-75% x ^{233}U: 90%
- Excess reactivity is higher than for Th-U cycle: ^{239}Pu: ν=2.9 x ^{233}U: ν=2.5
- U-Pu cycle has better neutron economy, Th-U cycle better neutron efficiency.



Closed cycle capability of MSR systems

- **FHR** (salt cooled HTR, $^7LiF\text{-}BeF_2$):
  excess reactivity is negative, **no closed cycle capability**. Neutron economy even worse than He cooled HTR. (higher specific power = higher ^{233}Pa capture)
- **MSBR** (graphite moderated, Th-U cycle, $^7LiF\text{-}BeF_2$ or ^7LiF)
  excess reactivity is small, needs **intensive reprocessing** (FPs removal) to provide **closed cycle capability**. **Graphite** has **limited lifespan**.
  Other moderators (ZrH, etc.) have no closed cycle capability.
- **MSFR** (fast reactor, ^7LiF)
  Excess reactivity is acceptable. Reprocessing: on-line or in batch. **Th-U** cycle is possible, unclear initial fuel? U-Pu cycle not possible (limited PuF_3 solubility).
  Core wall **structural material** will have **limited lifespan**.
- **MCFR** (fast reactor, $Na^{37}Cl$)
  High excess reactivity. Reprocessing: on-line, in batch, or **breed-and-burn**.
  Th-U and U-Pu cycles possible, e.g. Pu as initial fuel.
  Core wall **structural material** will have **limited lifespan**.

New feature, sustainability, may conflict with others

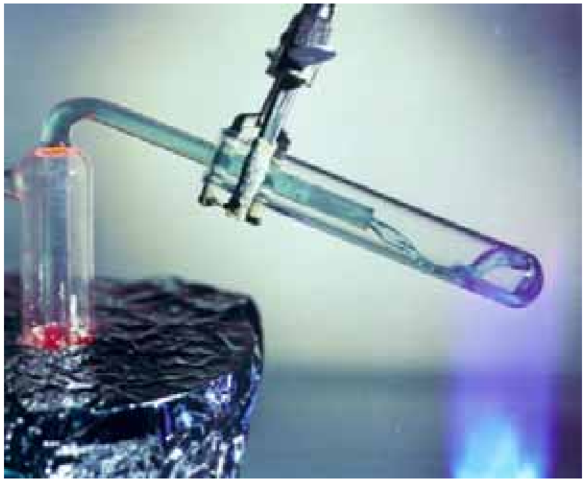


SAFETY

MSR safety = liquid fuel safety

- **Liquid fuel**, similarly as the UO_2 solid fuel, retains: uranium, TRU, and soluble FPs.

- On the other hand, it provides **zero confinement for mobile FPs!** (volatile and gaseous FPs)



- Not only that the **mobile FPs** are not confined, they **must be removed** from the fuel.

- **Decoupling of mobile FPs** from major heat sources may strongly change the **safety philosophy.**

- MSR operates at **atmospheric pressure** with low mobile FPs content and may be designed with **negative feedback coefficients**.

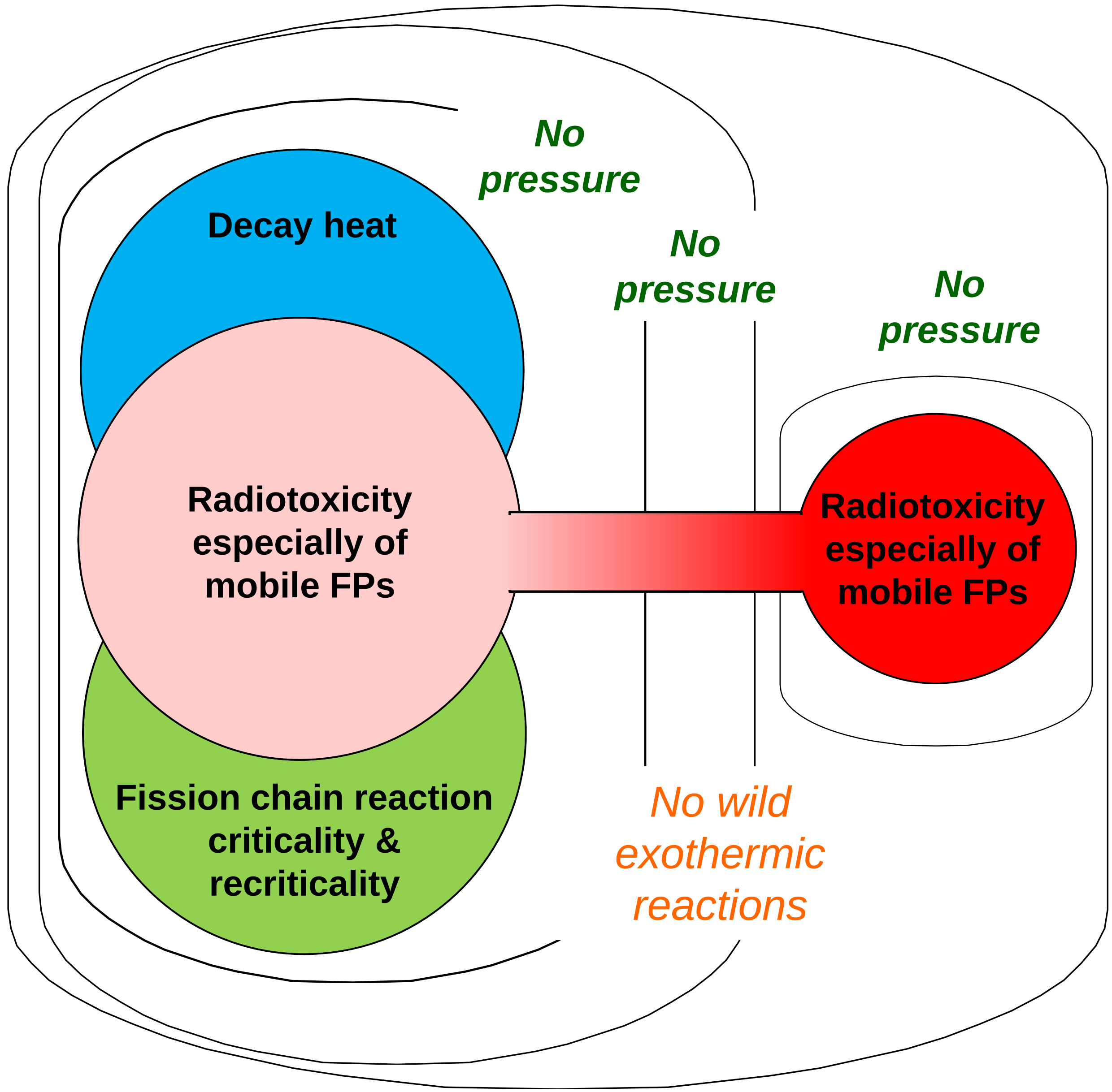
- Liquid fuel enables **re-shaping** for ultimate **decay heat removal**.

- **Off-gas** system can be possibly designed to handle also accidental situations.

Safety philosophy: decoupling from heat sources

MSR

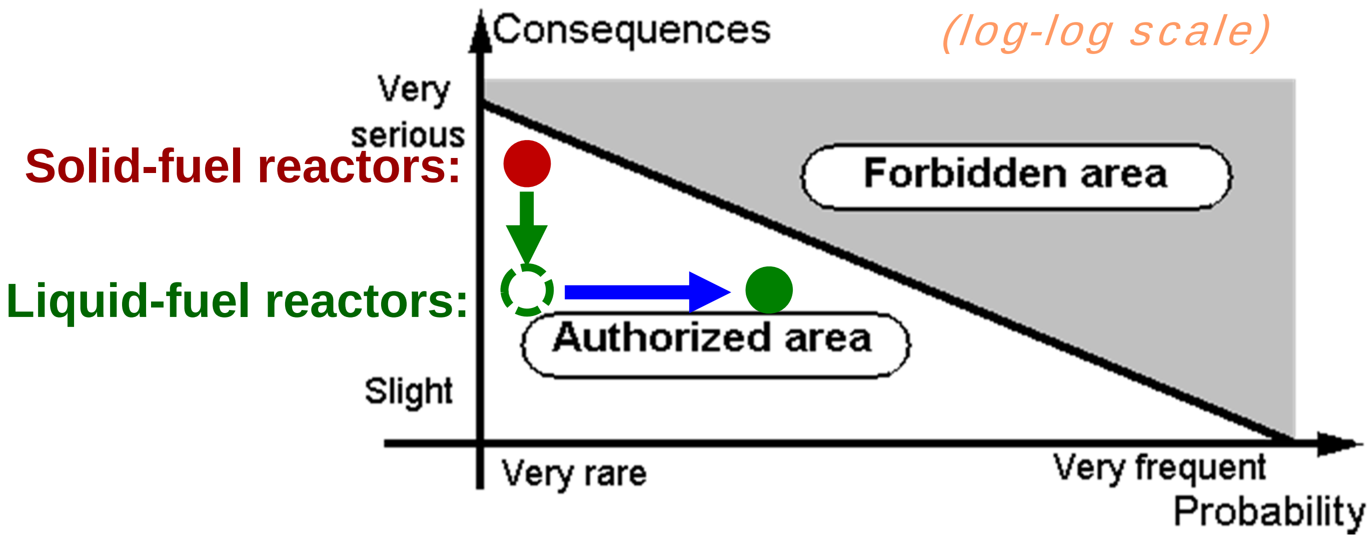
- *If the mobile FPs would be decoupled from the major heat sources, the risk would be strongly reduced.*
- *Absence of driving forces.*
- *Potential for deterministic reduction of serious hazard and consequences.*
- *Regulation for reprocessing plants may be applicable to the removed FPs.*



Deterministic reduction of hazards?

- ***Technological requirement*** *of volatile FPs* ***continuous removal*** *may, together with the negative temperature feedbacks (criticality safety) and possible passive fuel drainage, provide "****deterministic" safety****.*

Farmer curve illustration (log-log scale)



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

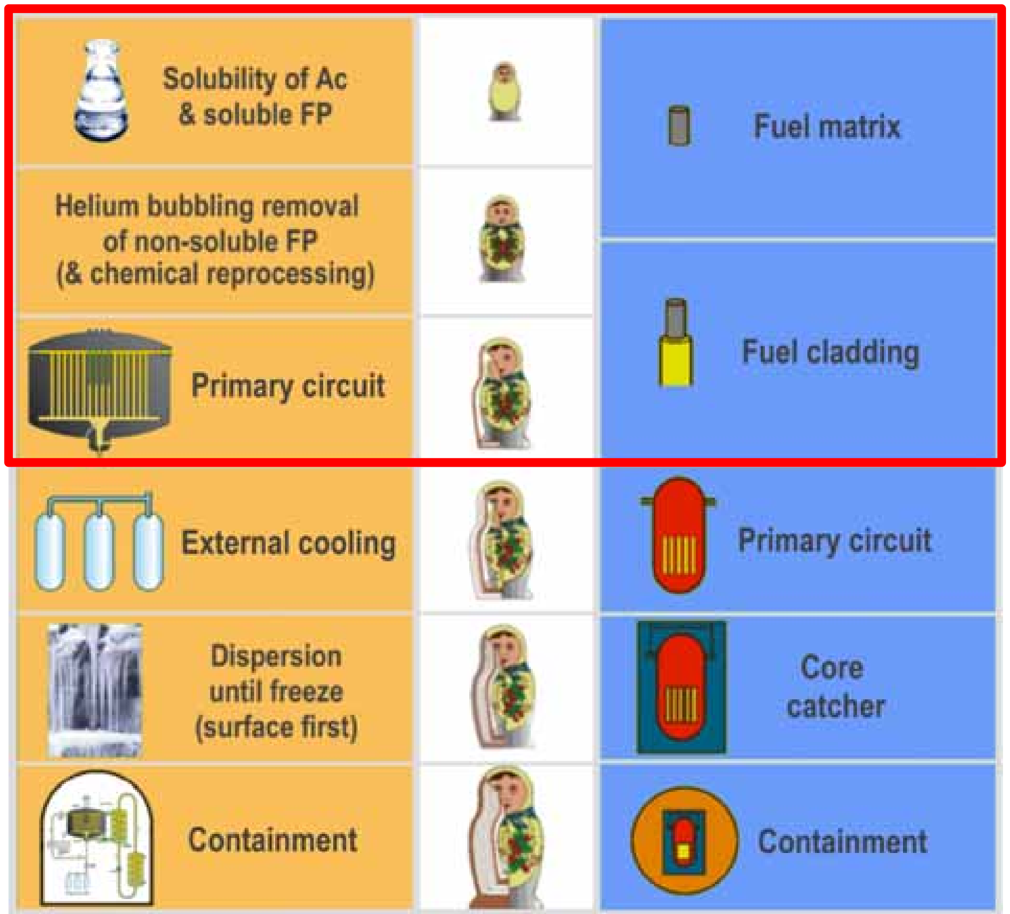
Online removal of highly mobile gaseous and volatile FP
(Ac and remaining FP are embedded in the salt)

Daily removal = possibly higher frequency of accidents
(safety standards for reactor X reprocessing plant)

Online FPs removal as a pseudo barrier?

- ***The removal*** *may increase the frequency of small localized incidents.*
- *In the same time, it significantly reduces the hazard and may act as the strongest* ***pseudo-barrier*** *for FPs releases by severe accidents.*

Hazard reduced by decoupling



Encapsulated hazard

MSR RESEARCH AT NES

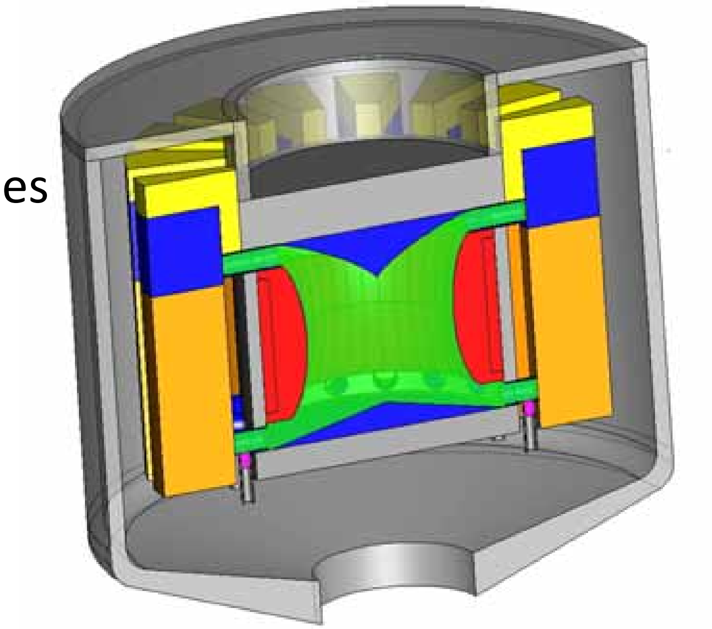
Ongoing project and involved staff

- Euratom **Horizon2020 project**
    1) **SAMOFAR** - Safety Assessment of the MOlten salt FAst Reactor.
- **4 national projects** fully or partly related to MSR:
    2) **SNF** PhD: Modular MSR Designing for Low Waste Production.
    3) **SNF** PhD: Nuclear Data Assimilation in Reactor Physics (Pu & Th).
    4) **Swiss Electricity Producers & ETHZ** financed project:
    Feasibility and plausibility of innovative reactor concepts (HTR & MSR).
    5) **Swiss Nuclear** financed project:
    Chemical thermodynamic aspects of LWR Pu and MA burning in MSR.
- Involved labs: **LRS**[1,2,3,4,5], **LTH**[1,4,5], **AHL**[1,5], **LEA**[1,4], **LES**[5].
- **Status of MSR** Research at **Nuclear Energy Division** of PSI**:**
    - 7 accomplished, 1 ongoing, and several proposed MSc theses.
    - 2 ongoing PhD theses financed by SNF at PSI and EPFL Lausanne.
    - 3 accomplished and 1 ongoing PhD theses in cooperation with PSI.
    - 2 Scientist and 3 PostDoc working partly on MSR.

H2020 SAMOFAR

SAMOFAR | The way forward to the ultimate safe nuclear reactor

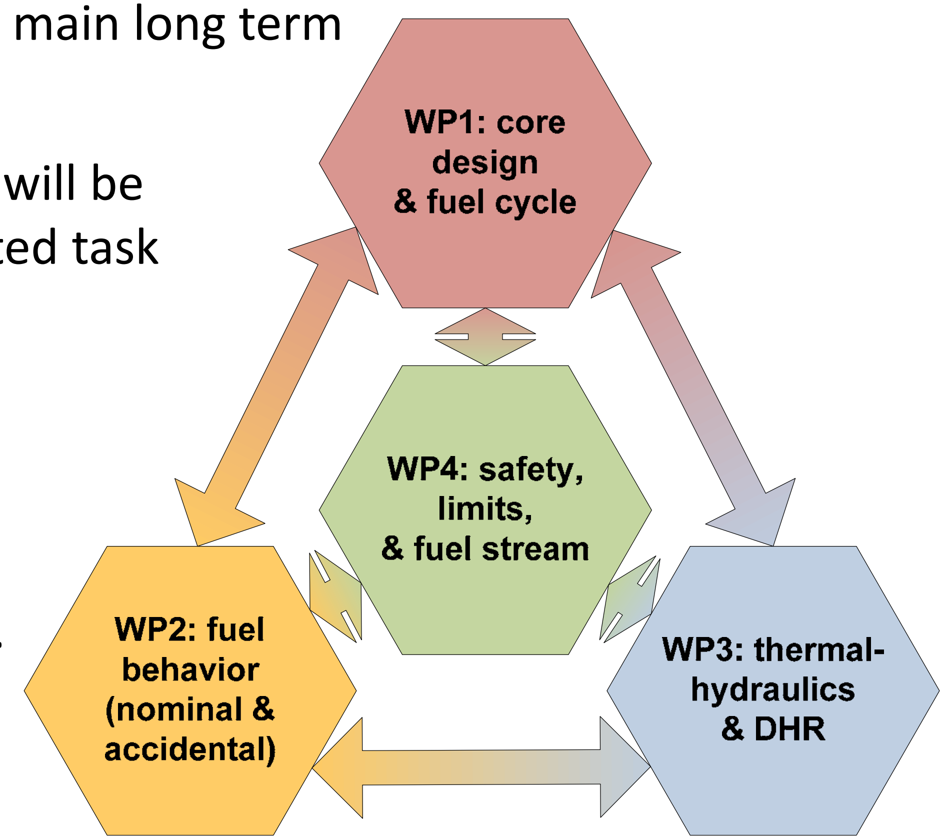
- SAMOFAR is a 5M€ 4-year project of EU H2020 program.
  It Started in August 2015 and the consortium has 11 partners: CNRS, JRC, CIRTEN, IRSN, CINVESTAV, AREVA, CEA, EDF, PSI, KIT and TU Delft.
- Goals:
  - prove innovative safety concepts of MSFR by advanced experimental and numerical techniques
  - deliver a breakthrough in nuclear safety and optimal waste management
  - create a consortium of stakeholders to demonstrate MSFR beyond SAMOFAR.



Molten Salt Fast Reactor Concept

NES Division Project as an umbrella

- **4 working packages** are proposed for the NES project to group similar research topics.
- **WP1:** core designing is ongoing in the frame of SNF PhD and PSEL project, but it should not be the main priority of the project at this stage.
- **WP4:** safety of MSR should be the main long term aim of the project.
- However, knowledge from **WP1-3** will be necessary for **WP4** and only selected task can be done independently.
- **WP2** and **WP3** include many design-independent topics.
- Especially **WP2** has the potential to involve all PSI/NES laboratories.



WP1: MSR core design and fuel cycle

- **Initial studies** were based mainly on **fluoride salts MSR.**
- Later on the **chlorides MSR** were accessed.
- Main applied tools are EQL0D and EQL3D developed at PSI:
  - **EQL3D[1] - ERANOS** based procedure for core level simulation.
  - **EQL0D v1** MATLAB-**ERANOS ECCO**, reaction rates based, cell level.
  - **EQL0D v2** MATLAB-**SERPENT**, reaction rates based, cell or core level.
  - **EQL0D[2] v3** MATLAB-**SERPENT**, adopts directly the **SERPENT burn-up matrix**, cell or core level, **includes fission products** (v1 and v2 not).

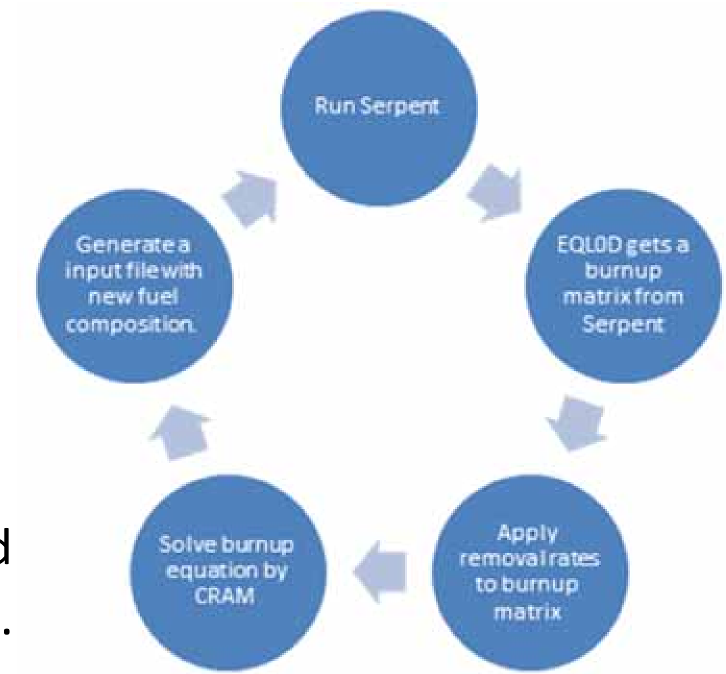
	2013				2014				2015				2016				2017	
WP1: MSR designing	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II
Parametric spectral study	MSc - B. Hombourger																	
Design option evaluation				PhD - B. Hombourger														
Optimal design identification											PhD - B. Hombourger							
Its detailed NK & TH analisis													PhD - B. Hombourger					
Evaluation of inovative ideas				J. Krepel														
PSEL - fuel cycle simplification											J. Krepel							
Pool type MSR with cold jet												J. Bao						

1) Křepel, J. et al., 2013. Fuel Cycle Advantages and Dynamics Features of Liquid Fueled MSR. Annals of Nuclear Energy. vol. 6 pp. 380–397.

2) Hombourger, B. et al., 2015. Parametric Lattice Study of a Graphite-Moderated Molten Salt Reactor. Journal of Nuclear Engineering and Radiation Science. Vol. 1, JANUARY 2015.

WP1: EQL0D v3 routine

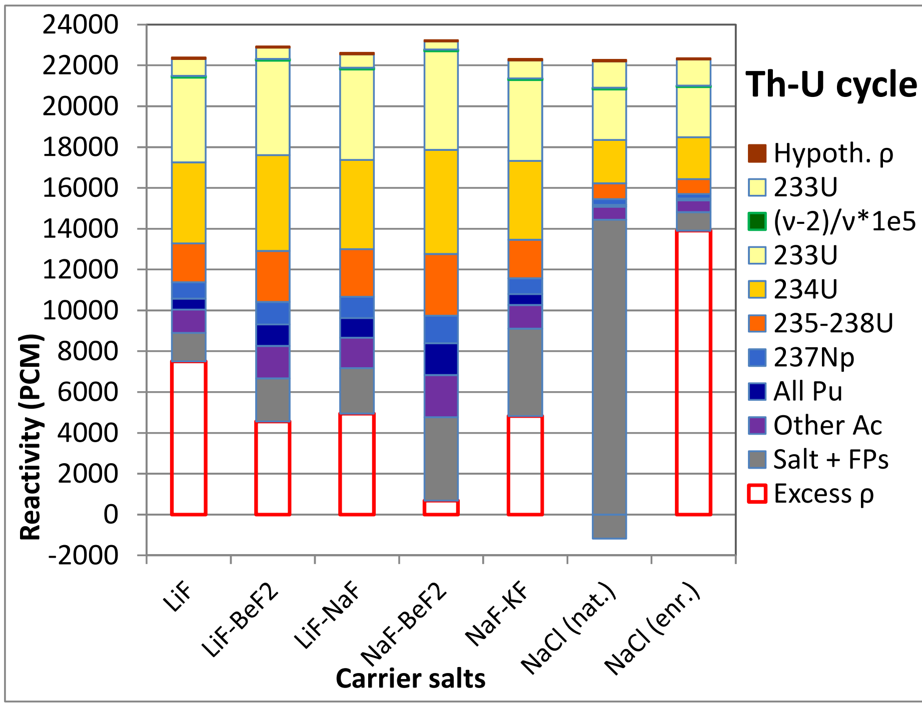
- MATLAB-SERPENT based routine.
- Burn-up matrix adopted from SERPENT including fission products.
- Chebyshev Rational Approximation Method (CRAM) as in SERPENT.
- Multi-medial coupled burn-up.
- Composition and e.g. decay heat is traced in off-gas system and online reprocessing.

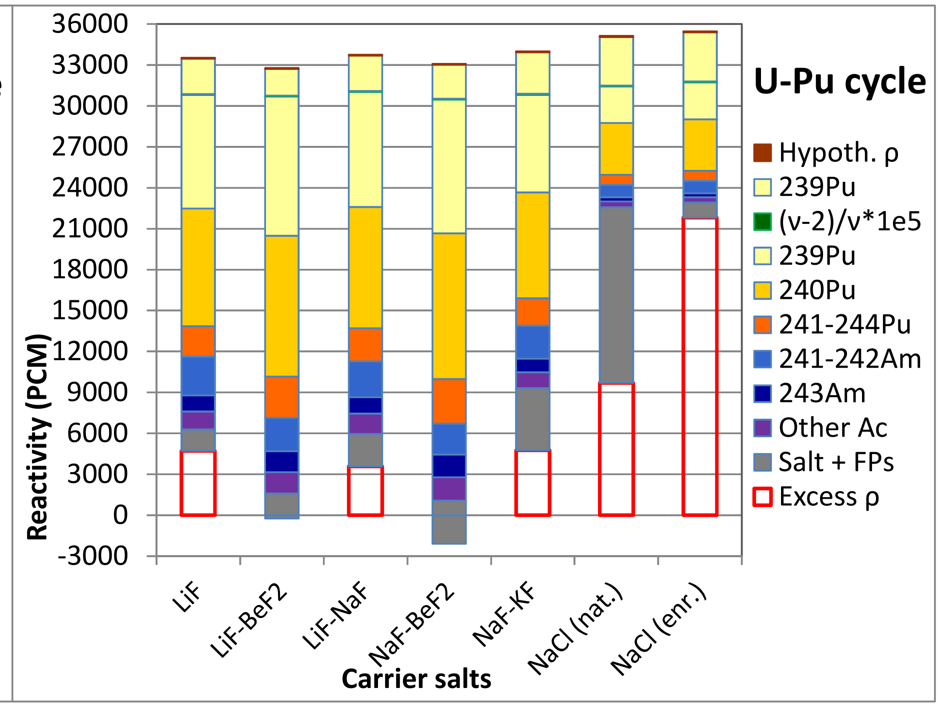


$$\frac{dN}{dt} = AN = \begin{pmatrix} -\lambda_1 - r_1^{(1)} - \lambda_1^{rem} & \cdots & \gamma_{n\to 1}\lambda_n & \cdots & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \gamma_{n\to 1} r_n^1 & \vdots & -\lambda_n - r_n^{(1)} & \vdots & 0 & \vdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ \lambda_1^{rem}\frac{V^1}{V^m} & \vdots & 0 & \vdots & -\lambda_1 - r_1^{(m)} & \vdots & \gamma_{l\to 1}\lambda_l \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & \cdots & \gamma_{1\to l} r_1^{(m)} & \cdots & -\lambda_l - r_l^{(m)} \end{pmatrix} \begin{pmatrix} N_1^{(1)} \\ \vdots \\ N_n^{(1)} \\ \vdots \\ N_1^{(m)} \\ \vdots \\ N_l^{(m)} \end{pmatrix}$$

WP1: EQL0D v3 results, 7 MSR salt comparison

- 7 selected MSR salts were compared assuming homogeneous fast reactor.
- Both U-Pu and Th-U closed cycles were evaluated be equilibrium reactivity.
- It confirmed that for U-Pu cycle chlorides are preferable.
- Th-U cycle has two favorites LiF and NaCl carrier salts.
- The reactivity excess may enable breed and burn mode.

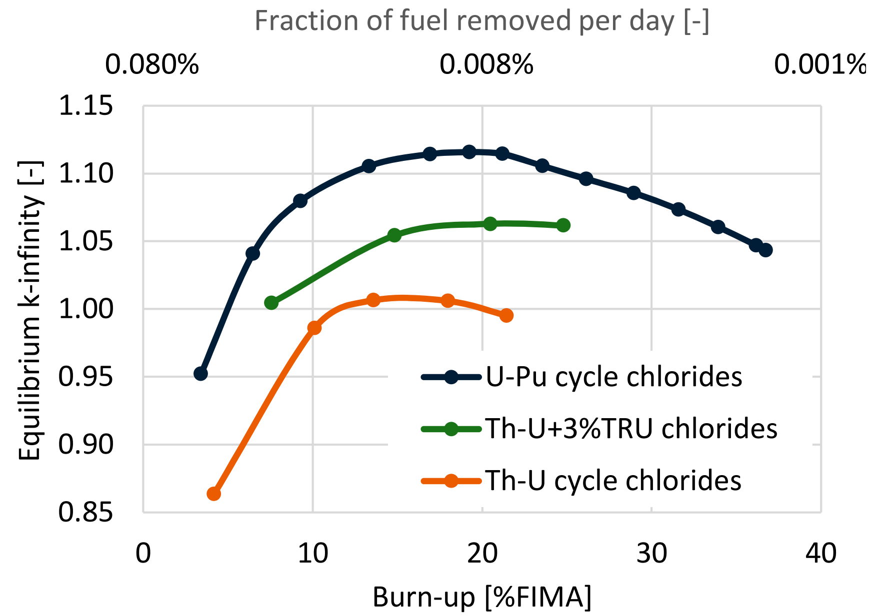




WP1: MSRs in Breed-and-Burn (B&B) mode

- **Assumptions for Breed-and-Burn (B&B)**:
  - No reprocessing: discharged fuel is lost.
  - Fresh fuel is fertile: no fissile support.
  - High breeding maintains criticality & compensates losses from refueling.
  - Solid fuel B&B are limited by max. cladding fluence, no issue in MSRs.

Results on a cell level =>



- **Main conclusions – cell level:**
  - B&B mode is possible only with enriched ^{37}Cl based chlorides MSR.
  - B&B mode in Th-U cycle and chloride salts may require fissile support.
  - LWR TRU waste can act as the fissile support => pseudo B&B mode.

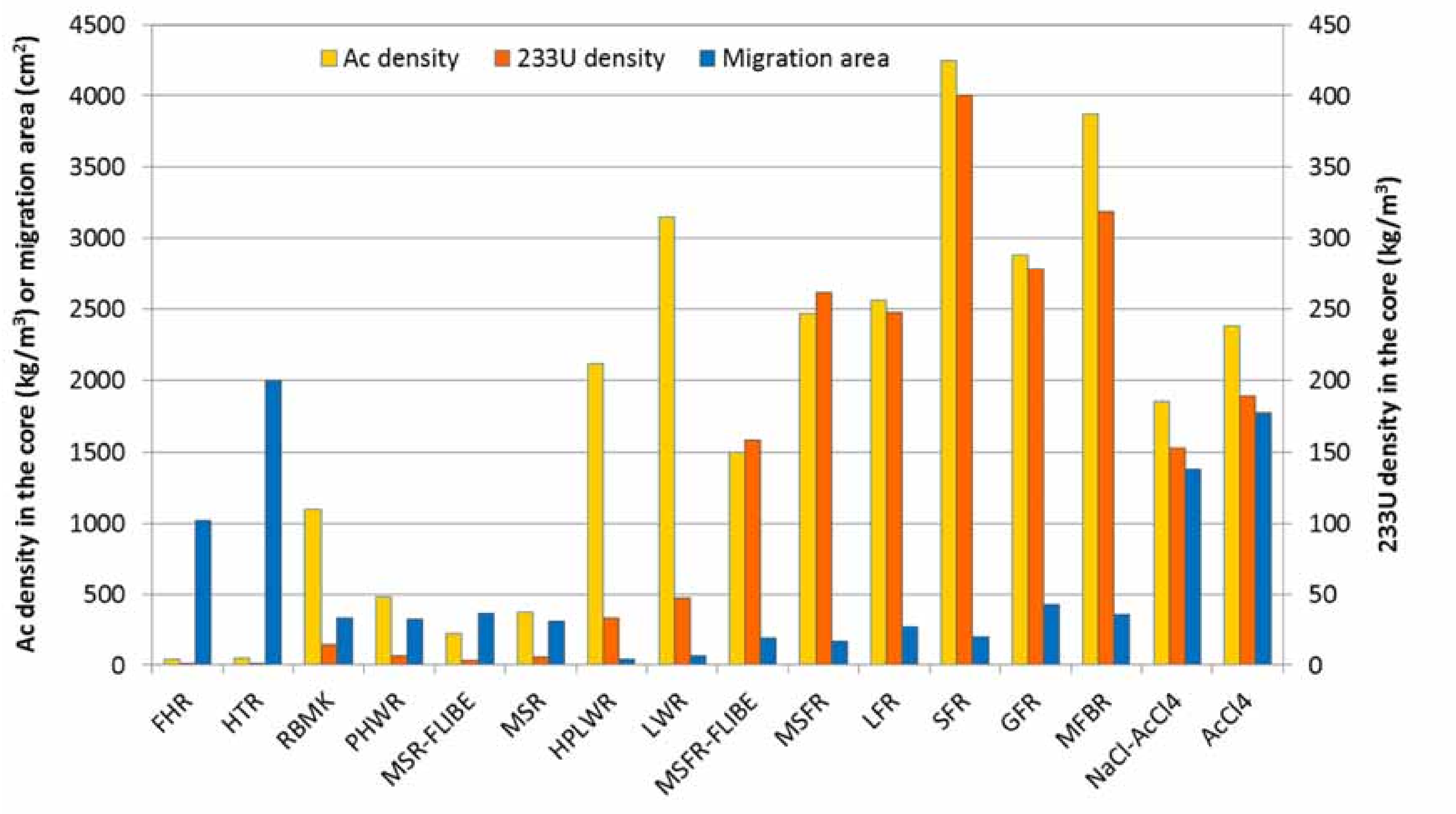
- **Design issues:** Chlorides are transparent => leakage utilization (reflector, multi-zone).
  At the deep burnup, the solubility limit may be reached for FPs.

Hombourger, B. et. al., Fuel cycle analysis of a molten salt reactor for breed-and-burn mode, ICAPP 2015, Nice

Th-U cycle: actinides density and migration area

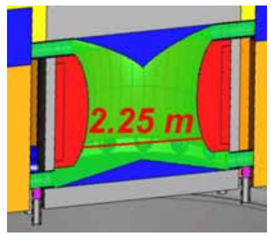
o **Chlorides disadvantage**: transparency

- Both chlorides and fluorides salts have low specific Ac density.
- Furthermore chlorides area transparent for neutrons.
- High migration area => high leakage => bigger reactor or blanket or reflector.



WP1: MSR Breed-and-Burn: core level

B&B – PSI design



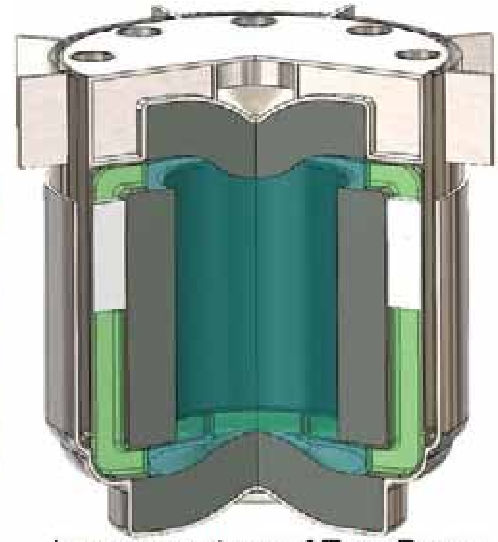


Image courtesy of TerraPower

Concept	MSFR	B&B - PSI	MCFR
B&B capability	No	Yes	Yes
Core dimensions	2.25 m x 2.25 m	3.6 m x 3.6 m	?
Core volume	9 m^3	36 m^3	?
Blanket volume	7.3 m^3	None	None
Reflector	Axial only - Hastelloy	Yes - Enriched lead	Yes - ?
Processing	Volatile & Soluble FP	Volatile FP only	Volatile FP + ?
Processing flow	3-8 L/day	2 L/day	?
Cycle time	6-16 years	52 years	?

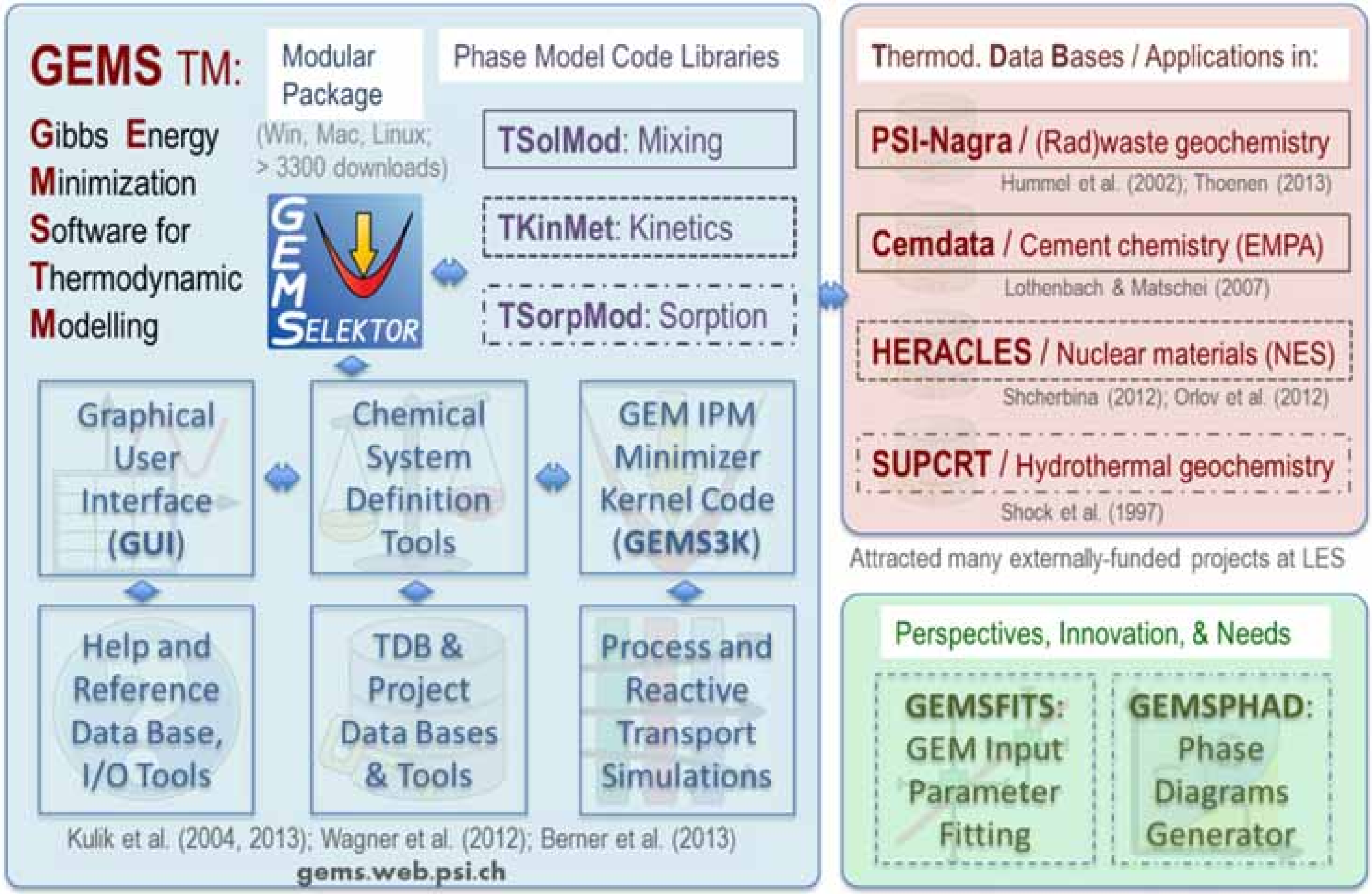
WP2: Nominal and accidental fuel behavior

- Chemistry is the **main MSR challenge**. It influences all other WPs.
- PSI has a competence in **thermodynamics and MD** simulations.
- In-house code **GEMS** (Gibbs Energy Minimization Software for Thermodynamics Modelling) is unique open source alternative to the commercial FactSage code.
- The respective database **HERACLES** needs modification and extensions. Cooperation with **ITU** (experimental data) may be crucial.

	2015				2016				2017				2018		
WP2: GEMS dev. & app.	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III
12MM AHL AcF behavior in $LiF-AlF_3$		EU Sacsess project													
6MM AHL MD of PuF_3 in fluoride salts			EU project Samofar												
MSc AHL & LRS FPs chemical behavior in MSR (GEMS)					MSc - N. Vozarova										
GEMS: phase diagram for MSFR salt							Swiss Nuclear								

WP2: Nominal and accidental fuel behavior

- The work on the GEMS modification and **HERACLES** database has already started.

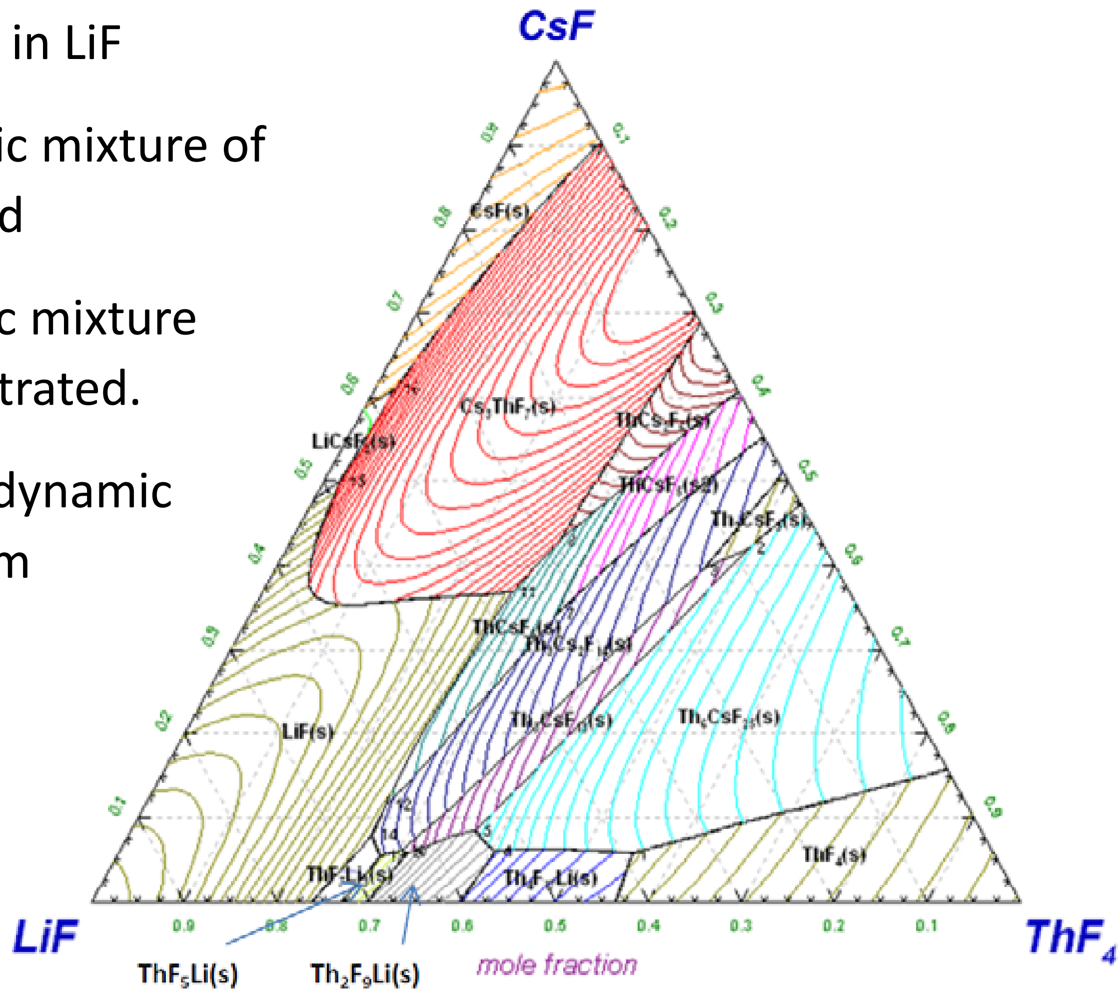


Kulik D.A., Dmytrieva S.V., Wagner T., Kosakowski G., Thoenen T, Berner U., et al. (2004-2014): Gibbs Energy Minimization Software (GEMS) homepage (http://gems.web.psi.ch).

WP2: FPs behavior in the salt

- CsI dissolution in a eutectic mixture of LiF-ThF_4 could not be demonstrated due to low solubility of CsI in LiF
- CsF dissolution in a eutectic mixture of LiF-ThF4 was demonstrated
- CsI dissolution in a eutectic mixture of LiF-NaF-KF was demonstrated.
- Development of a thermodynamic model of a CsF-ThF4 system using Factsage software.
- Subsequent calculation of phase equilibria using GEMS. (using different mixing)

N. Vozarova, ITU Karlsruhe & AHL, **MSc** thesis **2016**



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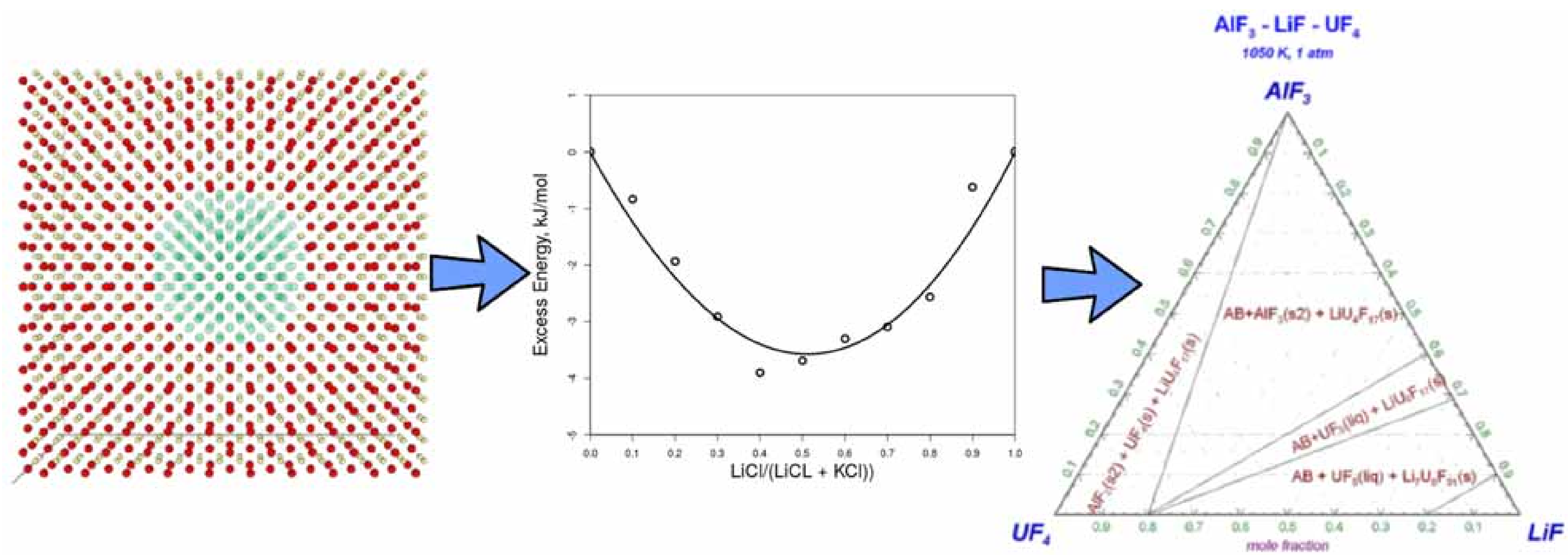
WP2: Molecular Dynamics (SAMOFAR)

Application of Molecular Dynamics for:

- Thermal conductivity calculation
- Melting behavior study
- Specific heat behavior
- Binary excess properties

Goal:

Combine Molecular Dynamics / DFT with Thermodynamic Simulation methods to simulate the systems of interest - speciation



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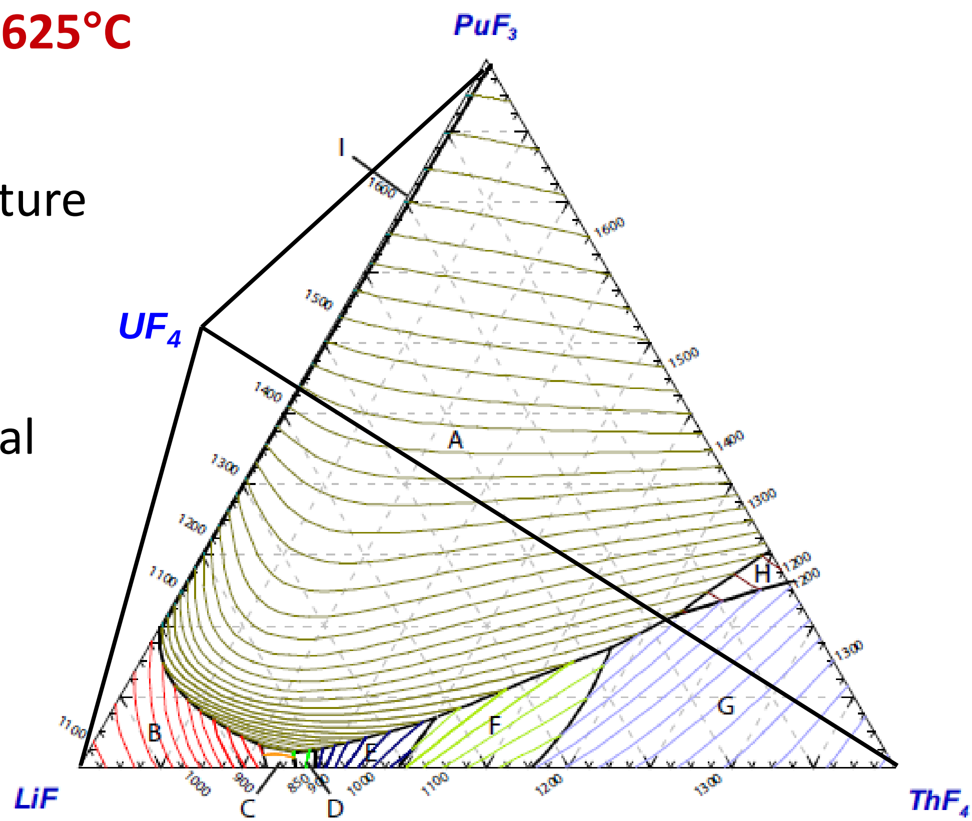
WP2: Swiss Nuclear project

- Burning of TRans-Uranic (TRU) isotopes faces the problem of PuF_3 solubility in fluoride salts.
- **MSFR**, Pu started Th-U cycle, **$T_{melt.}$=625°C**
  78%LiF - 16%ThF_4 - 6%PuF_3
- **Alternative** is to start MSR with mixture of **Pu** and **enriched uranium**.
- The main aim of the project is the phase diagram with **UF_4** and proposal of convenient start-up fuel
- We may consider to extend the study to chlorides..?

MCFR, Pu started Th-U cycle,
55%NaCl - 39%ThCl_4 - 6%PuCl_3 .
$T_{melt.}$=425°C



LiF-ThF_4-PuF_3 ternary phase diagram
w/ fixed 1% mol UF_4 concentration
E. CAPELLI et al., "Thermodynamic Assessment of the LiF–ThF4–PuF3–UF4 System," J. Nucl. Mater., ***462****, 43 (2015).*

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WP3: MSR thermal-hydraulics and DHR system

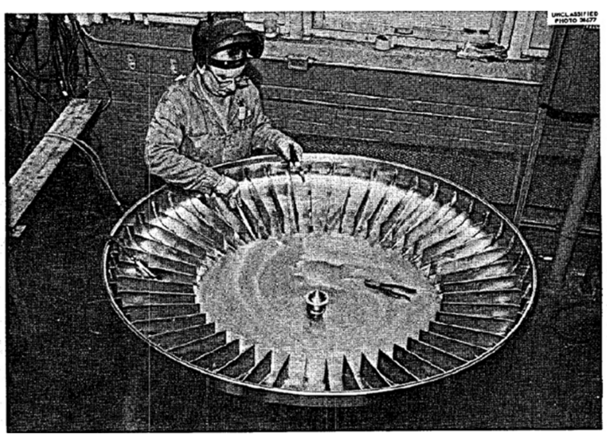
- MSR thermal-hydraulics is specific.
  (volumetrically heated liquid; moderator cooled by fuel; delayed neutron drift; etc.)
- WP3 aim:
  - thermal-hydraulics design of the core and DHR system,
  - transient system behavior (TRACE-point kinetics or TRACE-PARCS),
  - transient core behavior (GeN-Foam – Open-FOAM based solver).

	2014				2015				2016				2017				2018		
WP3: Thermal-hydraulics	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III
LRS: Heat exchanger analysis	MSc - V. Ariu																		
LRS: MSR decay heat evaluation					MSc - J. Choe														
LRS: Trace-PARCS MSR modification					MSc - H. Kim														
LRS: GeN-Foam development	PostDoc C. Fiorina																		
LRS: 12MM Multiphysics simul. of transient							EU project Samofar - will be transformet into PhD position												
LRS Gen-Foam application to MSRE									MSc - J. Bao										
LTH: MSR turbulence modeling									MSc - E. Pettersen										
LTH & ETH: salt instrumentation Doppler velocimetry						visitng PosDoc at ETH													

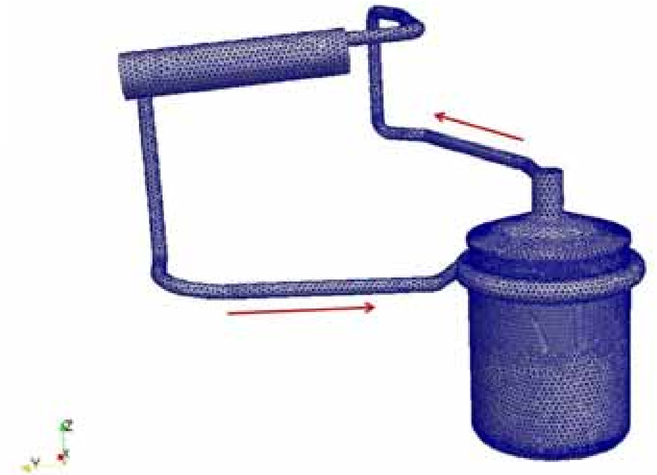
WP3: Multi-physics code at PSI – GeN-Foam

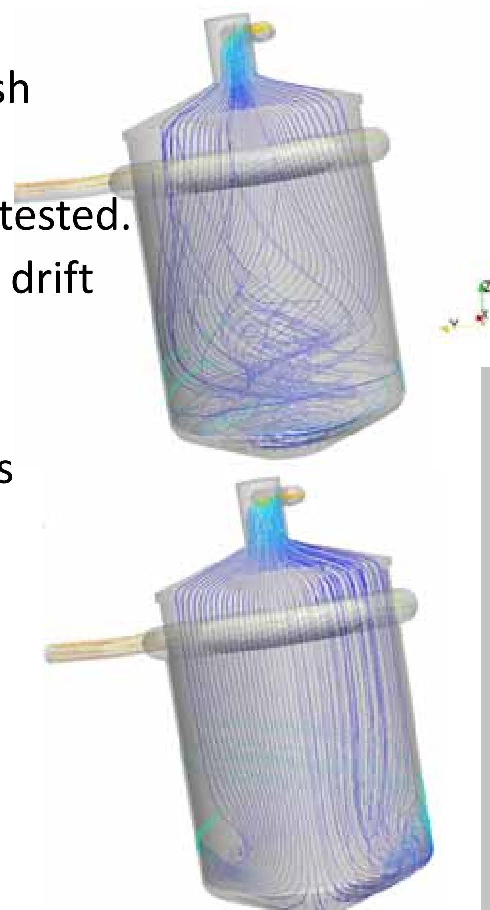
- PSI in-house solver **GeN-Foam** was applied to **MSRE**.
- It was part of the initial verification of the code.
- Coarse MSRE model and mesh was developed.
- Porous media approach was tested.
- Delayed neutrons precursors drift was modeled.

- Illustration of anti-swirl vanes influence.



J. Bao, LRS, **MSc** thesis **2016**





GeN-Foam coding:

```
fvm::ddt(IV,flux[energyI])-
fvm::laplacian(D,flux[energyI])-
fvm::Sp(nuSigmaFis[energyI]/keff*
        (1.0-Beta)*chiPrompt)-
        sigmaDisapp,flux[energyI])-
delayedNeutroSource*chiDelayed-
scatteringSource

fvm::ddt(rho, U)
+ (1/porosity)*fvm::div(phi, U)
+ turb.divDevRhoReff(U)
- porousMedium.
  semiImplicitMomentumSource(U)

fvm::d2dt2(Disp) ==
fvm::laplacian(2*mu + lambda, Disp,
"laplacian(DD,D)")+ divSigmaExp
```

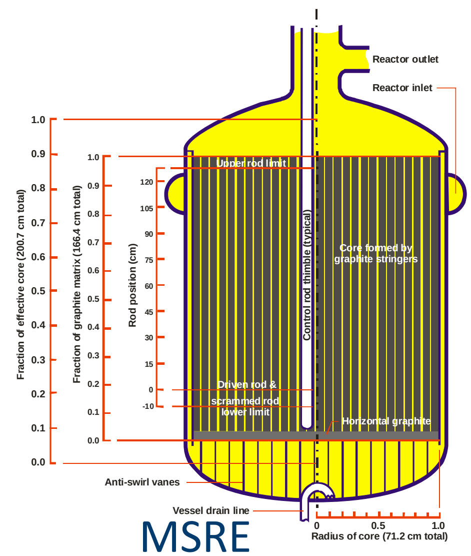
Fiorina C. at al., 2015. GeN-Foam: a novel OpenFOAM® based multi-physics solver for 2D/3D transient analysis of nuclear reactors. Nuclear Engineering and Design, Volume 294, 1 December 2015, Pages 24–37.

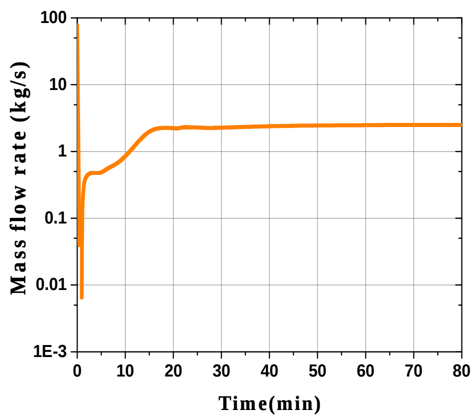
WP3: TRACE application to MSRE

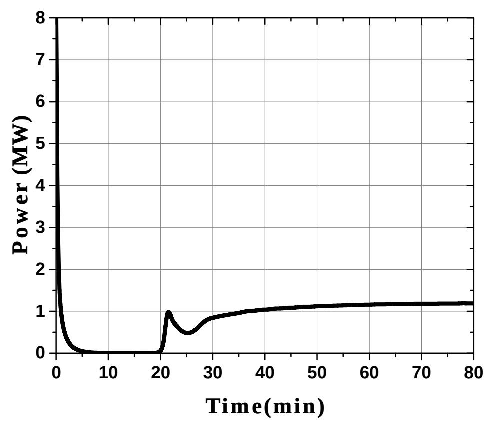
H. Kim, LRS, **MSc** thesis **2015**

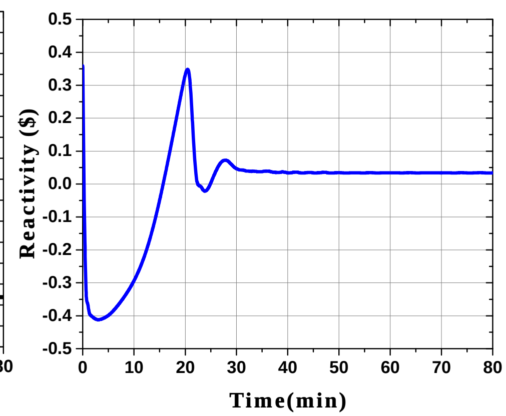
FAST system code (TRACE or TRACE-PARCS)

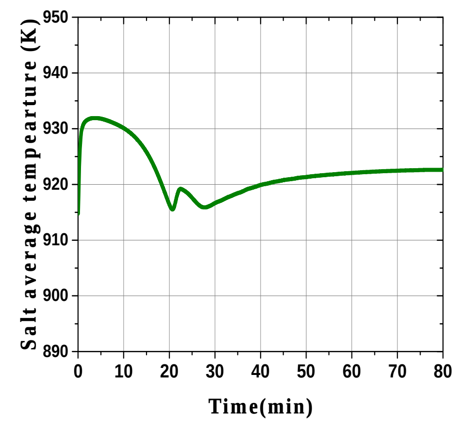
- System analysis tool modelling primary, intermediate and secondary circuits.
- Individuation and preliminary assessment of major accidental transients or optimization of the design.
- Unprotected pump trip as example result
  - Initial overheating stops the chain reaction
  - Natural circulation leads later to stabilized power level,









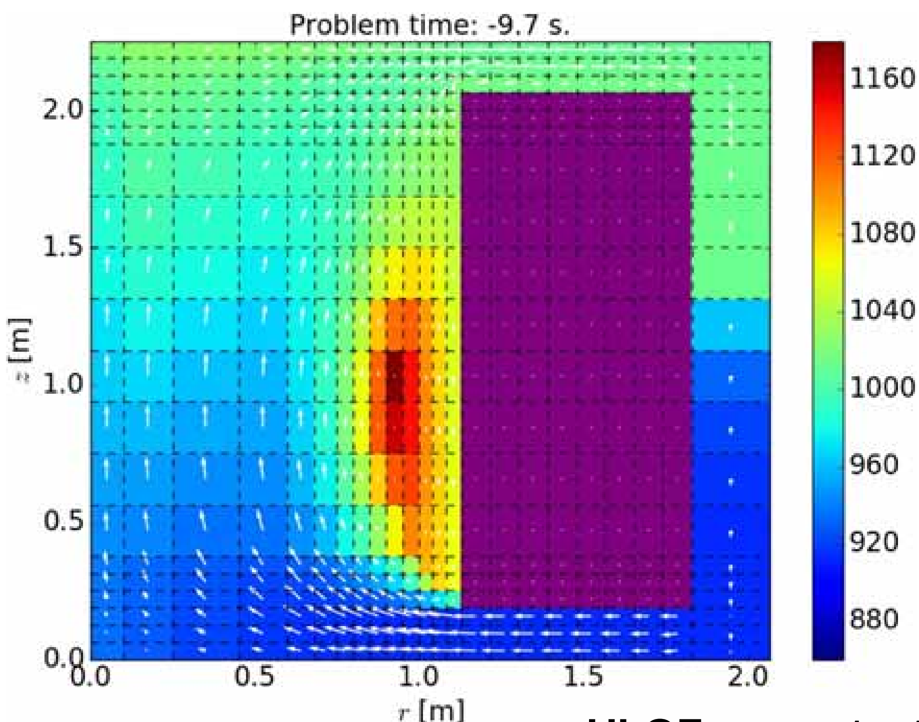


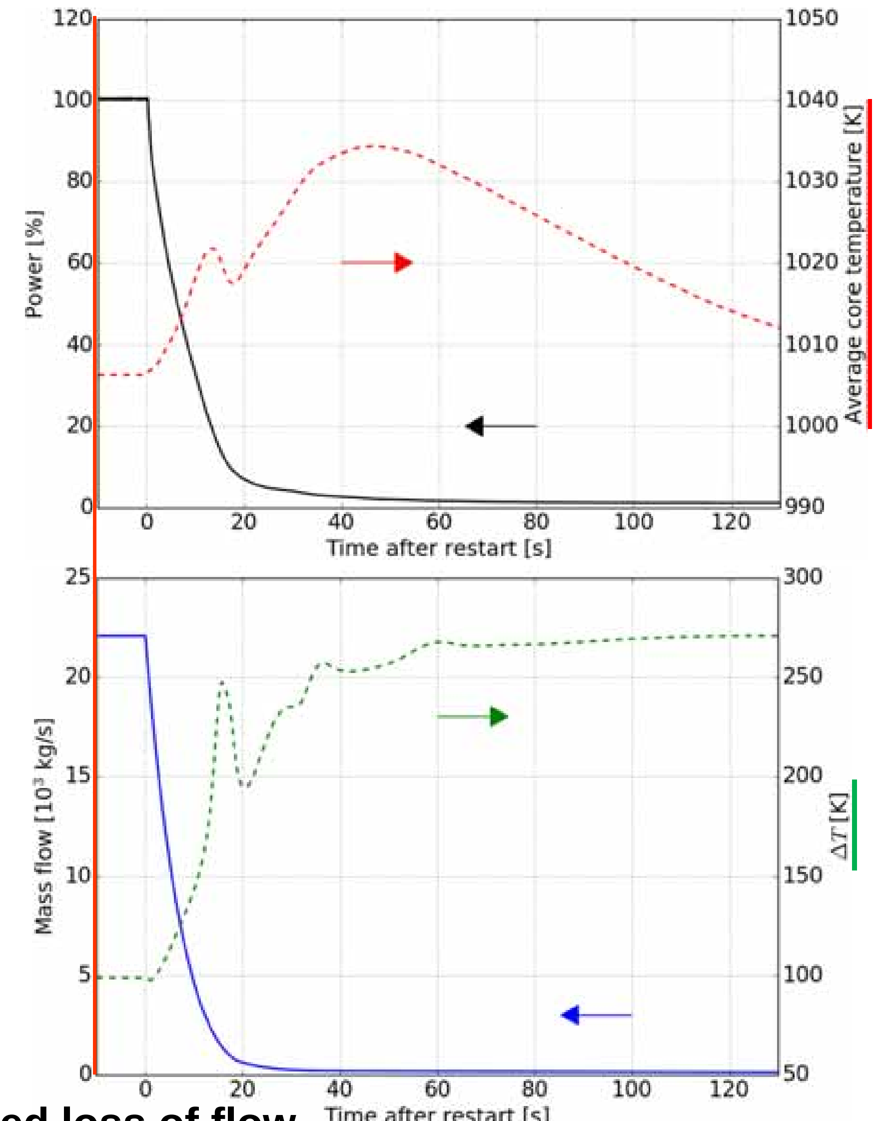
WP3: TRACE application to MSFR

E. Pettersen, LRS, **MSc** thesis **2016**

FAST system code (TRACE-PARCS)

- Application to **MSFR** using vessel component.
- Applicable for 3D transients. (2D symmetric transients)
- Capability system analysis with acceptable accuracy and CPU time.





ULOF- unprotected loss of flow

WP4: MSR safety, fuel stream and relevant limits

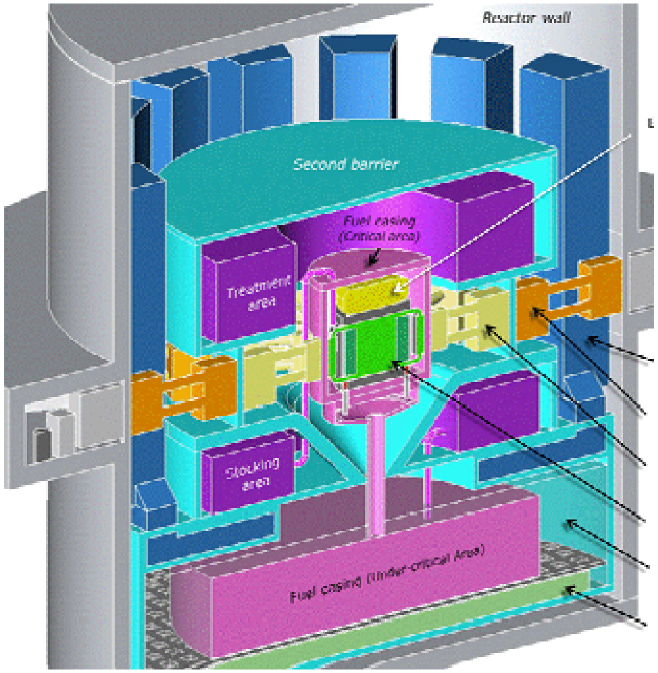
- MSR safety should be the **main long-term aim** of the **NES project**. (it strongly depends on the results from WP1-3. Thus only **selected tasks** can be addressed in the initial phase.)
- Material research for MSR may deserve additional WP. (e.g. structural integrity of Hastelloy in accidental conditions) Since there are no proposals, it is mentioned in WP4 at the moment.
- Ongoing research:
  - LTH: Aerosols formation and migration in the containment
  - LEA: MSc thesis on PSI level 1 for FUJI MSR design.
  - LEA: Simplified PSA level 3 (SAMOFAR project).

	2015				2016				2017				2018		
WP4: MSR safety	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III
8MM LEA Simplified PSA level 3			EU project Samofar												
6MM LTH Aerosols formation			EU project Samofar												
MSc LEA PSA level 1 MSR					MSc - D. Pyron										
MSc LEA Risk information in MSR designing									MSc proposal?						

WP4: Aerosol formation and migration

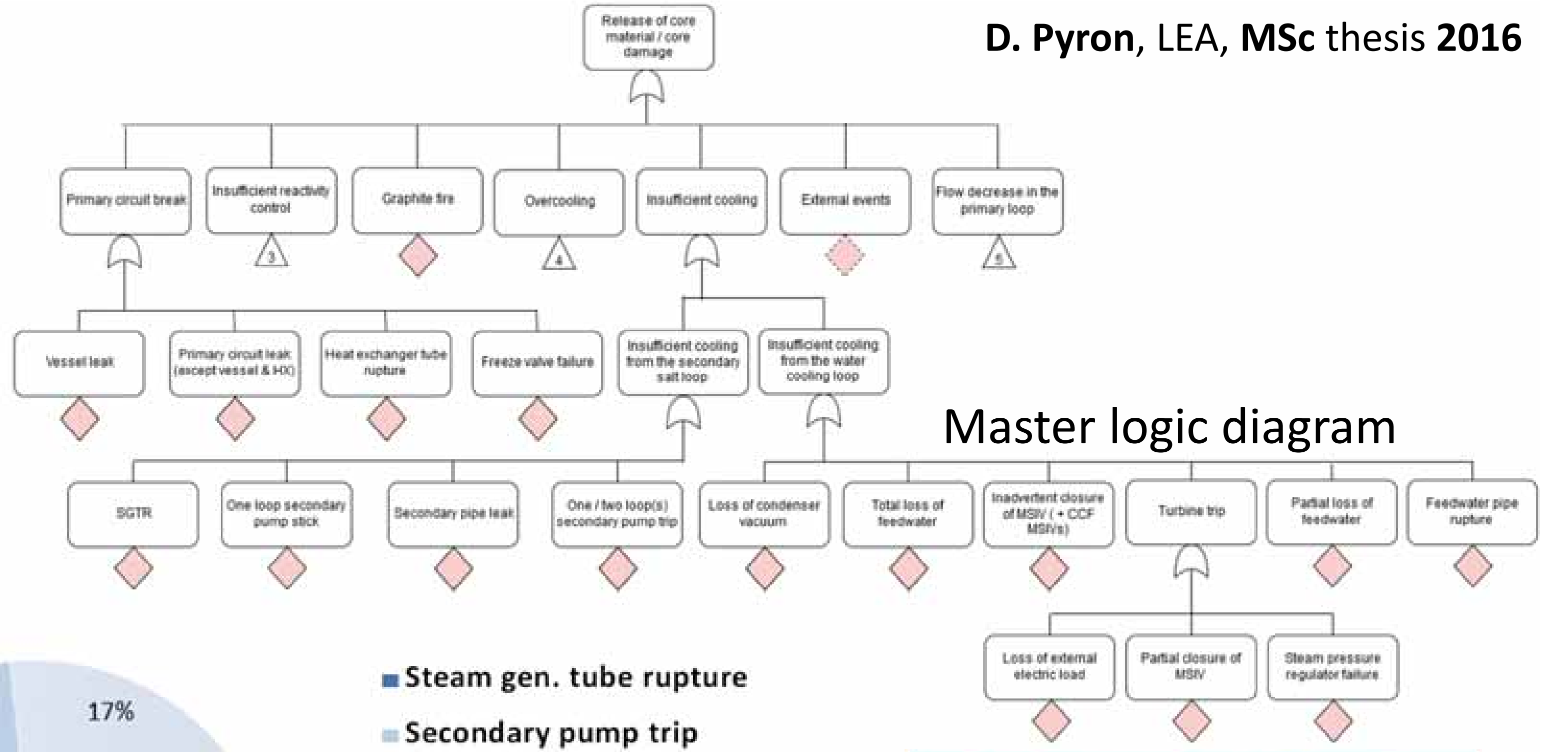
- Determine the behavior of released species from the molten salt and investigate the **transport** of FPs in an MSR in accident conditions:
  - Concentration in the gas phase
  - Concentration as aerosols
  - Deposition on the structures
- Review the applicability of different severe accident codes like **MELCOR** and **ASTEC** as well as stand-alone aerosol codes
- Build a simple input model
  - TH boundary conditions and geometry of the core/containment defined in SAMOFAR
- Sensitivity of the results regarding unknown / uncertain data and boundary conditions

MSFR containment

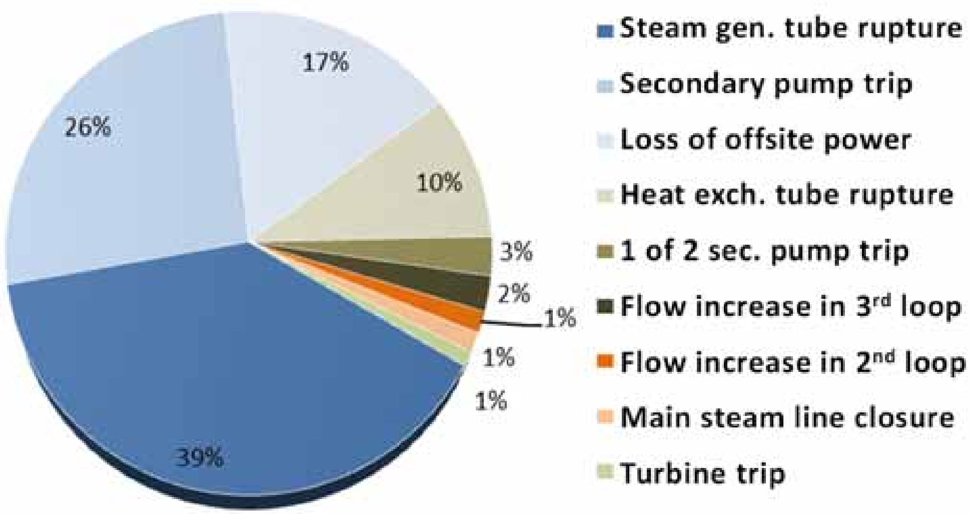


WP4: Accident scenarios & PSA 1 modeling

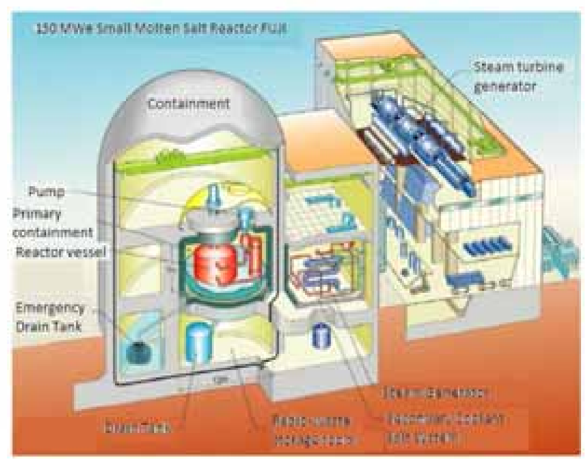
D. Pyron, LEA, **MSc** thesis **2016**



Master logic diagram



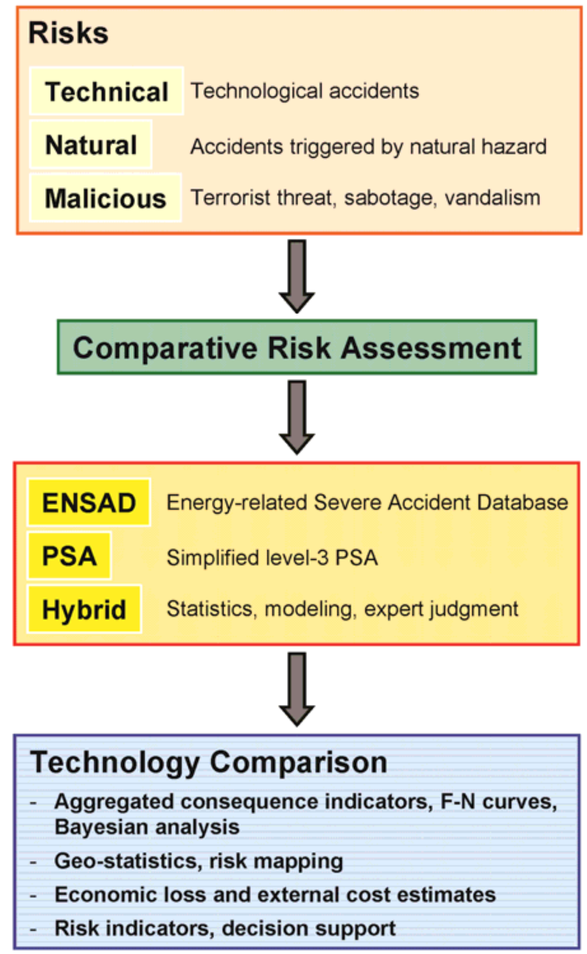
Main events with vessel damage



Mini FUJI MSR

WP4: Simplified PSA level 3

- **Simplified method** for accident consequences and risk assessment.
- Risk is based on **MACCS2** calculations for reference site plant data (**Swiss power plants**) using conversion factors.
- The information needed for the analyzed plant:
  - For consequences: source terms, power level, site
  - For risk assessment: frequencies of releases
- Tasks within **SAMOFAR** (according to proposal):
  - Update, adaptation and extension of existing method
  - Application to MSFR
  - Consideration of representative plant designs and sites



MSR is a very promising energy source, which can provide us enough time for mastering of the nuclear fusion! ☺

It can combine unparalleled safety features with high fuel utilization.

…. in far future..?

Already today it provides many interesting research topic, which are attractive for students and young scientist.

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Announcements

- 4-5 October 2016, 2nd Molten Salt Reactor **workshop at ORNL**
  (DOE has several open calls dedicated to MSR,
  ORNL will re-launch the MSR research, …).

- 31 October – 3 November 2016, Technical meeting on MSR at IAEA (**IAEA** is considering to open **MSR technological branch**).

- 23-24 January 2017, GIF MSR PSSC meeting **at PSI.**

- 23 January 2017, **public MSR workshop at PSI** presenting the key national programs (USA, China, Russia, EU, Switzerland).

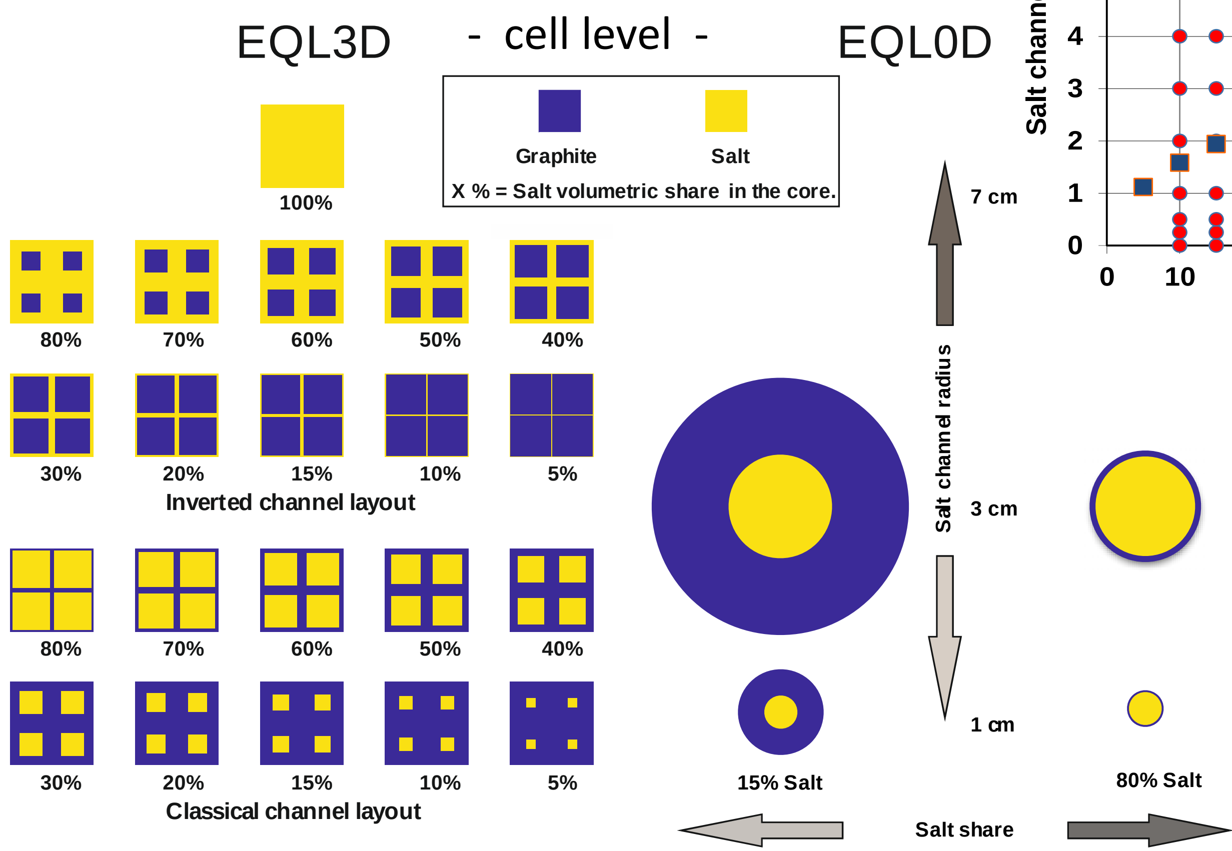
- 25-26 January 2017, **SAMOFAR** project meeting **at PSI.**

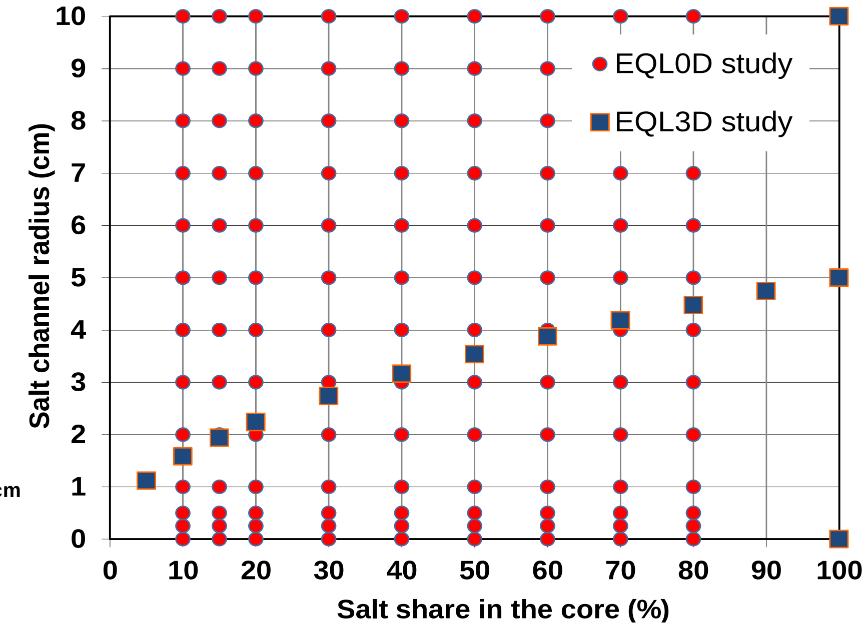
- 26-29 June 2017, IAEA Conference on Fast Reactors and Related Fuel Cycles in Russia.

EQL3D/EQL0D v1 equilibrium cycle analysis

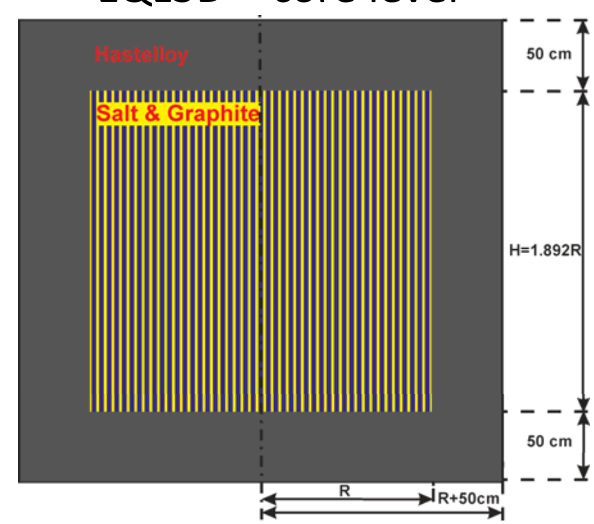
B. Homburger, LRS, **MSc** thesis **2013**

- **MSR equilibrium closed cycle** was simulated by **EQL0D** procedure on a cell level. And by **EQL3D** on the cell and core levels.



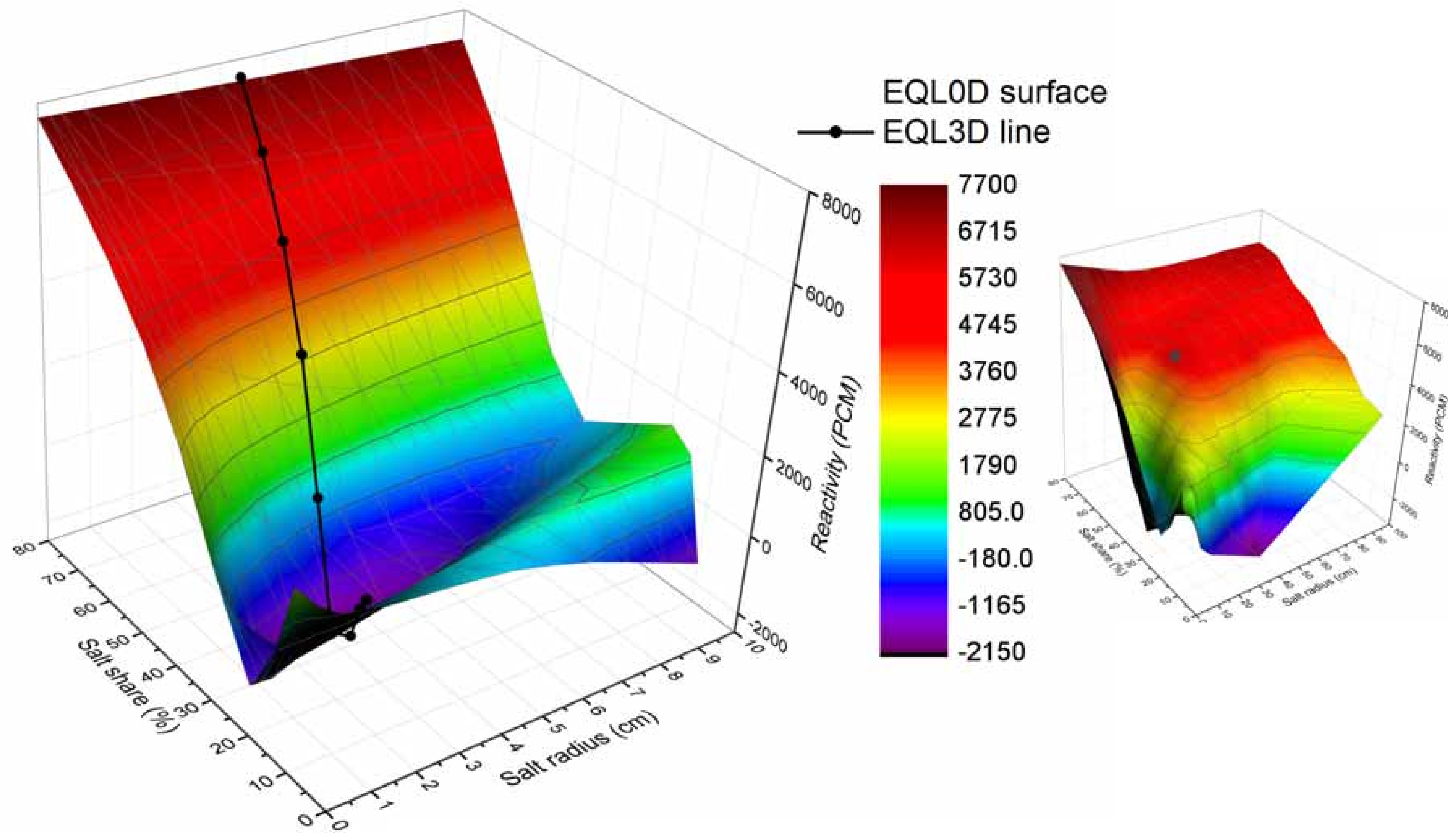


EQL3D – core level



EQL3D/EQL0D v1: inf. equilibrium reactivity

- The moderation as well as the heterogeneity effect is strong.
- EQL3D results seems to be arbitrary line on EQL0D surface.

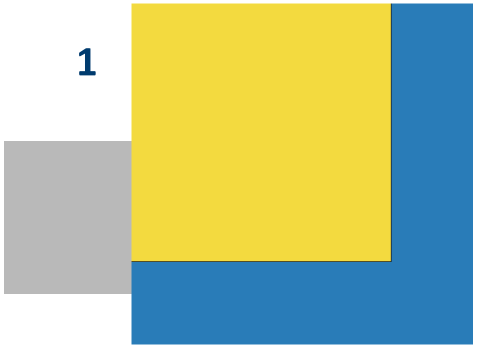


Krepel, J. at. al., HYBRID SPECTRUM MOLTEN SALT REACTOR. Physor 2014, Kyoto

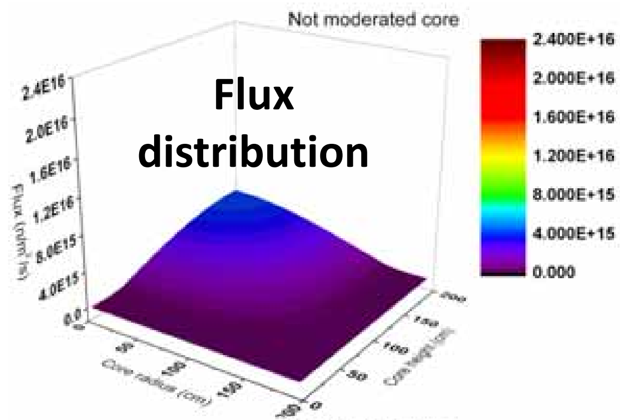
PAUL SCHERRER INSTITUT

EQL3D: Hybrid spectrum core

1

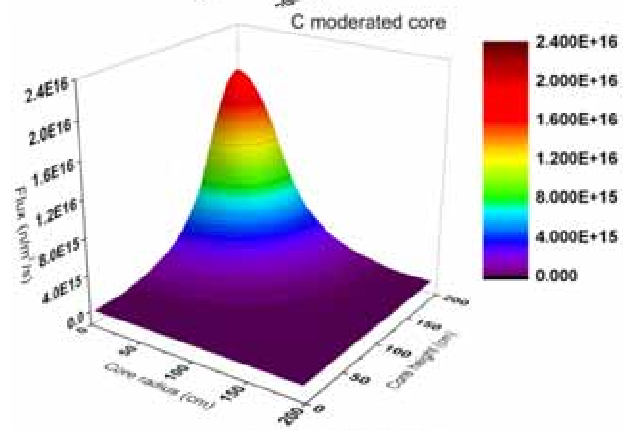


not-moderated



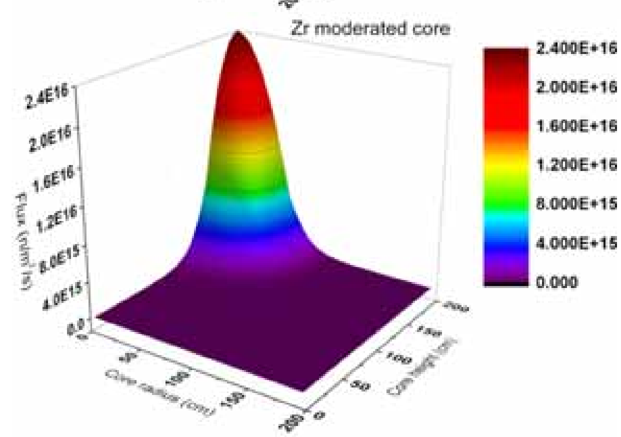
2

Graphite moderated



3

ZrH moderated



1. Equilibrium cycle: $\mathbf{k_{eff} = 1.01797}$
   Critical share for initial fuel:
   A) ^{233}U: **10.91%** of Ac
   B) LWR Pu: **25.1%** of Ac
2. Equilibrium cycle: $\mathbf{k_{eff} = 1.02810}$
   Critical share for initial fuel:
   A) ^{233}U: **5.72%** of Ac
   B) LWR Pu : **25.5%** of Ac
3. Equilibrium cycle: $\mathbf{k_{eff} = 0.88691}$
   Critical share for initial fuel:
   A) ^{233}U: **2.15%** of Ac
   B) LWR Pu : **3.40%** of Ac

Main conclusions:

- Graphite does not provide strong reduction of the fluence on the core wall, ZrH does.
- ZrH is applicable for the initial, but not for the equilibrium cycle.

Krepel, J. at. al., HYBRID SPECTRUM MOLTEN SALT REACTOR. Physor 2014 Kyoto

Comparison of recycling strategies for MSR

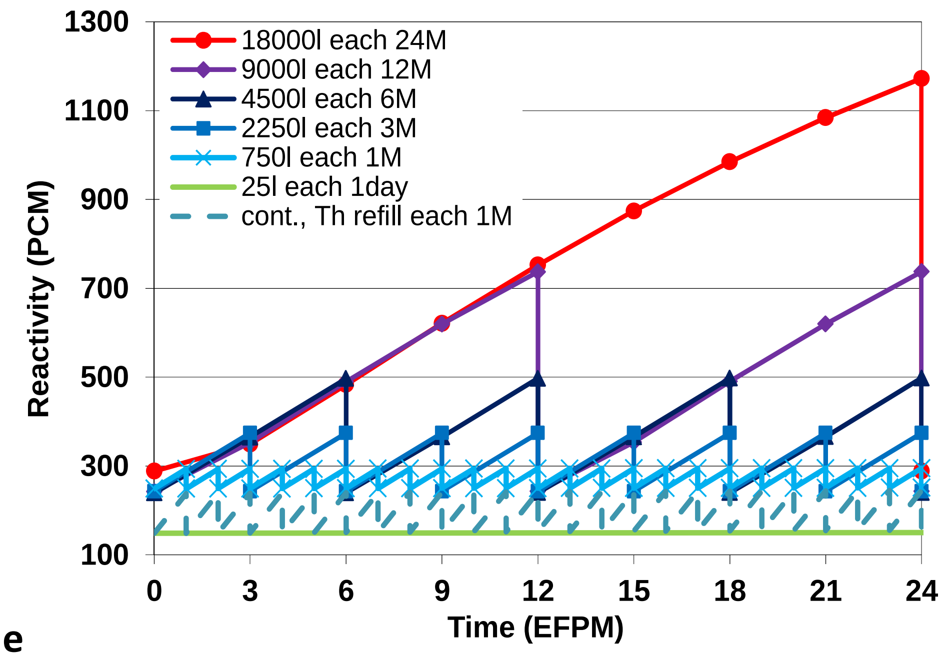
Strategy Nr.	Salt clean-up from FPS	Th refilling	Min. salt volume for operation
1	18000l each 24M	each 24M	36 m^3
2	9000l each 12M	each 12M	27 m^3
3	4500l each 6M	each 6M	22.5 m^3
4	2250l each 3M	each 3M	20.25 m^3
5	750l each 1M	each 1M	18.75 m^3
6	25l each 1day	each 1day	18 m^3
7	continuous	each 1M	18 m^3

Assumptions:

- Reprocessing unit capacity **25 L/day**.
- The volume for reprocessing is taken from **core** (cases 6 and 7) or from **temporary storage tank** (cases 1-5).

Main conclusions:

1. Reactivity **swing is positive** and proportional to the reprocessing time. (decreasing Th mass = +2.2 PCM/kg; increasing FPs mass = -2.0 PCM/kg)
2. Continuous **Th refilling** can be used as **reactivity control**, independently of the selected salt clean-up treatment.
3. The strategy with **longest** reprocessing **time** has **lowest average FPs content**. (it has also highest breeding gain)
4. Its **disadvantage** is the **biggest salt volume** (initial load) necessary for reactor operation.



Reactivity swing for 7 recycling strategies

Krepel, J. at. al., Comparison of Several Recycling Strategies and Relevant Fuel Cycles for Molten Salt Reactor. ICAPP 2015 Nice

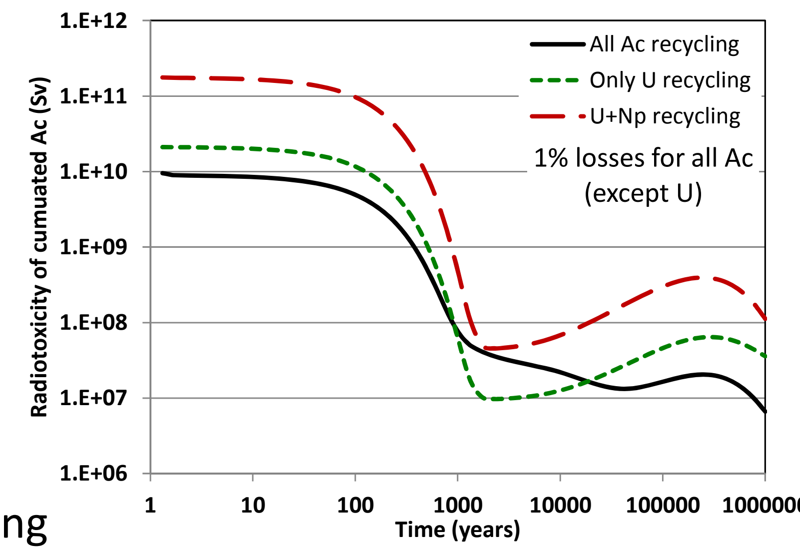
Simple fuel recycling using volatilization

- **Assumptions for the Th-U MSR fuel cycle**:
  - Isobreeding MSR initialized by ^{233}U.
  - Salt reprocessing every 12 months.
  - Reactor power of 2.6GWth.
  - Only volatilization method is used for simplified fuel recycling.
  - 3 scenarios:
    - I. **All Ac recycling** (not simplified) (U(100%)+Np(99%)+Pu(99%)+….)
    - II. **U**(100%)+**Np**(99%) **recycling**.
    - III. **U only** (100% efficiency) **recycling**

Recycling	All Ac	U+Np	Only U
NP237	59.7	59.7	1371.3
Pu238	60.3	1210.0	144.6
(U234)	*(14)*	*(290)*	*(36)*
Pu239	**16.9**	**47.7**	6.1
Other Ac	15.3	1.5	0.2
Sum	**152.2**	**1318.9**	**1522.3**

Cumulative Ac mass in kg in waste produced during 100 EFPY of operation.

- **Main conclusions**:
1. If **only U** is **recycled**, the cumulative Ac waste after 100 EFPY will be dominated by ^{237}**Np - 1371 kg** and ^{238}**Pu - 145 kg**.
2. The waste **radiotoxicity** for simplified recycling will be just **slightly higher**.



Radiotoxicity of cumulated Ac mass.

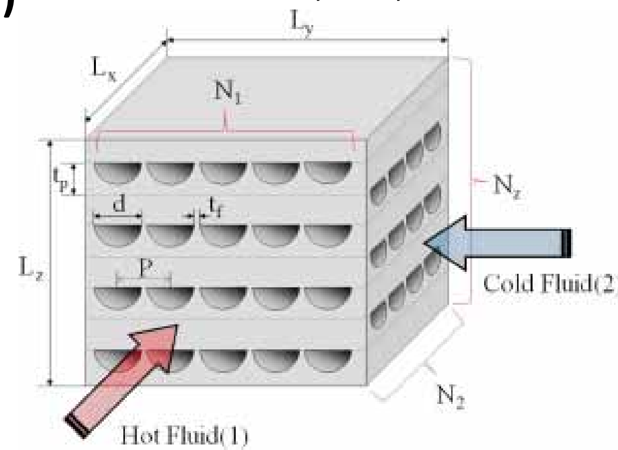
Krepel, J. at. al., Molten Salt Reactor with Simplified Fuel Recycling and Delayed Carrier Salt Cleaning. ICONE 2014, Prague.

WP3: recently finished MSc topics at PSI/EPFL

Assessment of primary heat exchanger (TRACE)

A. Valerio, LRS, **MSc** thesis **2014**

- Choice and preliminary design of the primary heat exchanger (shell and tube or printed circuit)
- Analysis of the proposed HX in steady state and accidental conditions

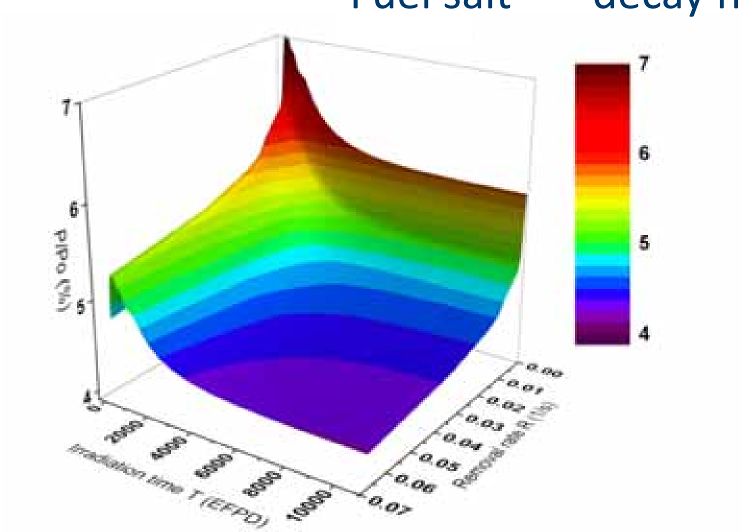


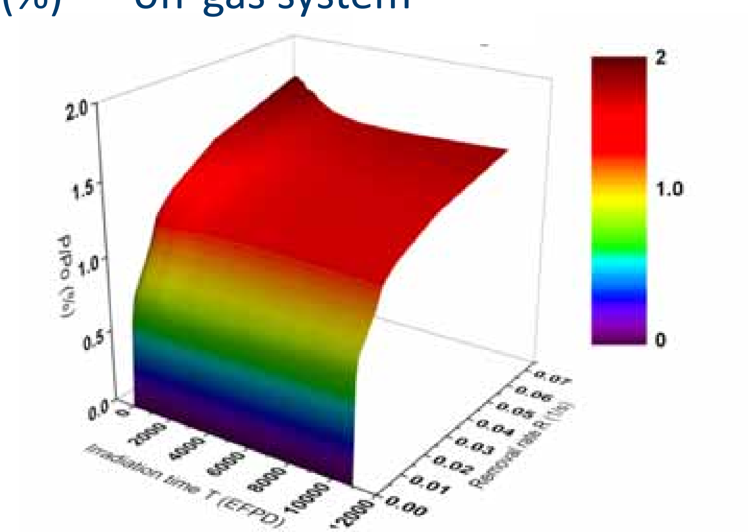
Printed circuit heat exchanger

Decay heat evaluation with EQL0D

J. Choe, LRS, **MSc** thesis **2015**

Fuel salt - decay heat (%) - off-gas system





Neutronics advantages: Th chain

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