Jiří Křepel :: MSR project manager :: Paul Scherrer Institut

Molten Salt Reactor Research in Switzerland

GIF MSR Workshop

24th January 2017, PSI Auditorium

NES Mission: Maintaining Nuclear Competence

Safety

Understanding relevant phenomena

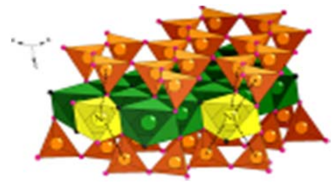
Normal Operation ··· Severe Accidents

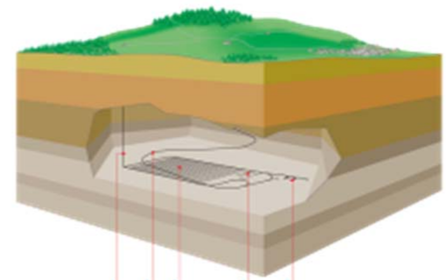
Materials performance (barrier integrity)

Waste Management

Multiscale reactive transport
of radio-isotopes

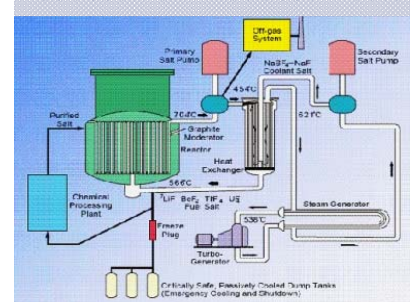
Safety of deep geological repository





New Technologies

Reduced risk - Reduced waste



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Main framework: Gen-IV International Forum

- In August 2015, Switzerland signed the **ten-year extension of GIF Framework Agreement** for International Collaboration on Research and Development of Generation IV Nuclear Energy Systems.

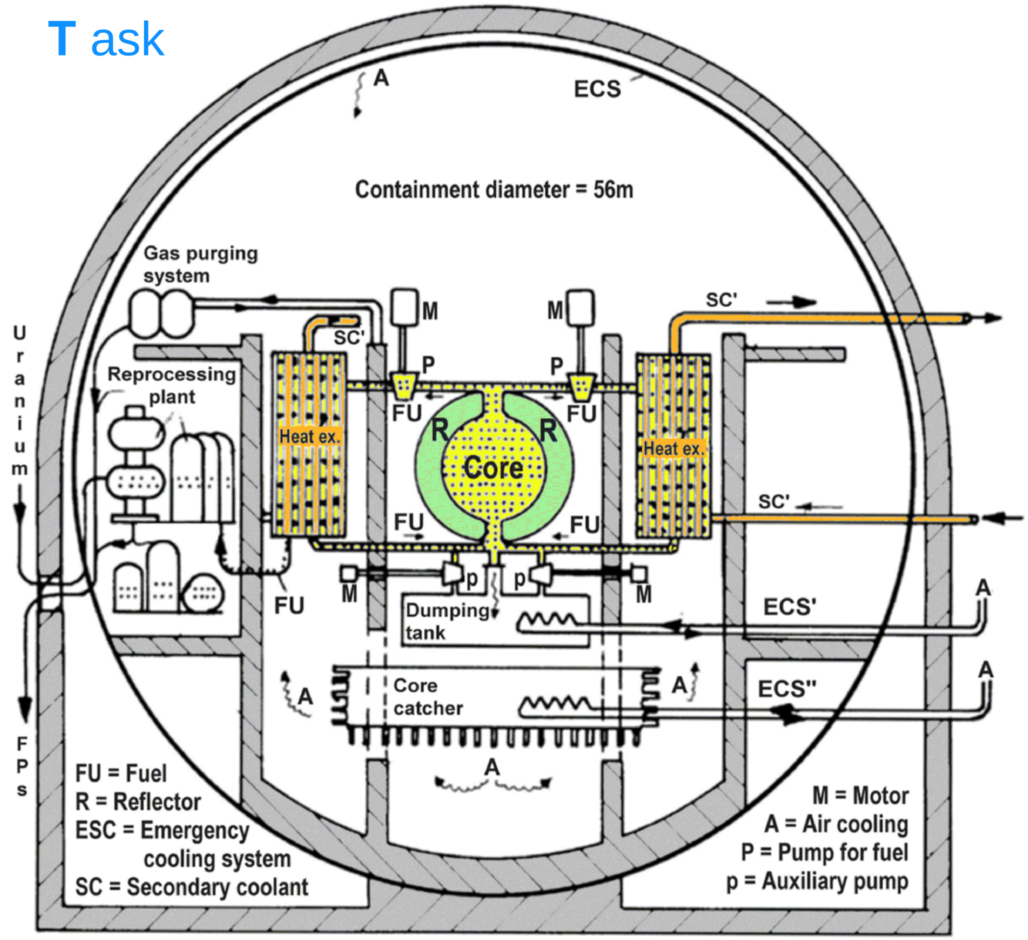
- In November 2015, Switzerland signed the Memorandum of Understanding and joined the **GIF Molten Salt Reactor Project.**
- In 2015 Switzerland withdrawn from GIF Gas Fast Reactor project.
- Switzerland continues participation in the **GIF Very High Temperature Reactor** project (LNM).
- **Swiss motivation for MSR**: unparalleled combination of safety features with high fuel utilization and waste minimization, multidisciplinary research topic, framework for PhDs and PostDocs projects, and for funding from alternative financial sources.

GEN IV International Forum™

MSR R&D at PSI in the past: 1973-1980

- Between **1973-1980** there was a project at EIR (PSI) focusing on **fast chlorides** MSR - called **SOFT**.
- **SOFT:** $3GW_{th}$, 4 loops design, fueled by **natural chlorides**, $75m^3$ in core, $32m^3$ outside, 1 $PuCl_3$ - 8 UCl_3 - 10 NaCl
- Core **reflected** by $122m^3$ of **$CaCl_2$-NaCl** & steel, closed cycle with reprocessing, breeding ratio ~ 1.04.
- Salt heat-up 180°C (470-650°C), volume flow $6.65m^3/s$, recirculation time 16.1 s.

S alt reactor
O n site reprocessing
F ast converter
T ask



EIR (PSI) study (report nr. 411, 1980)

*moltensalt.org/references/static/downloads/pdf/**EIR-411**.pdf*

MSR R&D at PSI nowadays: 2013+

- Switzerland is partner of the **GIF Molten Salt Reactor** Project.
- Bilateral cooperation with ITU, POLIMI, CTU Prague, Terrestrial Energy, …
- Nuclear Energy and Safety (NES) Division project on MSR, which serves as an umbrella for several ongoing national and international projects:

NES participates in Euratom **Horizon2020 project:**

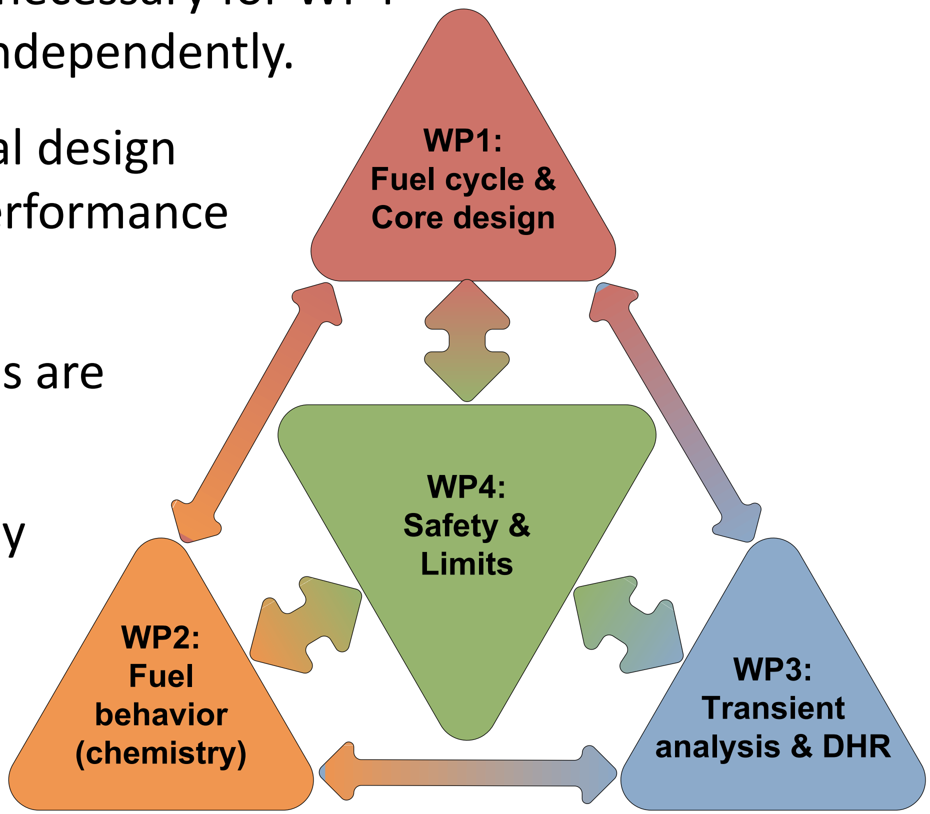
1) **SAMOFAR** - Safety Assessment of the MOlten salt FAst Reactor.

4 national projects at NES 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 (PSEL) 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.*

NES Division Project as an umbrella

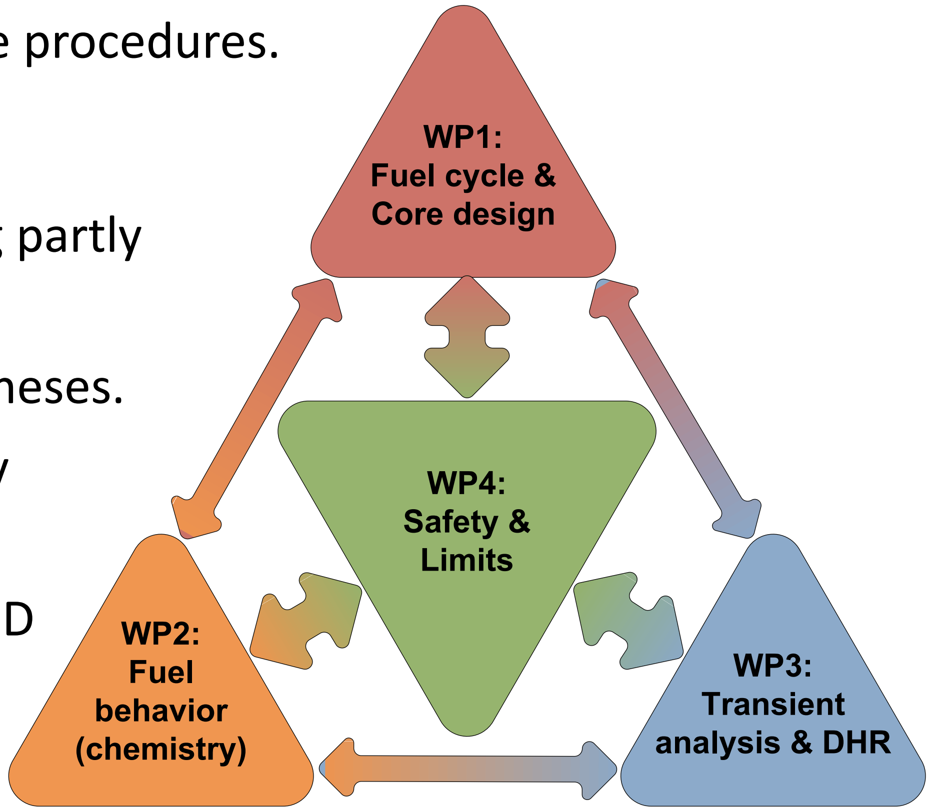
- The NES project is structured into **4 working packages** of similar research topics (general or design dependent) related to MSR.
- **Safety** of MSR (**WP4**) should be the **main long term aim** of the project.
- However, **knowledge** from **WP1-3** is necessary for WP4 and only selected task can be done independently.
- Core design evaluation (**WP1)**: several design options were evaluated looking at performance and safety related parameters.
- For **WP2** and **WP3** applications, codes are being developed or modified.
- All WPs are interconnected, especially **WP2** has strong influence on all the other WPs.



NES Division Project as an umbrella

- **Main tools:**
  - **GEMS** Gibbs Energy Minimization Software for Thermodynamics Modelling
  - **TRACE-PARCS** system code for MSR transient analysis
  - **GeN-Foam** multi-physics tool for MSR core analysis
  - **EQL0D & EQL3D** equilibrium cycle procedures.

- **Involved staff:**
  - 2 scientist and 3 PostDoc working partly on MSR projects.
  - 7 accomplished, 1 ongoing 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 (at POLIMI & TU Prague).



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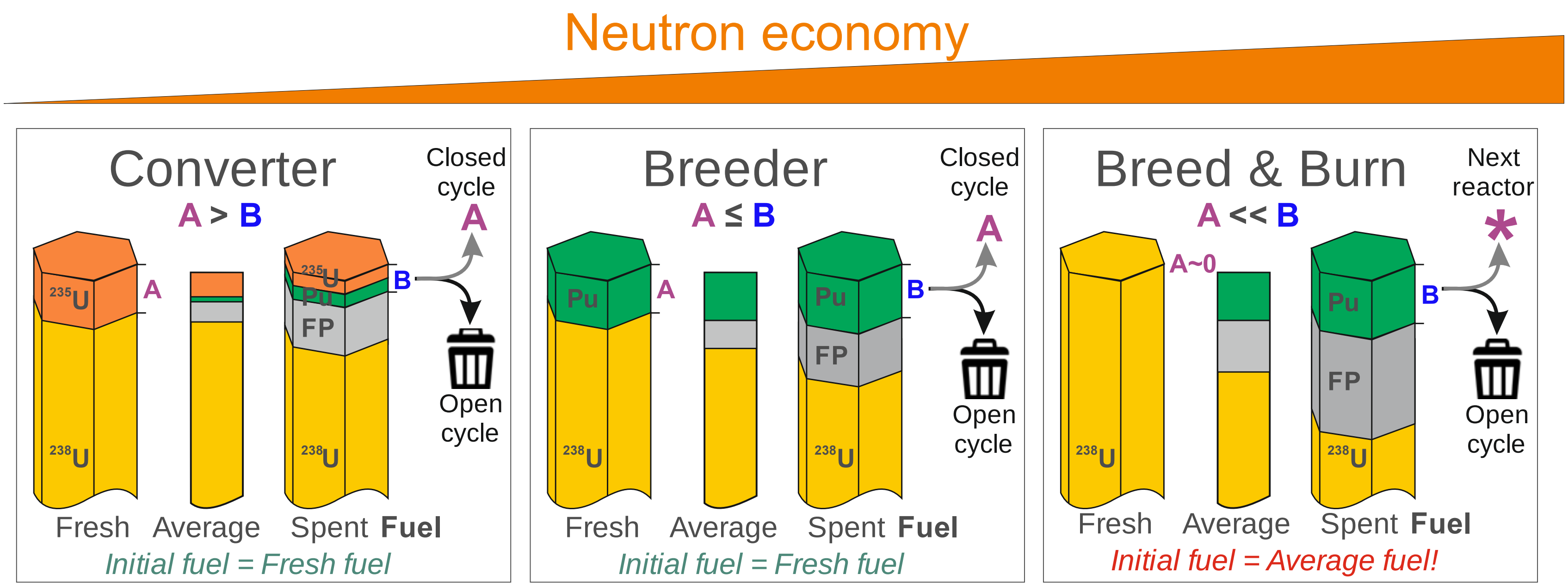
MSR fuel cycle & core design

WP1: Fuel cycle & Core design

- Evaluation of several design options (performance and safety)
- Applied tools are EQL0D and EQL3D procedures developed at PSI:
  - **EQL3D - ERANOS** based procedure for core level simulation.
    Křepel, J. et al., Fuel Cycle Advantages and Dynamics Features of Liquid Fueled MSR. Annals of Nuclear Energy. vol. 64, pp. 380–397, 2013.
    Krepel, J. at. al., Molten Salt Reactor with Simplified Fuel Recycling and Delayed Carrier Salt Cleaning. ICONE 2014.
    Krepel, J. at. al., Comparison of Several Recycling Strategies and Relevant Fuel Cycles for Molten Salt Reactor. ICAPP 2015.
  - **EQL0D v1** MATLAB-**ERANOS ECCO**, reaction rates based, cell level.
    B. Homburger, LRS, MSc thesis, Swiss nuclear master course, 2013
  - **EQL0D v2** MATLAB-**SERPENT**, reaction rates based, cell or core level.
    Krepel, J. at. al., HYBRID SPECTRUM MOLTEN SALT REACTOR. Physor 2014, Kyoto
  - **EQL0D v3** MATLAB-**SERPENT**, adopts directly the **SERPENT burn-up matrix**, cell or core level, **includes fission products** (v1 and v2 not).
    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.
- **Conclusion:** fast MSR has fuel cycle advantages, safety depends on reactor design: *graphite may have positive feedback coefficient in a breeder, fast multi-zone core may have positive salt density coefficient, etc..*

Fuel cycle in general – neutron economy

WP1: Fuel cycle & Core design



- **Convertor**, e. g. PWR or DMSR, is operated **usually** in **open fuel cycle**.
- **Breeder** profit from neutronics advantages only in the **closed cycle**.
- Extreme breeder can be operated in **Breed-and-Burn** mode.
  It can have **high fuel utilization** even **without reprocessing**.

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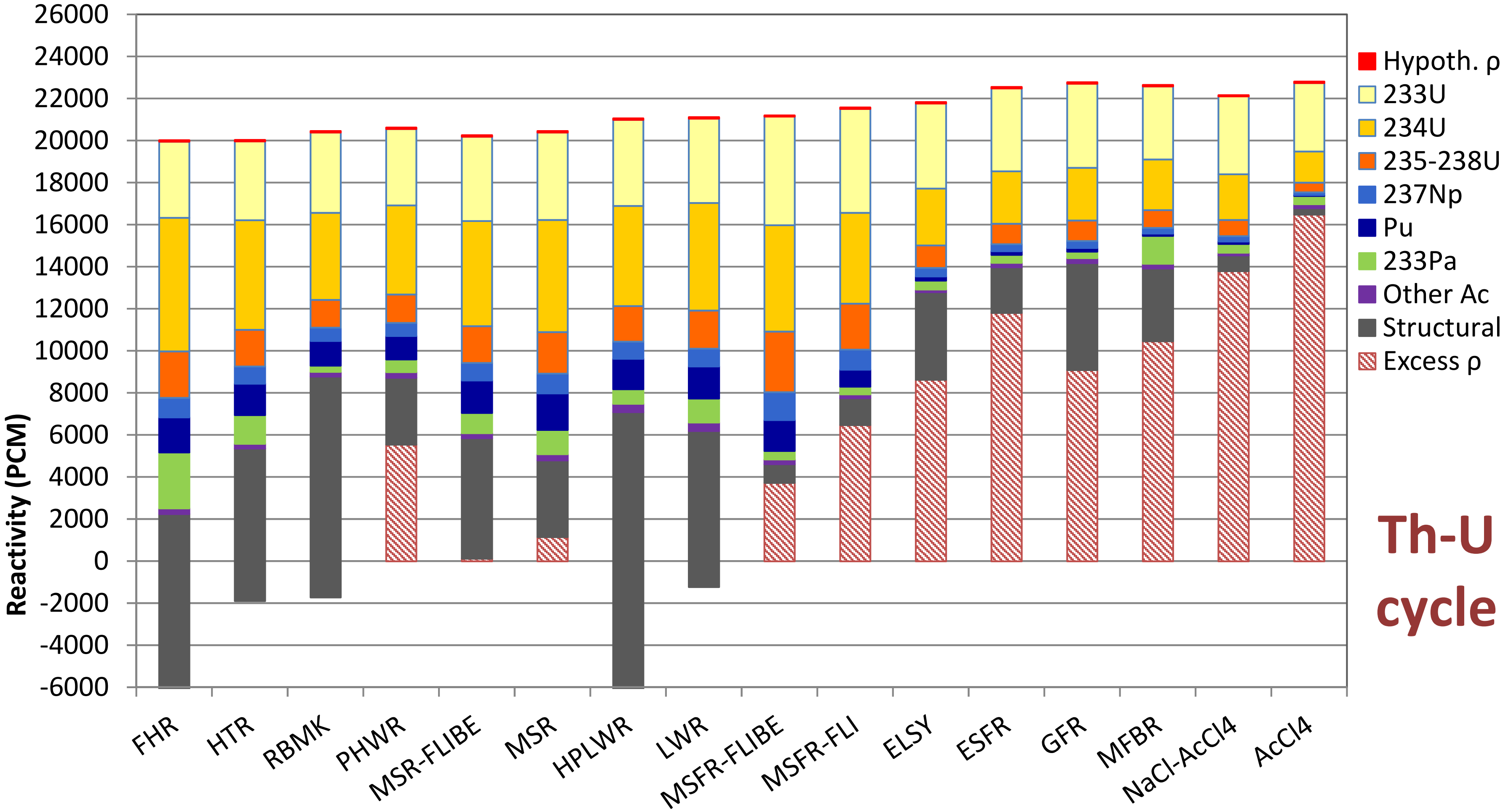
Excess reactivity in eql. cycle for **Th-U** cycle

WP1: Fuel cycle & Core design

- **Excess reactivity** for eql. fuel composition quantifies the **closed cycle capability**.
- Comparison of **16 reactors** is based on infinite lattice calculations with no FPs.
- **Th-U cycle**: **low ^{233}U** capture, **power effect** due to **^{233}Pa capture** (FHR, MFBR,…).

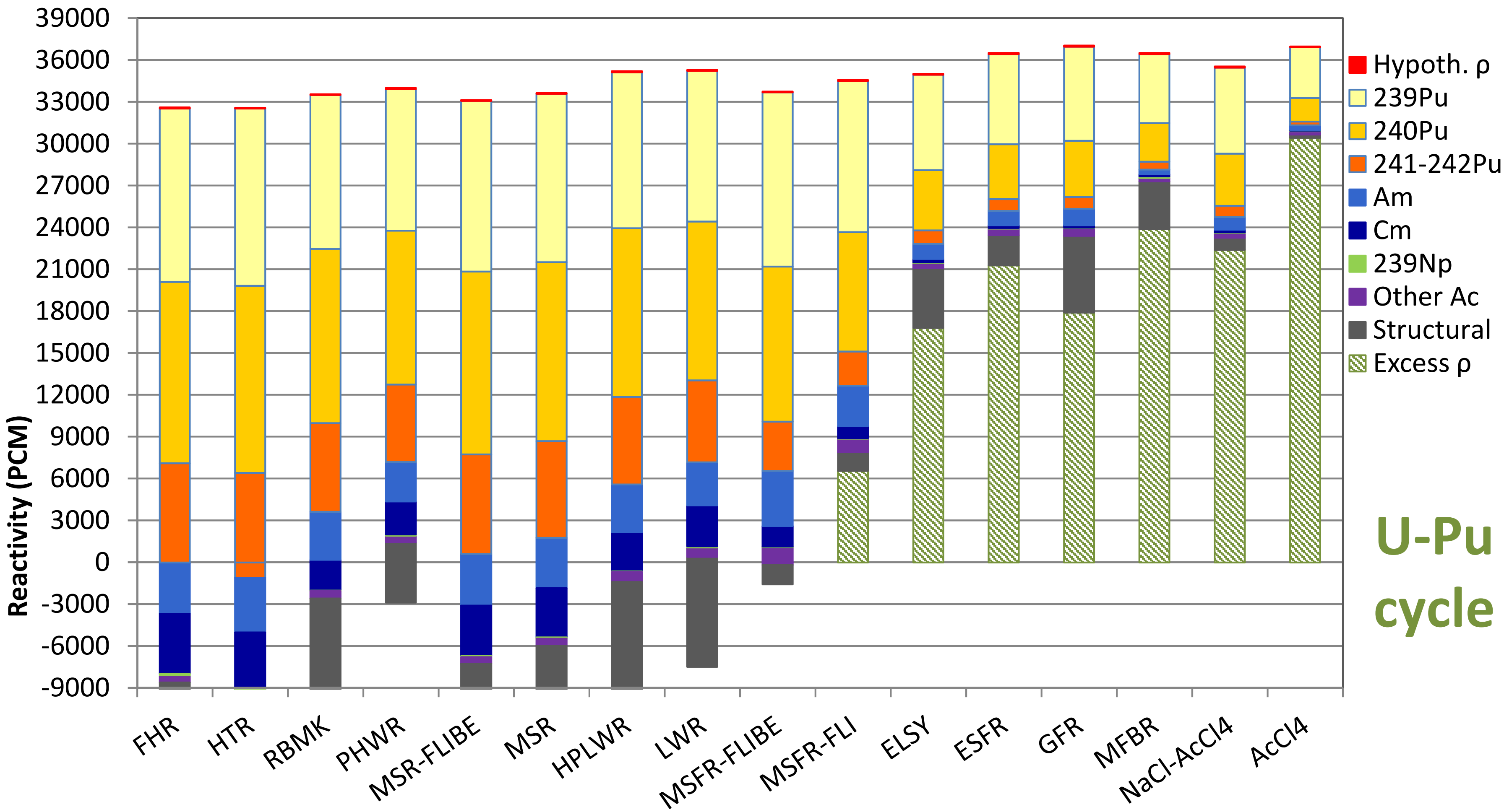


Krepel, J. at. al., Chapter for IAEA document, Near Term and Promising Long Term Options for Deployment of Thorium Energy, in preparation.

Excess reactivity in eql. cycle for **U-Pu** cycle

WP1: Fuel cycle & Core design

- Low ^{239}Pu fission probability: ^{239}Pu: 65-75% x ^{233}U: 90% => ~~thermal reactors~~.
- Excess reactivity is higher for fast reactors: ^{239}Pu: v=2.9 x ^{233}U: v=2.5
- U-Pu cycle has better neutron economy, Th-U cycle better neutron efficiency.



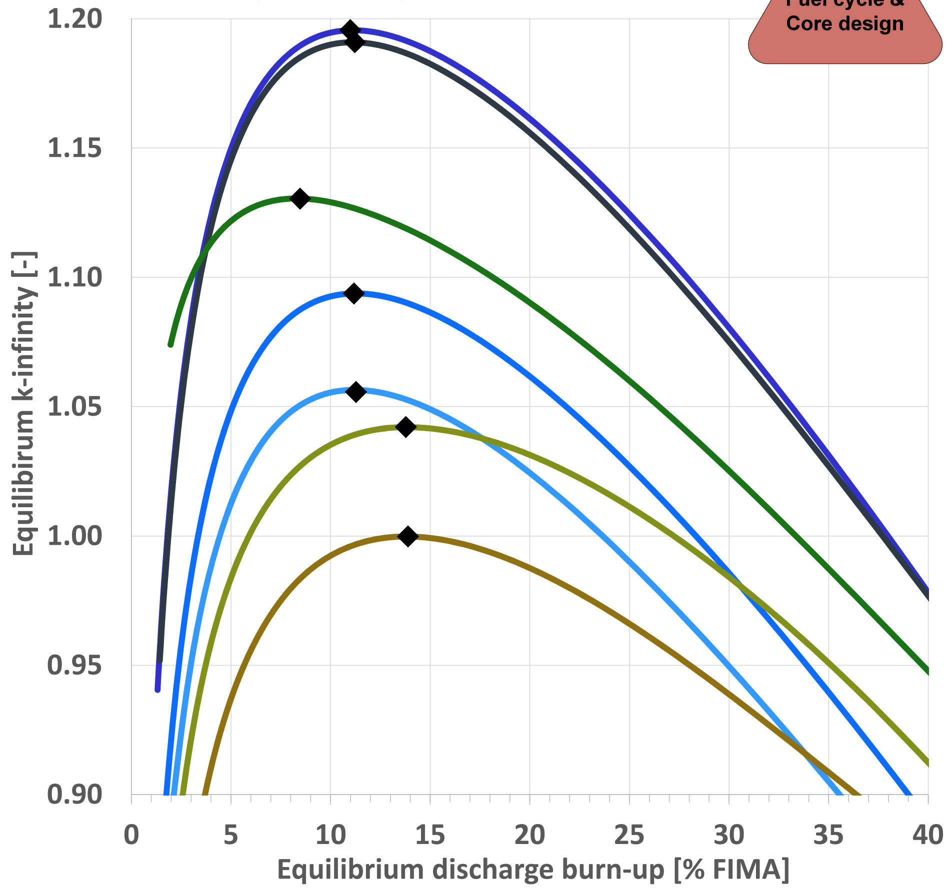
MSR in Breed-and-Burn (B&B) mode

WP1: Fuel cycle & Core design

Breed-and-Burn (BNB) mode is an open fuel cycle where reactor:

- is fueled by poorly fissile ^{232}Th or ^{238}U,
- breed its own fuel during irradiation,
- operates without fuel reprocessing,
- need an excellent neutron economy.

- **Main conclusions on cell level: =>**
  - **B&B** mode is possible only with **enriched ^{37}Cl** based chlorides MSR.
  - U-Pu is much better that Th-U cycle.
  - B&B in **Th-U** cycle may require **fissile support** (for instance LWR Pu).



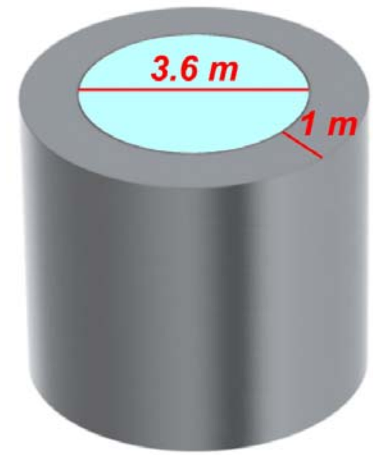
Fuel	Total and Actinides densities			Melt. T
68NaCl-32UCl$_3$	3.32	1.66	g/cm^3 at 900K	520°C
60NaCl-40UCl$_3$	3.64	1.97		590°C
80UCl$_4$-20UCl$_3$	3.79	2.38		545°C
UCl$_4$	3.56	2.20		590°C
55NaCl-45ThCl$_4$	3.15	1.61		375°C
ThCl$_4$	3.82	2.33		770°C
55NaCl-40ThCl$_4$-5PuCl$_3$	~3.15	~1.76		~375°C

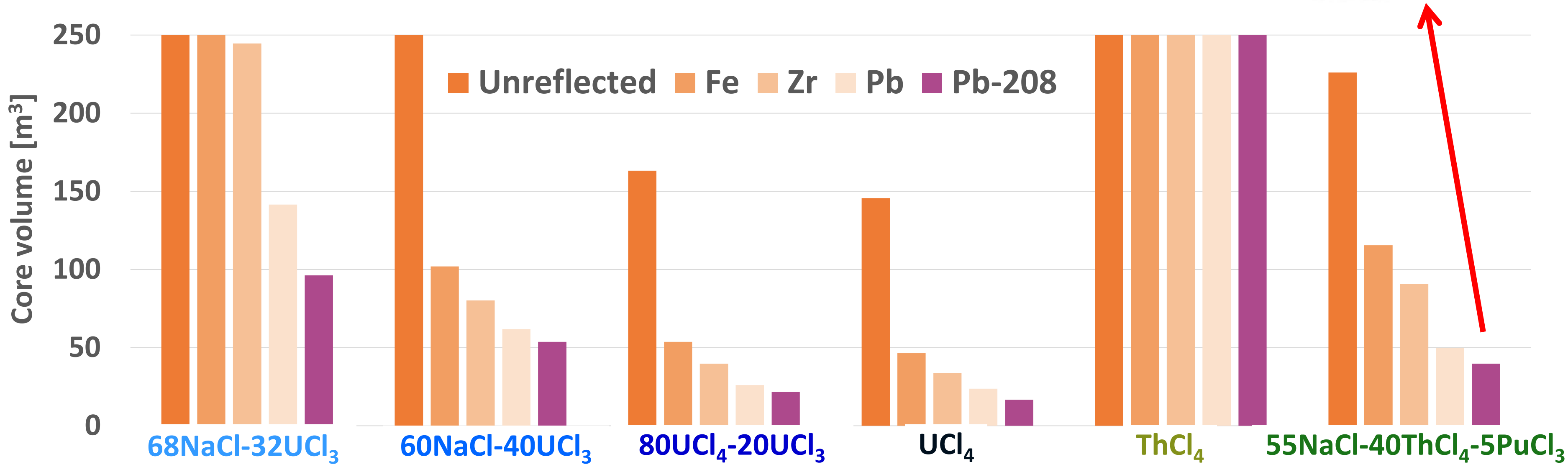
Hombourger, B. et. al., Fuel cycle analysis of a molten salt reactor for breed-and-burn mode, ICAPP 2015, Nice

B&B MSR: core level

WP1:
Fuel cycle &
Core design

- **Chlorides are transparent**
  leakage utilization =>l reflector, multi-zone,...
- Illustration for **^{208}Pb** reflected **B&B** core =>
- **Solubility limits a**t the deep burnup
  (part of the reprocessing strategy?).



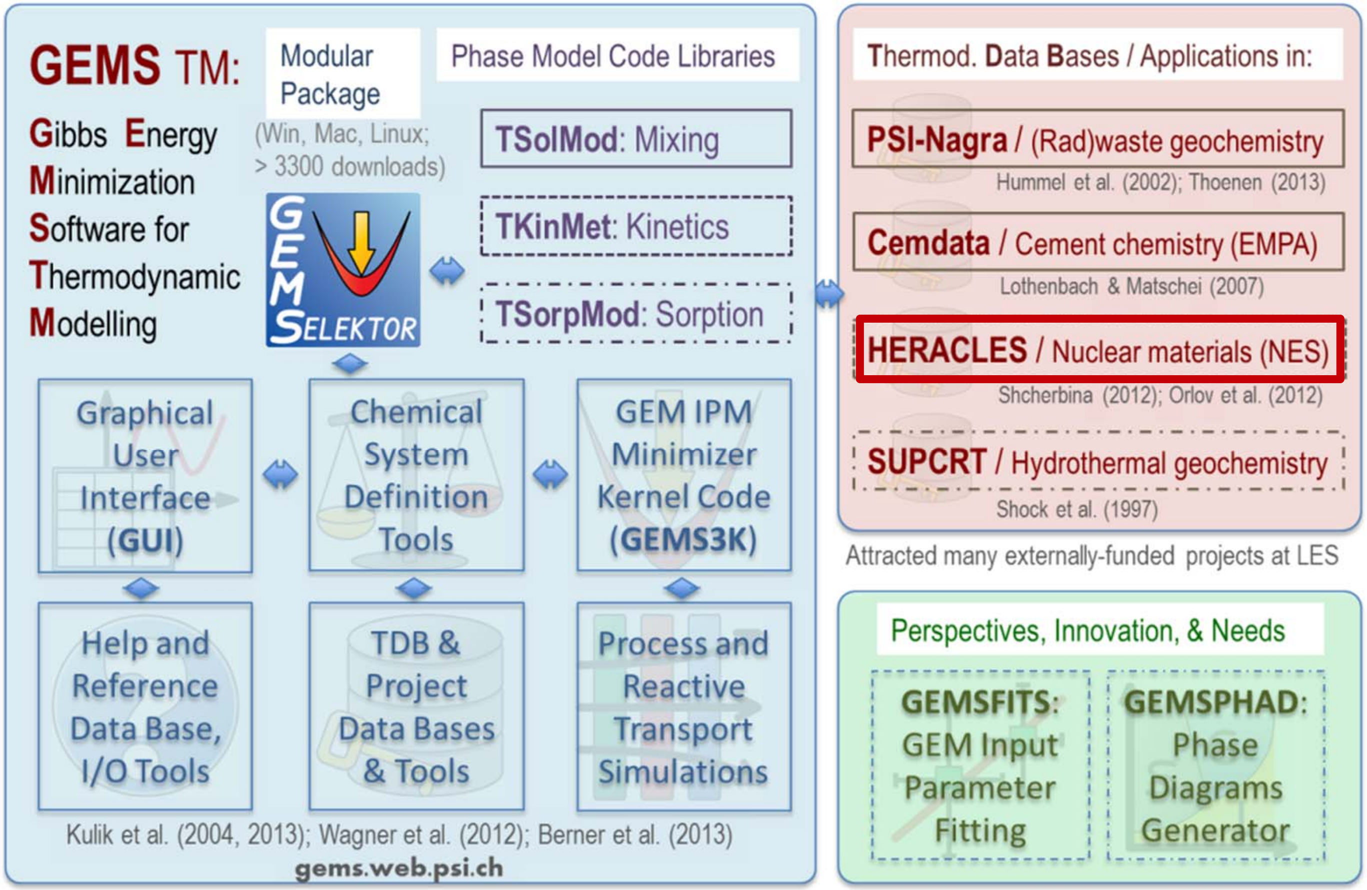


Critical core volume with various reflectors and salts at equilibrium.

Fuel behavior (chemistry)

WP2: Fuel behavior (chemistry)

- PSI has a competence in **thermodynamics and MD** simulations. In-house code **GEMS** (**G**ibbs **E**nergy **M**inimization **S**oftware) is **unique open source** alternative to the commercial FactSage code.
- The respective **HERACLES** database and selected models needs extension or modification.



homepage http://gems.web.psi.ch

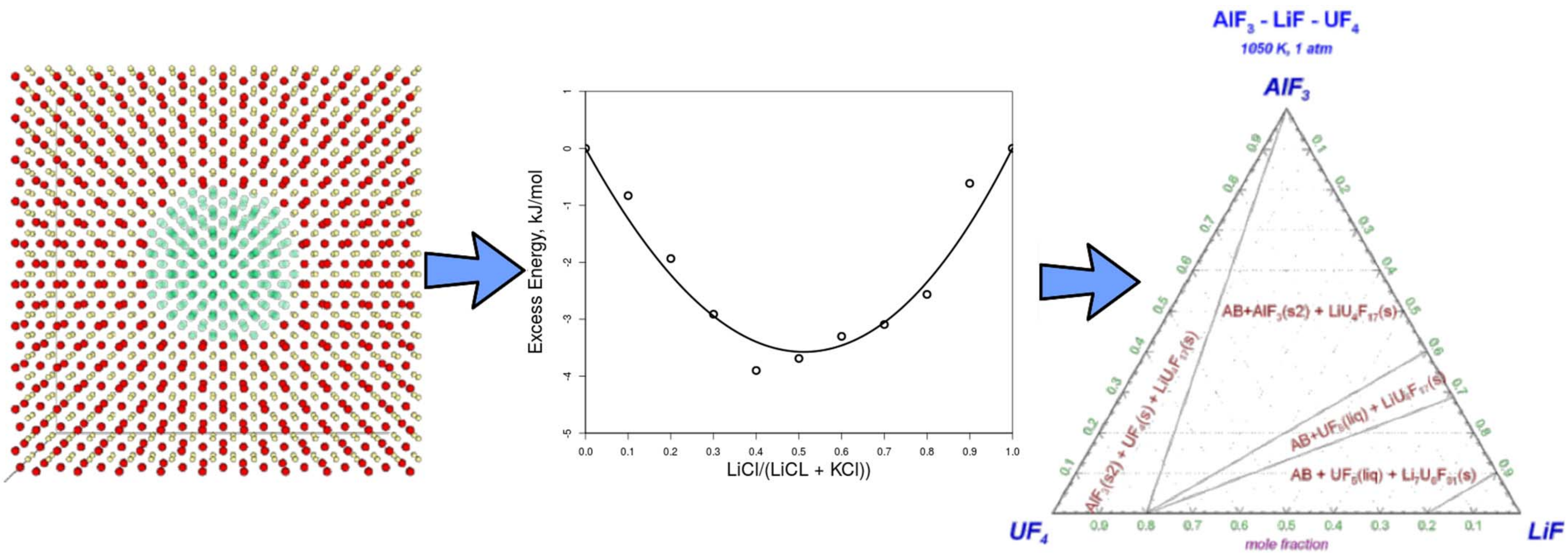
Kulik D.A., Dmytrieva S.V., Wagner T., Kosakowski G., Thoenen T, Berner U., et al. (2004-2014): Gibbs Energy Minimization Software (GEMS)

Molecular Dynamics

WP2: Fuel behavior (chemistry)

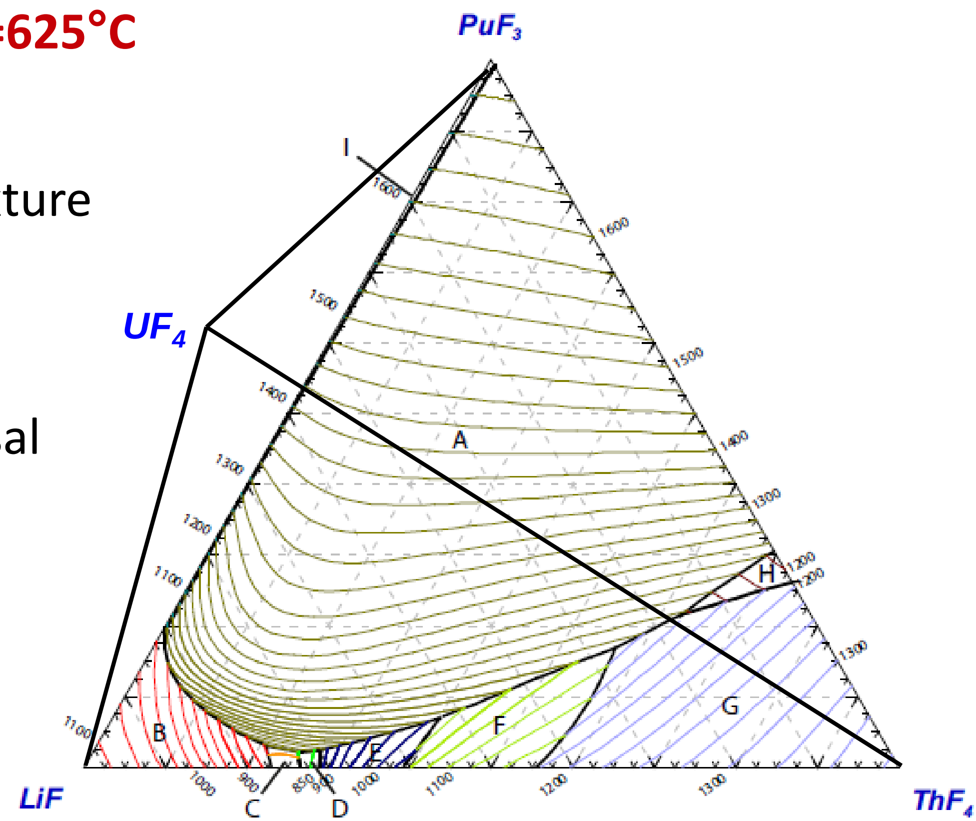
- Application of Molecular Dynamics for:
  - Thermal conductivity calculation
  - Melting behavior study
  - Specific heat behavior
  - Binary excess properties

- **Goal:**
  Combine MD / DFT with Thermodynamic methods to simulate the systems of interest – speciation.



WP2: Fuel behavior (chemistry)

- 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 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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Transient analysis & DHR system

WP3: Transient analysis & DHR

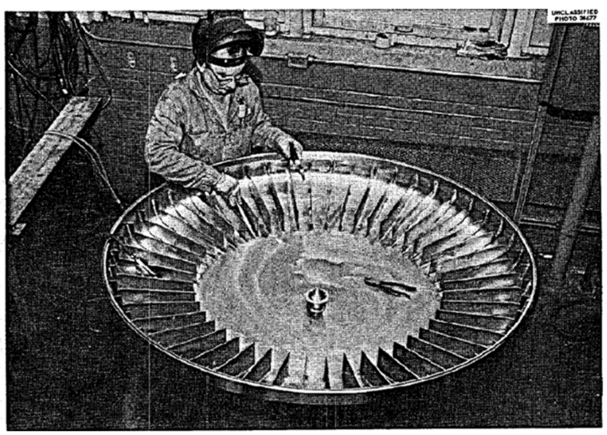
- **Aim:**
  - transient core behavior and system behavior.
- **TRACE-PARCS** system code:
  - System analysis tool for primary, intermediate, and secondary circuits.
  - Salt properties for MSRE, delayed neutron precursors drift model, …
- **GeN-Foam** 2D or 3D transient analysis of core and prim. Loop:
  - Neutronics (Multi-group time-dependent diff.).
  - Coarse (porous media)/fine (CFD) mesh thermal-hydraulics.
  - Subscale fuel temperature field (coarse mesh).
  - Thermal mechanics (Mesh deformation).
  - Three independent unstructured meshes, adaptive time step.

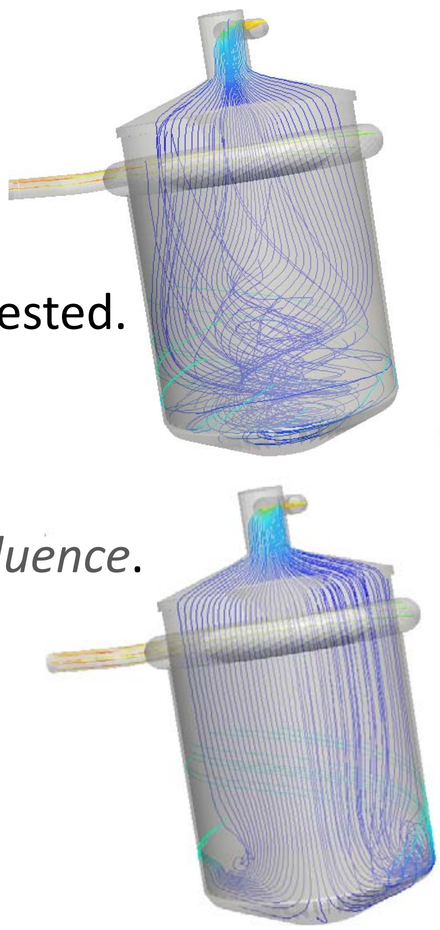
Multi-physics code at PSI – GeN-Foam

WP3: Transient analysis & DHR

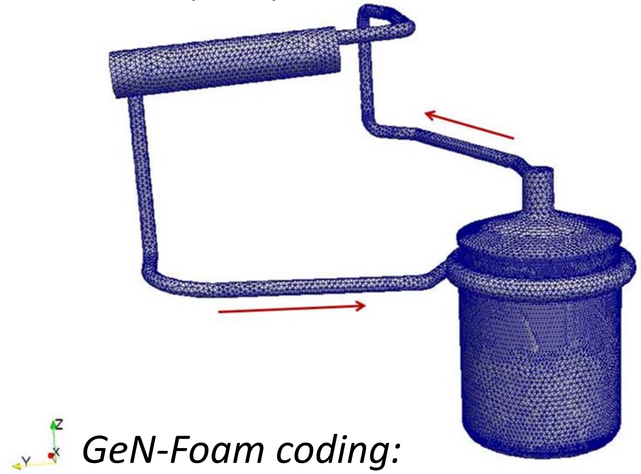
- **GeN-Foam** was applied to **MSRE**.
- It was part of the initial verification of the code.
- Coarse MSRE model and mesh was developed.
- Porous media approach was tested.
- Delayed neutrons precursors drift was modeled.

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
```

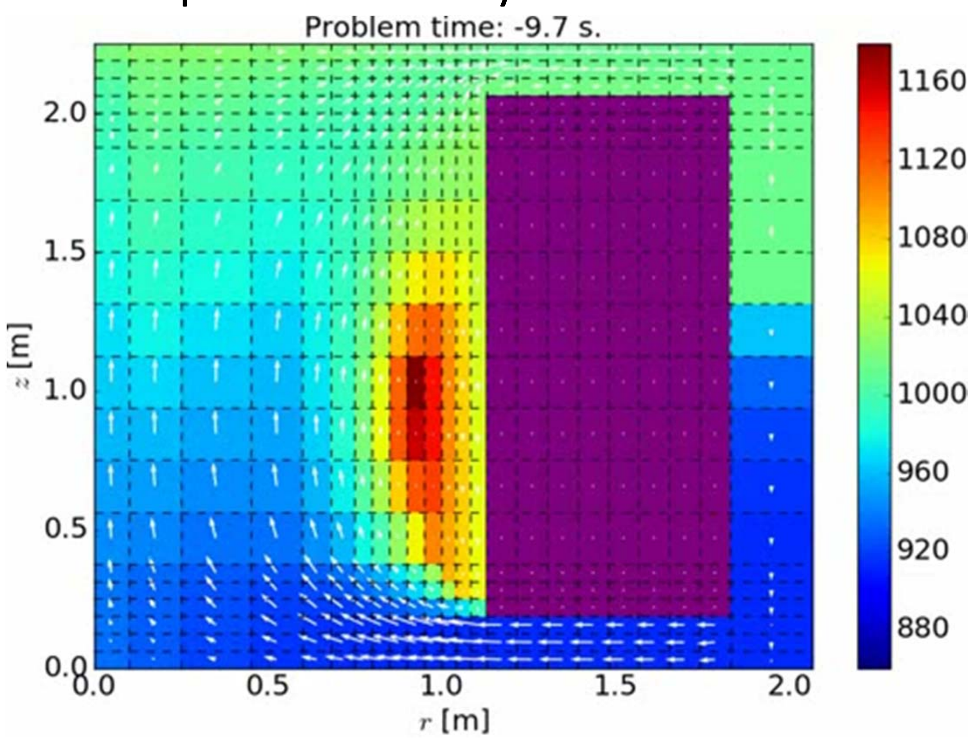
Fiorina C. at al., 2015. GeN-Foam: a novel OpenFOAM® based multi-physics solver for 2D/3D transient analysis of nuclear reactors. Nuclear Engineering and Design, Volume 294, 1 December 2015, Pages 24–37.

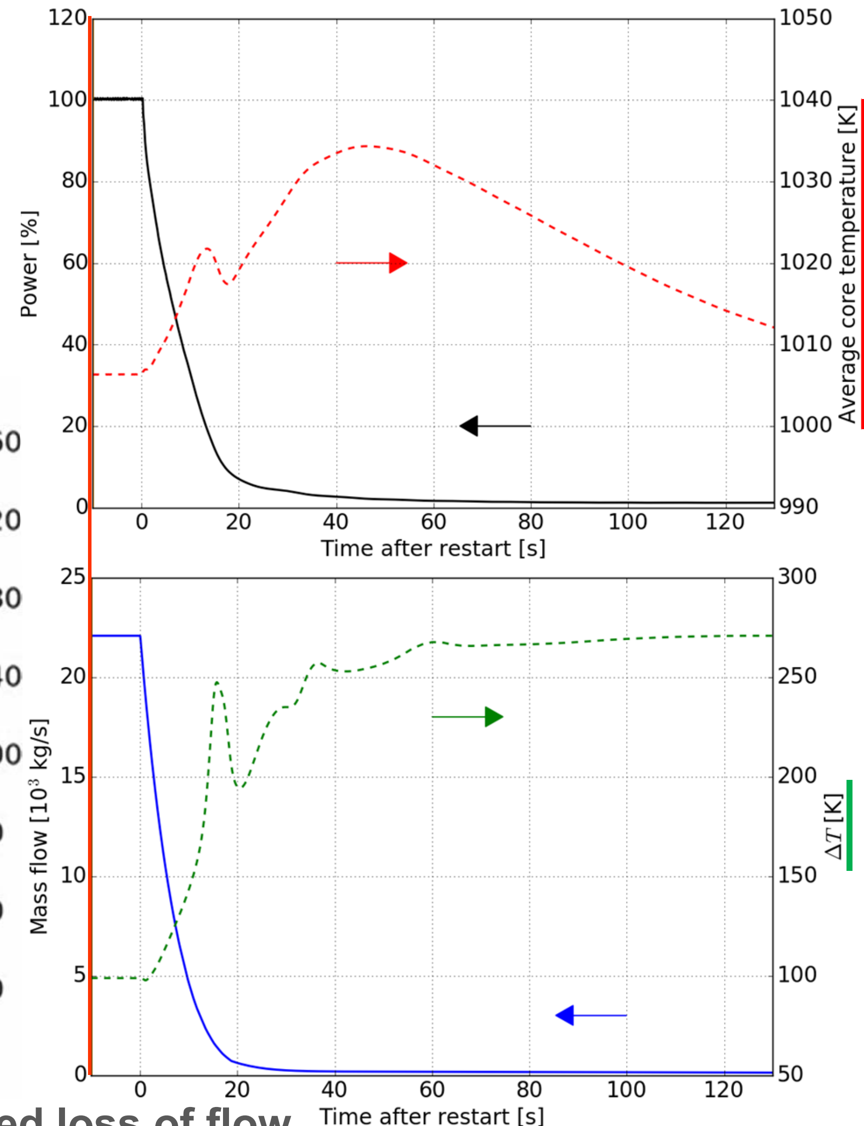
WP3: TRACE application to MSFR

WP3: Transient analysis & DHR

- **TRACE-PARCS** system code application to **MSFR**.
- Applying TRACE vessel component.
- Applicable for 3D transients. (2D symmetric transients)
- Capability of system analysis with acceptable accuracy and CPU time.

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





ULOF- unprotected loss of flow

MSR safety & limits

WP4: Safety & Limits

- Long term main aim of the NES project.
- Ongoing research:
  - Aerosols formation and migration in the containment (SAMOFAR project).
    Determine the behavior of aerosol from the molten salt and investigate the transport of FPs in an MSR in accident conditions
  - Simplified PSA level 3 (SAMOFAR project).
    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.
  - MSc thesis on PSA level 1 for FUJI MSR design.
    Enumeration of frequency for main events with vessel damage

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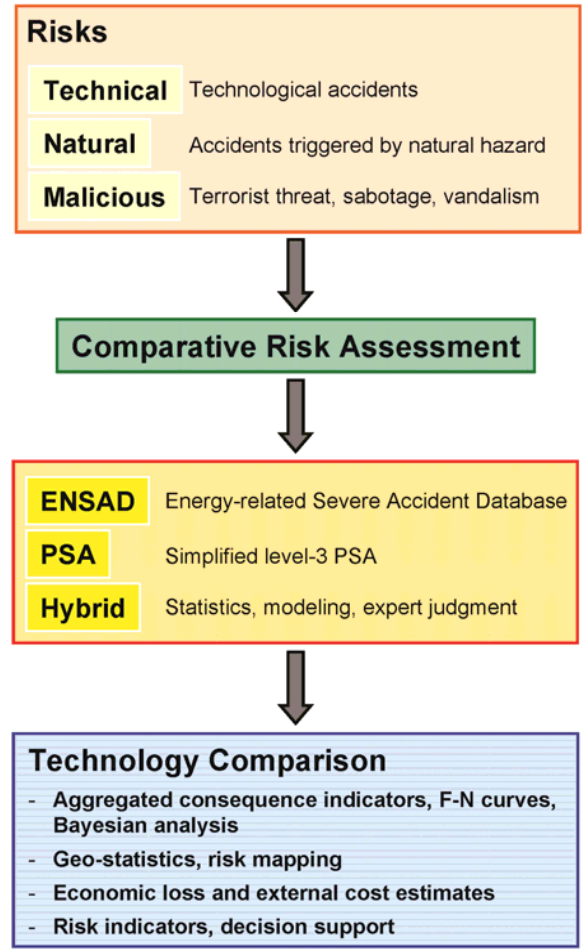
WP4: Simplified PSA level 3

WP4: Safety & Limits

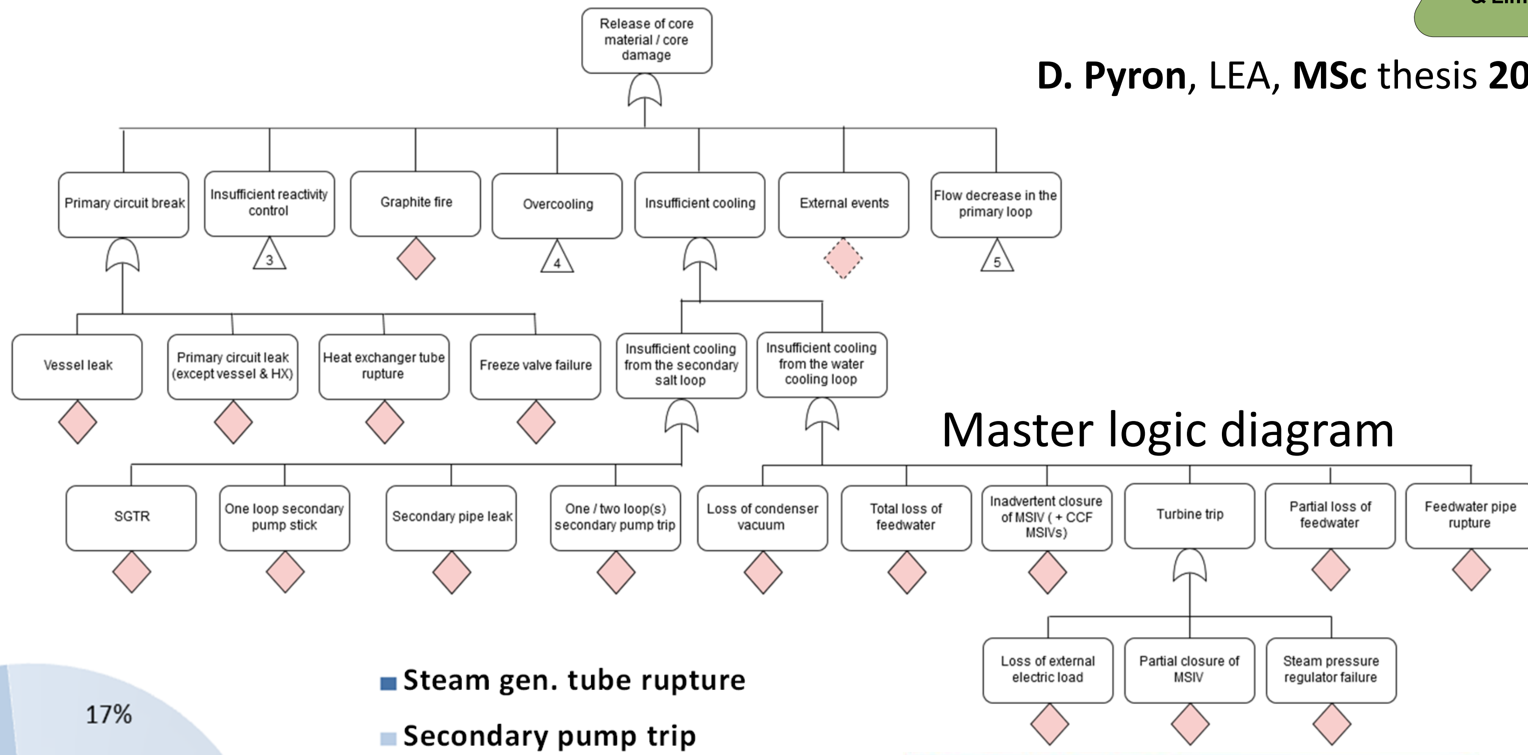
- **Simplified method** for accident consequences and risk assessment.
- Risk is based on **MACCS2** calculations for reference site plant data (**Swiss power plants**) using conversion factors.
- The information needed for the analyzed plant:
  - For consequences: source terms, power level, site
  - 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



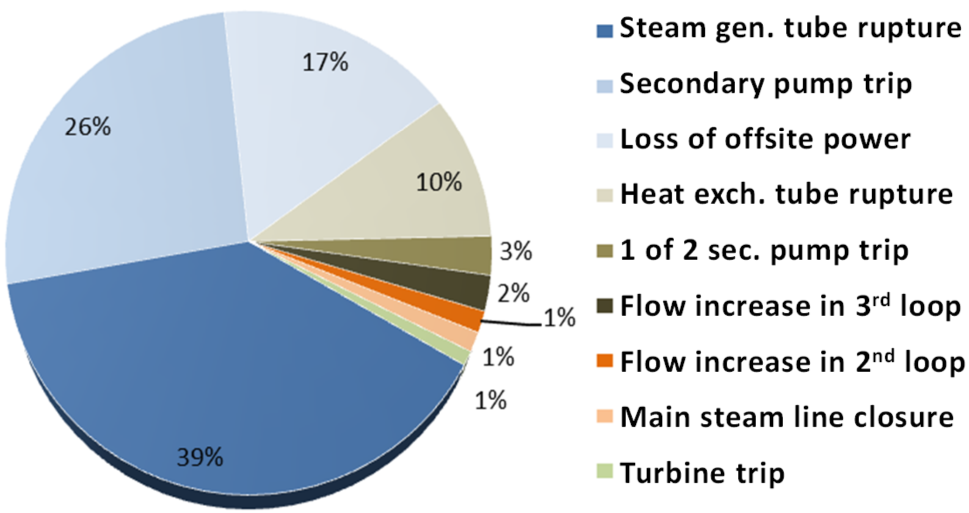
Accident scenarios & PSA 1 modeling

WP4: Safety & Limits

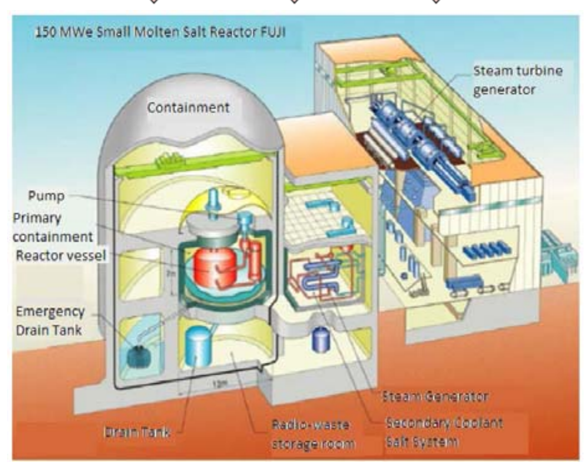
D. Pyron, LEA, **MSc** thesis **2016**



Master logic diagram



Main events with vessel damage



Mini FUJI MSR

MSR is a very promising energy source.

It can combine unparalleled safety features with high fuel utilization.

It can also provide us enough time for mastering of the nuclear fusion! ☺