PAUL SCHERRER INSTITUT

PSI

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

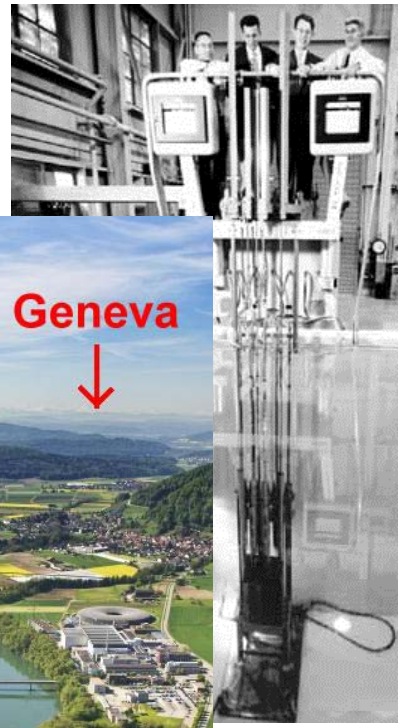
Molten Salt Reactor R&D at Paul Scherrer Institut in Switzerland

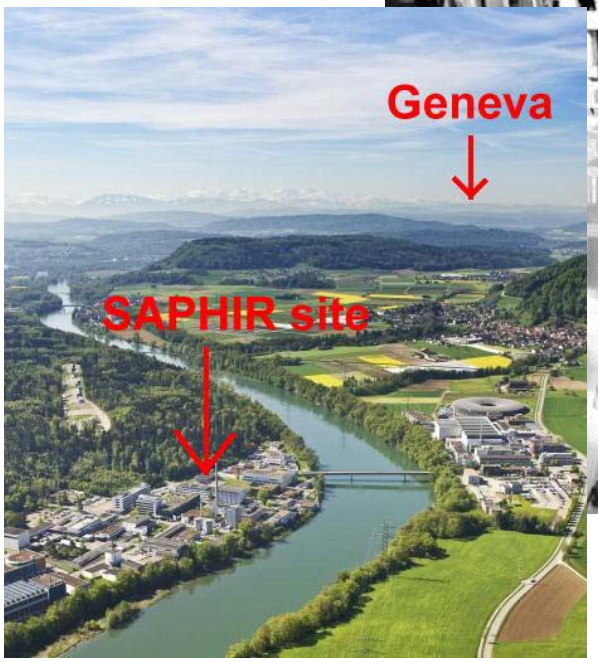
Molten Salt Reactor Workshop, ORNL, 4-5.10.2016

jiri.krepel@psi.ch

Paul Scherrer Institut – short introduction

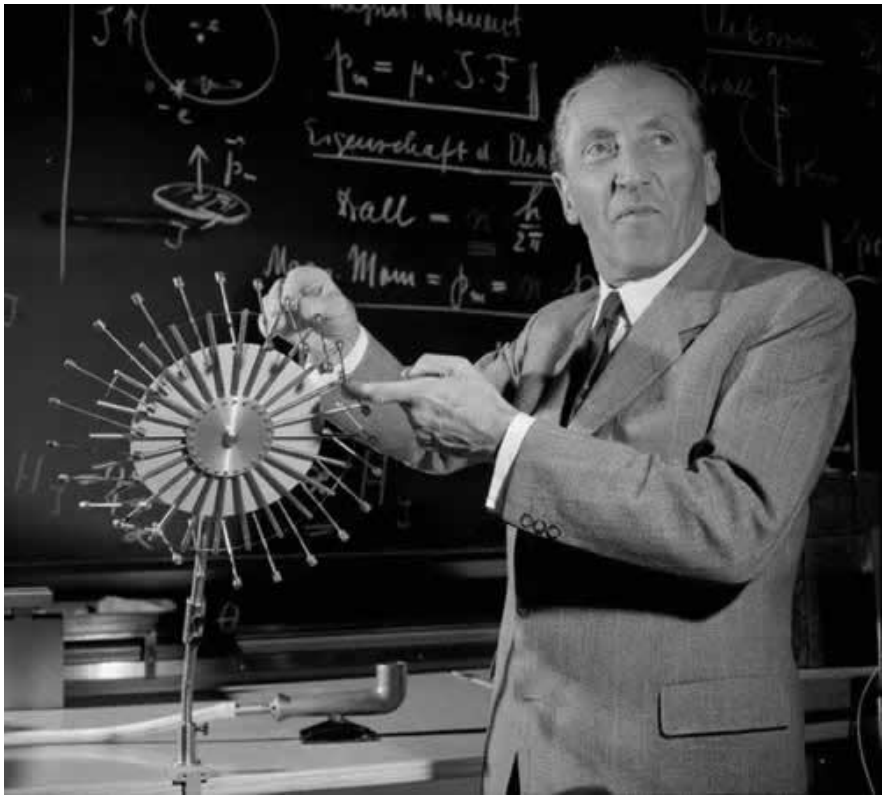
- **In 1955** after the **Geneva** conference on **Peaceful Uses of Atomic Energy**, thanks to Paul Scherrer, Switzerland could buy the conference reactor - **SAPHIR** from the **US**. *The "Geneva reactor" was made at ORNL.*





- The selected site was in northern Switzerland at the left bank of river **Aare** not far from Zurich and Baden (ABB home).
- **In 1960** the Federal Institute for Reactor Research (**EIR**) was established, converting an industry institute founded in **1955** with the help of **Paul Scherrer** into a government organization.
- In 1968 Swiss Institute for Nuclear Physics was established at the opposite river bank.
- **In 1988** the two institutes were merged into the **Paul Scherrer Institute - PSI**.

Paul Scherrer (1890–1969)



- Studied physics and mathematics at the Swiss Federal Institute of Technology (ETH) Zurich, in Koenigsberg and in Goettingen, Germany
- 1920: professor of experimental physics at ETH Zurich; 1927: Director of the Institute of Physics. Was famous for the clarity of his lectures
- Researched x-ray scattering on crystals, liquids and gases. Later research work was in nuclear physics
- 1946: President of the Swiss Study Commission on Atomic Energy
- Involved in the foundation of CERN

Switzerland – short introduction

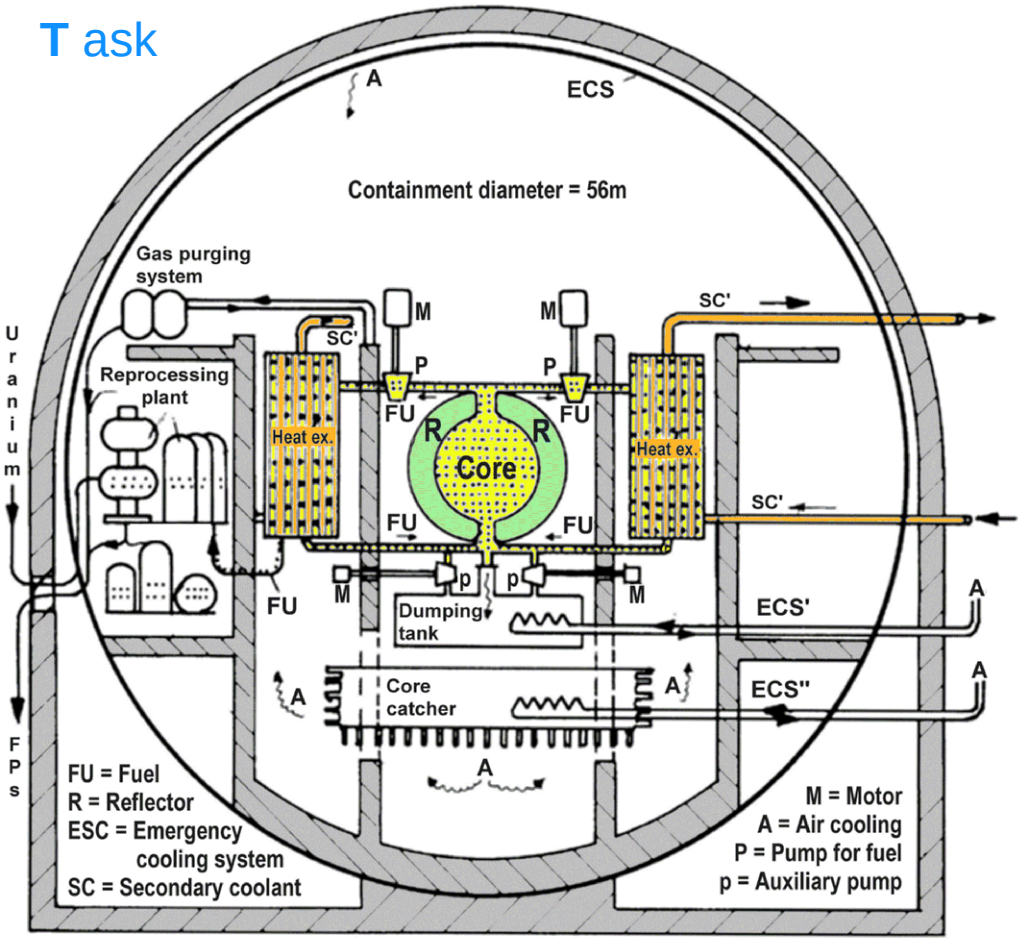
- Central-European state, **population 125%** and **area 38%** of **Tennessee;**
  5 reactors at 4 sites, installed nuclear power 55% of Tennessee.
- **Beznau 1** is the world wide **oldest nuclear power plant** in operation (*1969).
  Swiss nuclear law requires **continuous upgrades**.
- **New law denying** construction of **new nuclear** power plants was accepted last Friday by the parliament.
- **Since 2002** Switzerland is **member of Generation IV International Forum (GIF).** Implementing agent: **PSI**.
  In **2015** Switzerland joined the **GIF MSR project**.

- 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 the **potential to be cheaper** that current technology.
- **MSR** technology bears many innovative and **multidisciplinary features** that provide a **framework** for **PhDs** and **PostDocs** projects and for funding from alternative financial sources, e.g. Swiss national science foundation.

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:**

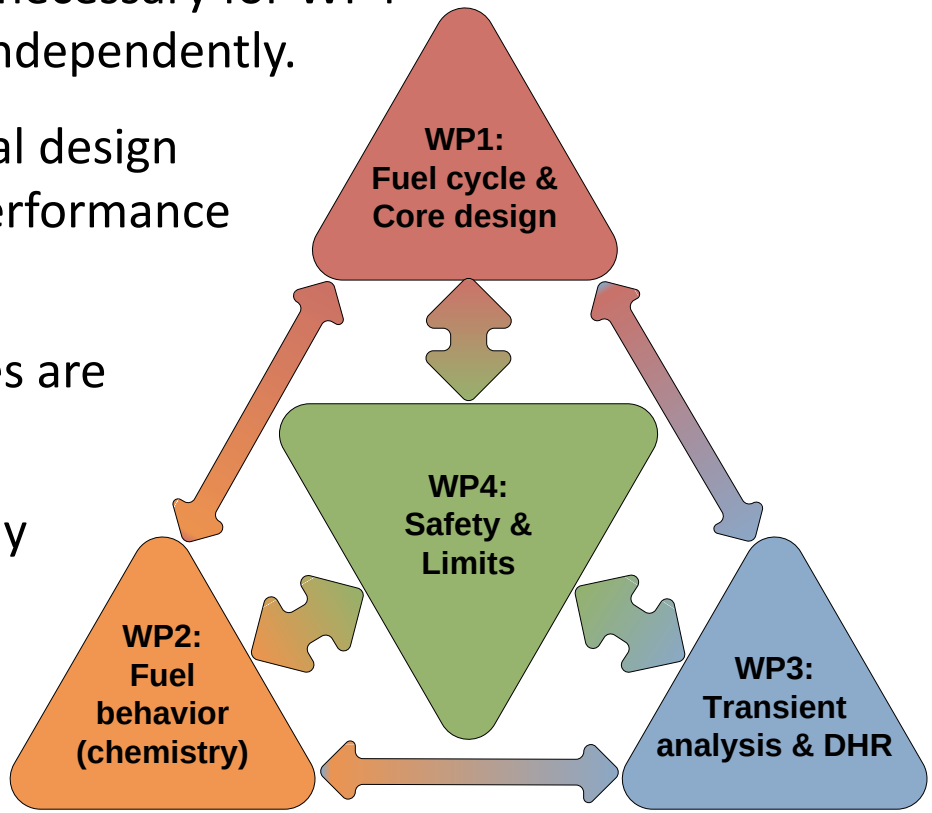
1) **SAMOFAR** - Safety Assessment of the MOlten salt FAst Reactor.

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.

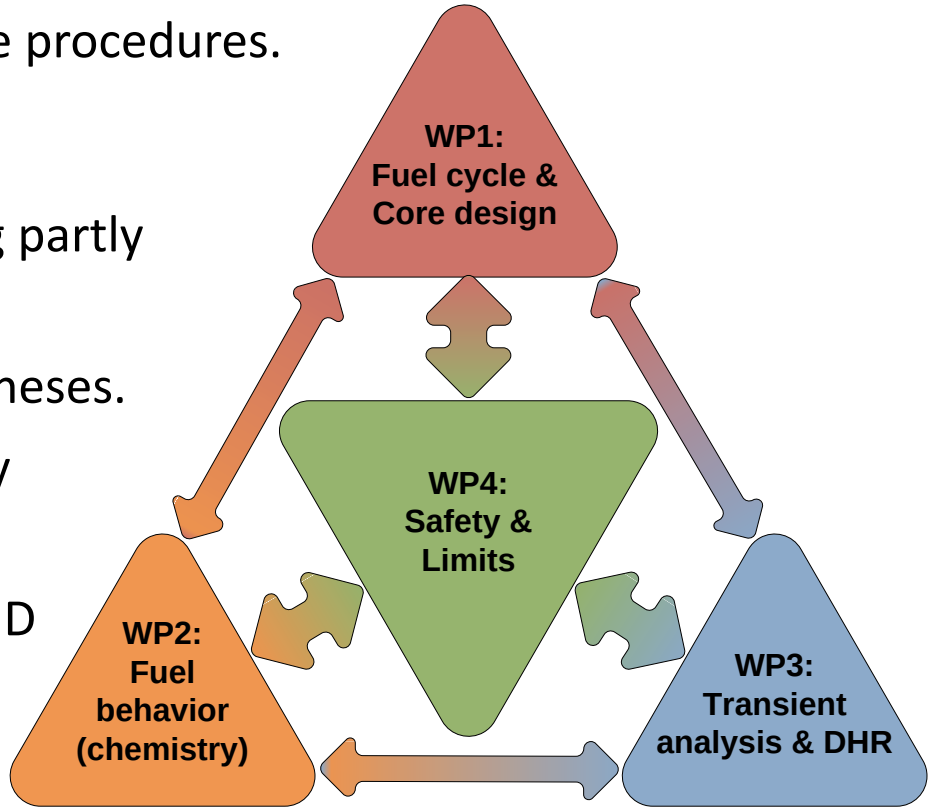
NES Division Project as an umbrella

- 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.

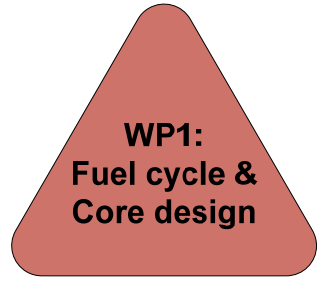


NES Division Project as an umbrella

- **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).



MSR fuel cycle & core design



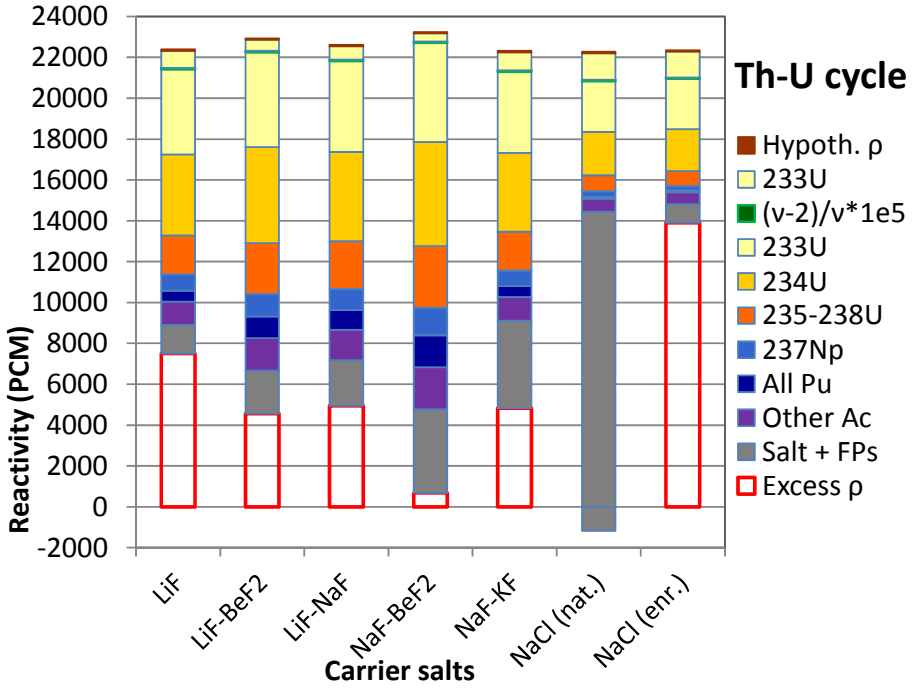
- Evaluation of several design options (performance and safety)
- Applied tools are EQL0D and EQL3D procedures developed at PSI:
  - **EQL3D - ERANOS** based procedure for core level simulation.
    Křepel, J. et al., Fuel Cycle Advantages and Dynamics Features of Liquid Fueled MSR. Annals of Nuclear 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..*

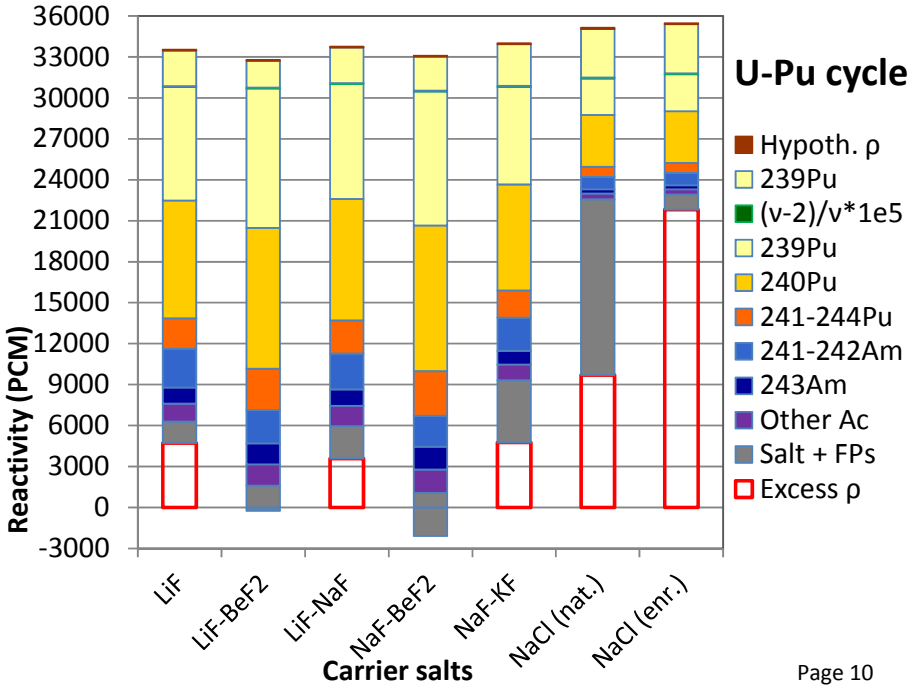
EQL0D v3: 7 MSR salts comparison

WP1: Fuel cycle & Core design

- **7 selected salts** were compared (**infinite medium** of fast reactor).
- **U-Pu** and **Th-U** equilibrium closed cycles were evaluated (by excess reactivity).
- It confirmed that for **U-Pu** cycle **chlorides** are preferable.
- The **reactivity excess in chlorides** may enable **breed and burn** mode.
- **Th-U** cycle has two favorites **LiF** and **NaCl** carrier salts.

^{233}U: *ν*=2.5, fission probability 90% X **^{239}Pu**: *ν*=2.9, fission probability 65-75%



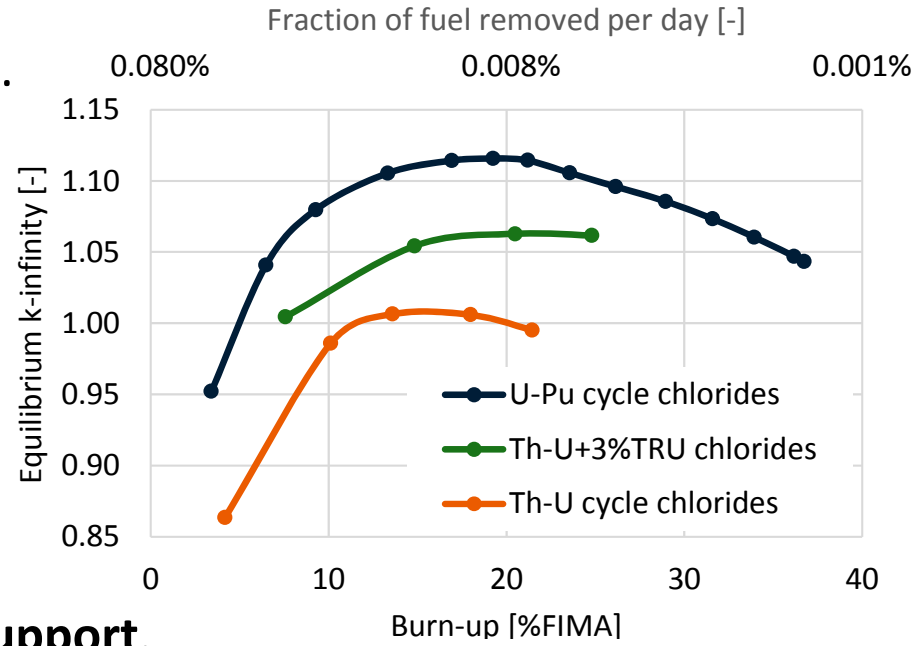


MSR in Breed-and-Burn (B&B) mode

WP1: Fuel cycle & Core design

- **B&B mode** requires supreme neutron economy.
  Breeding should compensate discharged fuel loss.
- Assumptions for B&B simulation:
  - No reprocessing: discharged fuel is lost.
  - Predominantly fertile fuel make-up.

Results on a cell level =>



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

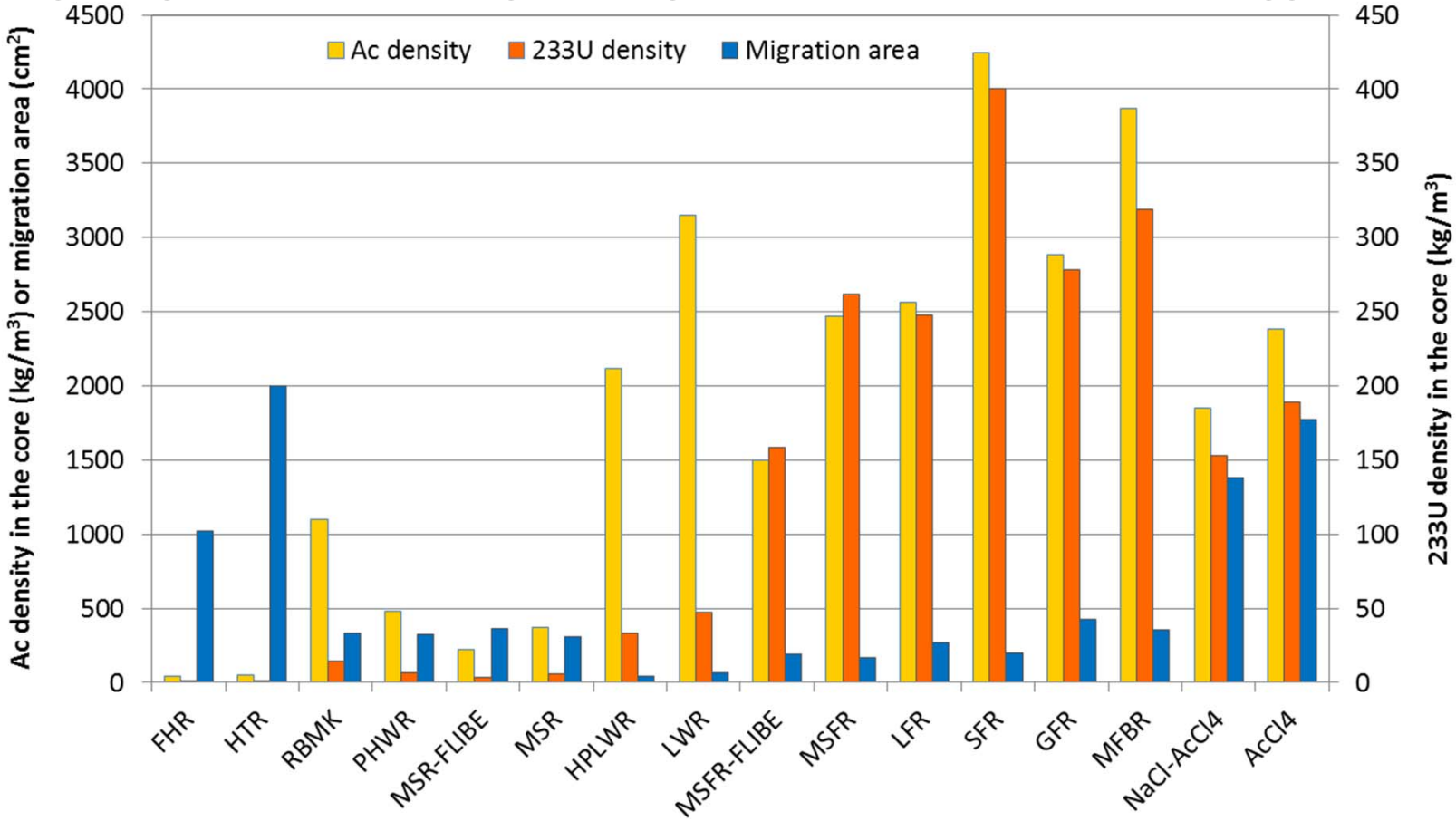
- **Features: Chlorides are transparent** => leakage utilization (reflector, multi-zone).
  At the deep burnup, the solubility limit may be reached for FPs.
  No issue in MSRs with max. cladding fluence as in solid fuel B&B.

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

Th-U cycle: density and migration area

WP1: Fuel cycle & Core design

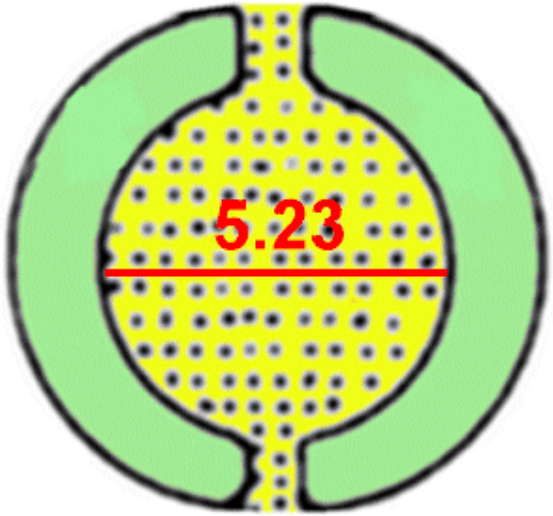
- **Chlorides disadvantage: transparency**
  - Both chlorides and fluorides salts have low specific Ac density.
  - Furthermore chlorides area transparent for neutrons.
  - High migration area => high leakage => blanket or reflector or bigger reactor.

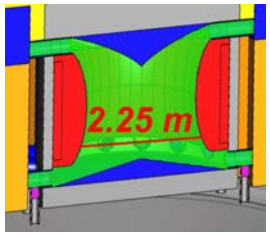


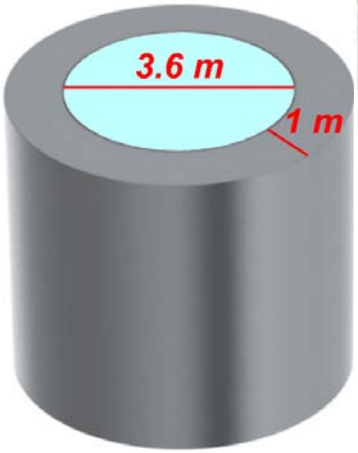
Krepel, J. at. al., Chapter for IAEA document, Near Term and Promising Long Term Options for Deployment of Thorium Energy, in preparation.

WP1: MSR Breed-and-Burn: core level

B&B – PSI test design







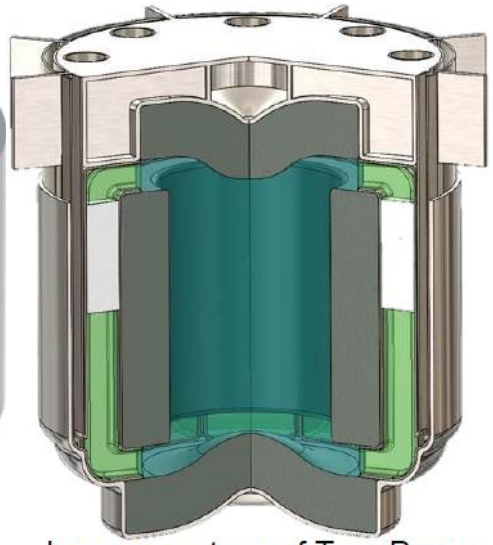


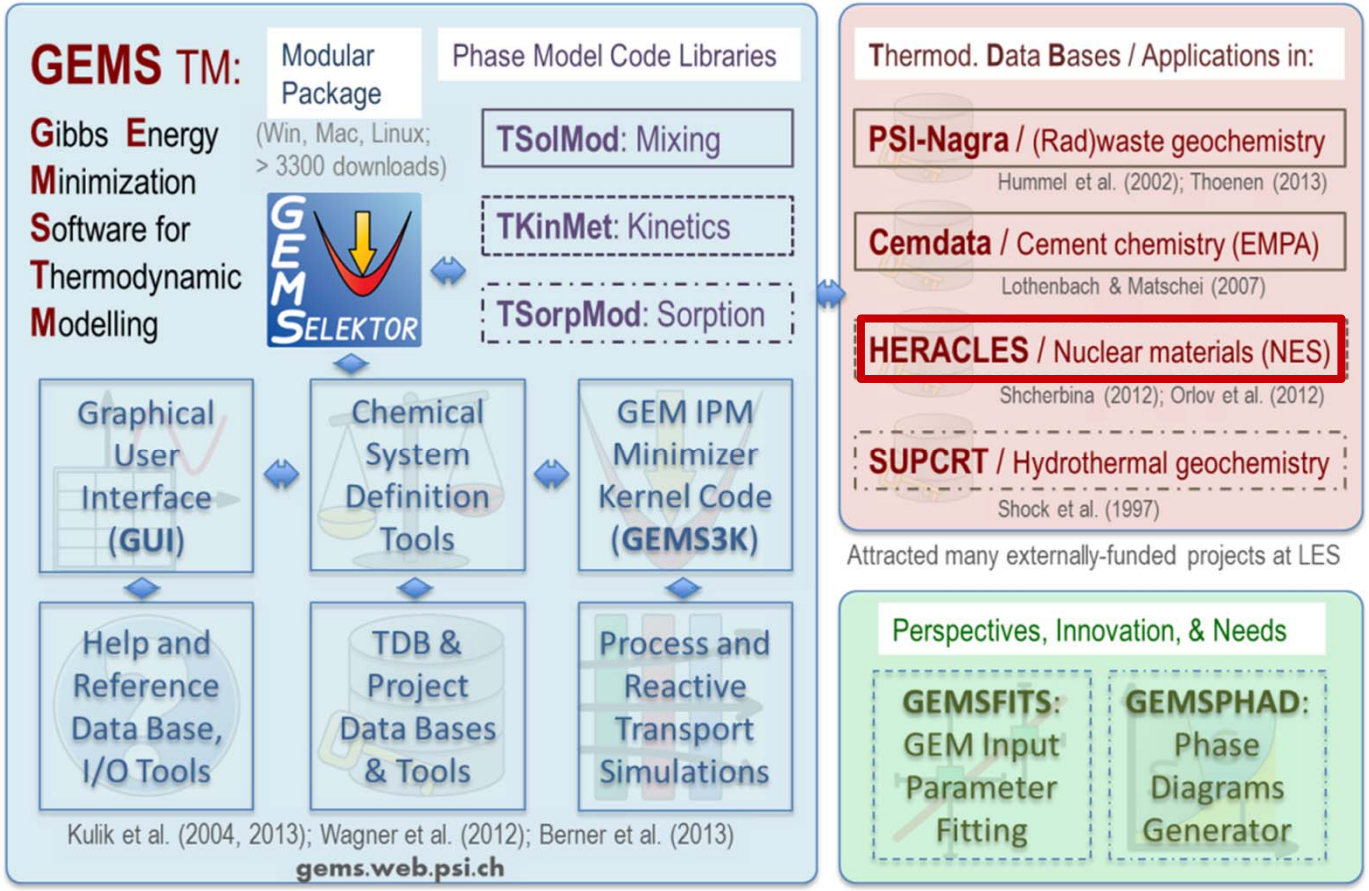
Image courtesy of TerraPower

Concept	SOFT-1980	MSFR	B&B - PSI	MCFR
B&B / salt	No / nat. chlorides	No / fluorides	Yes / enr. chlorides	Yes/ enr. chlorides
Core dimensions	5.23 m	2.25 m x 2.25 m	3.6 m x 3.6 m	?
Core volume	75 m^3	9 m^3	36 m^3	?
Blanket / cycle	None / U-Pu	7.3 m^3 / Th-U	None/ U-Pu, Th-U+Pu	None/ U-Pu
Reflector	$CaCl_2$-NaCl & steel	Axial only - Hastelloy	**Yes - Enriched lead**	**Yes - ?**
Processing	Volatile & Soluble FP	Volatile & Soluble FP	Volatile FP only	Volatile FP + ?
Processing flow	0.25 L/s	3-8 L/day	2 L/day	?
Cycle time	?/continuous electrolysis	6-16 years	52 years	?

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

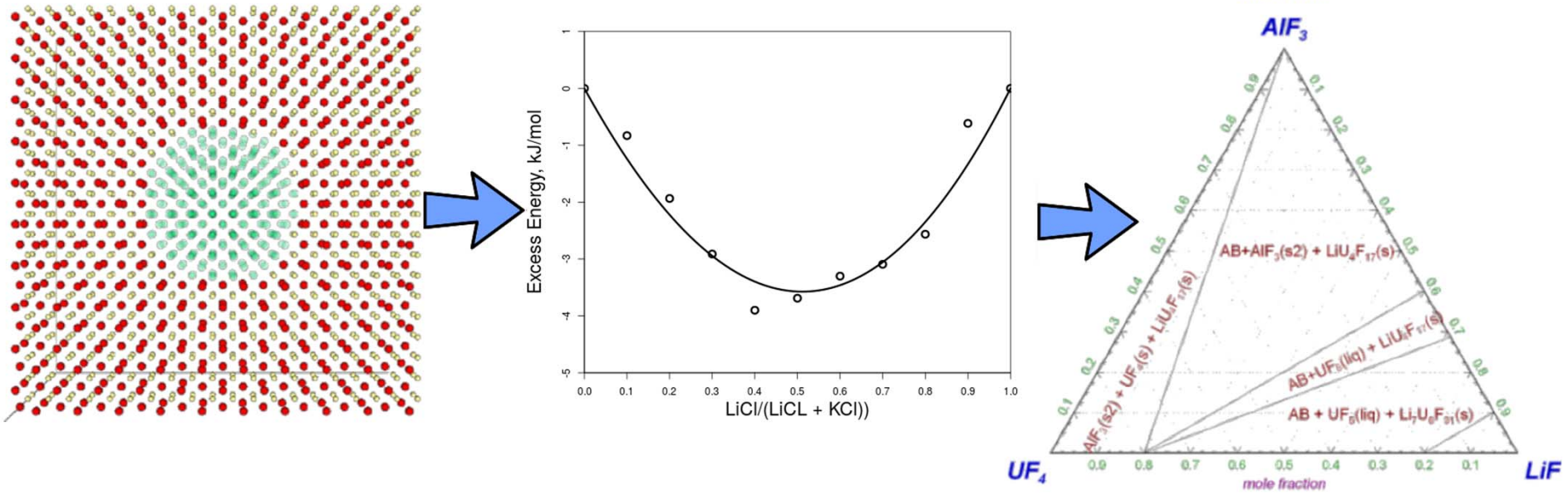
Kulik D.A., Dmytrieva S.V., Wagner T., Kosakowski G., Thoenen T, Berner U., et al. (2004-2014): Gibbs Energy Minimization Software (GEMS)

Molecular Dynamics

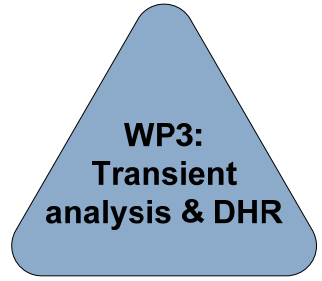
WP2: Fuel behavior (chemistry)

- 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.



Transient analysis & DHR system



- **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.

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

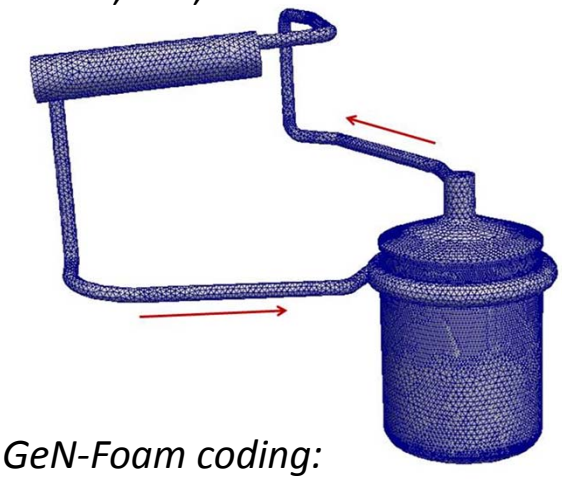
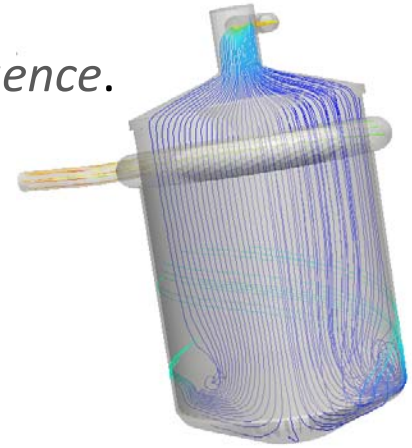


Illustration of anti-swirl vanes influence.

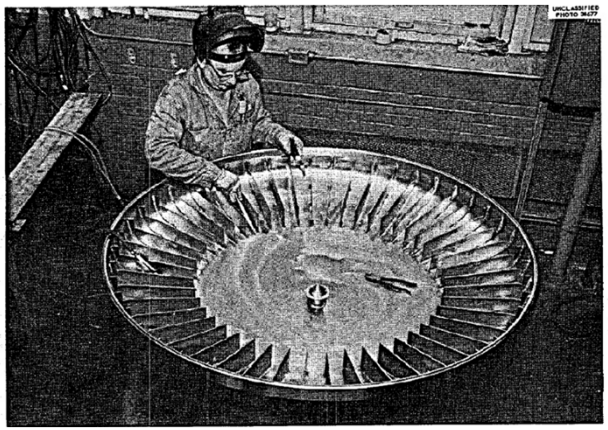


GeN-Foam coding:

```
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
```



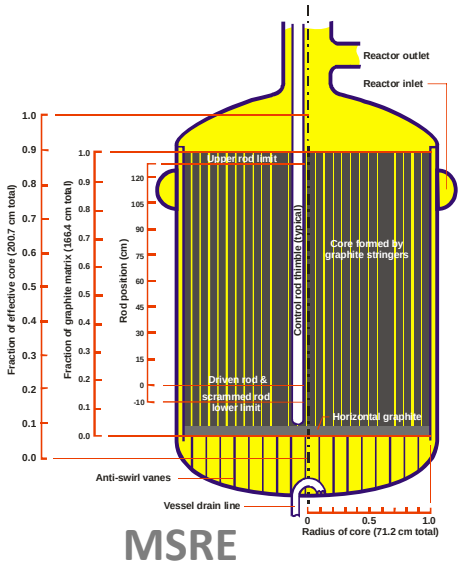
Fiorina C. at al., 2015. GeN-Foam: a novel OpenFOAM® based multi-physics solver for 2D/3D transient analysis of nuclear reactors. Nuclear Engineering and Design, Volume 294, 1 December 2015, Pages 24–37.

WP3: TRACE application to MSRE

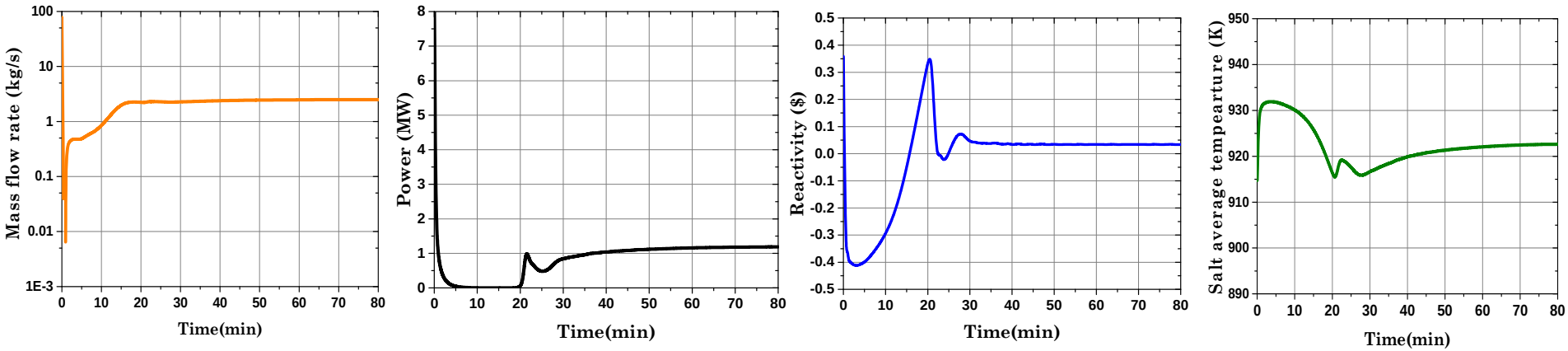
WP3: Transient analysis & DHR

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

- **TRACE-PARCS** system code application to **MSRE**.
- 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.



MSRE



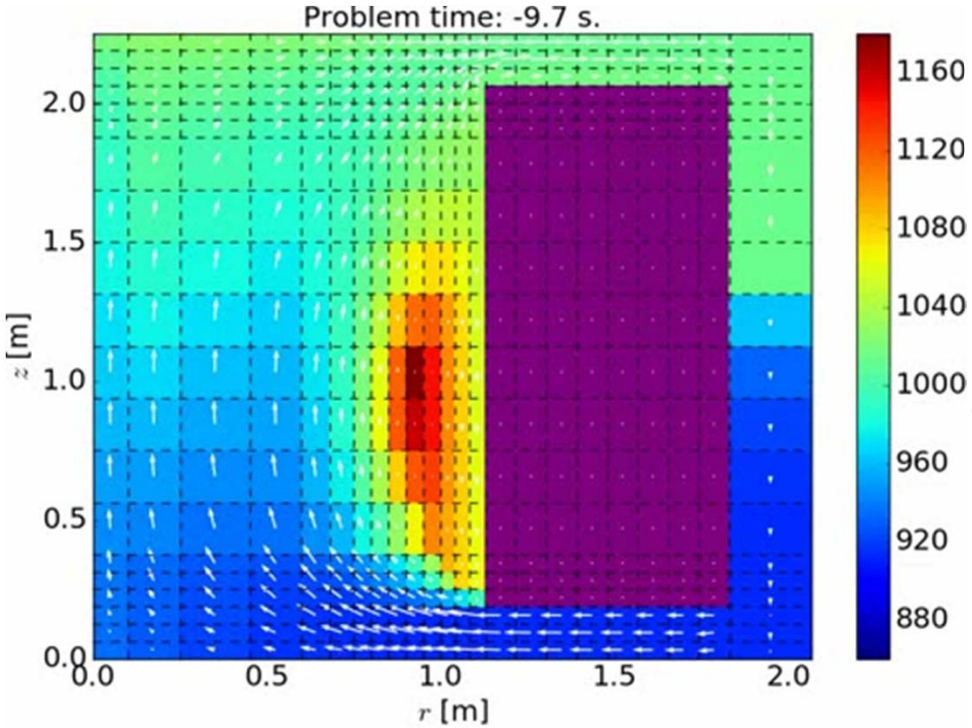
Zanetti, M., et al., Extension of the fast code system for the modeling and simulation of MSR dynamics Proceedings of ICAPP 2015.

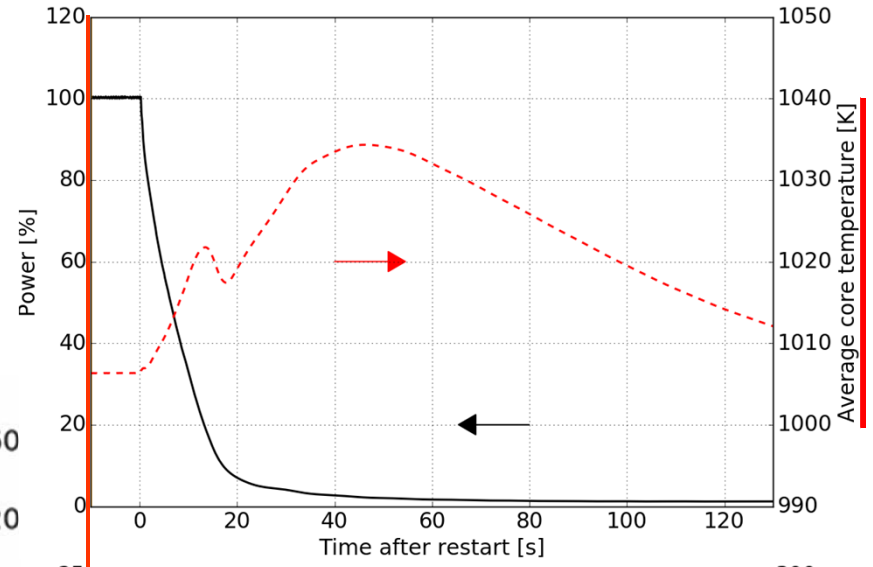
WP3: TRACE application to MSFR

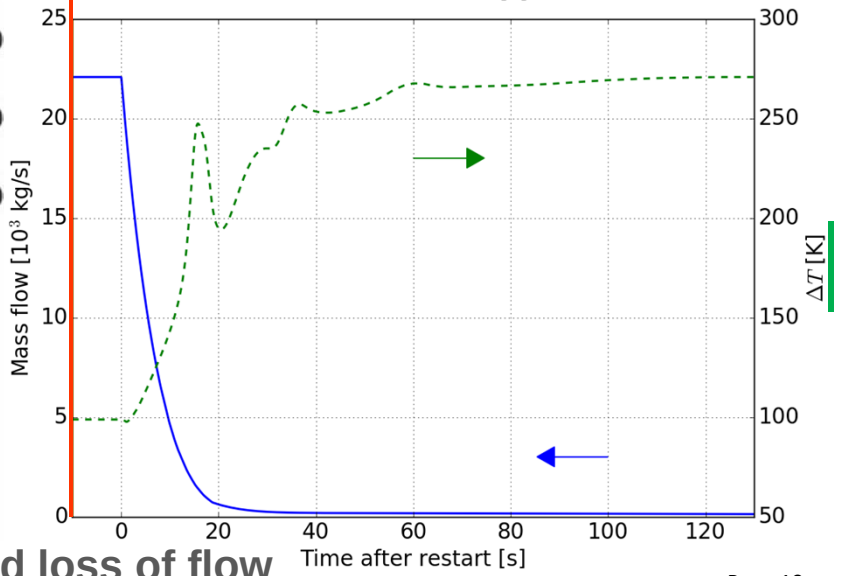
WP3: Transient analysis & DHR

- **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

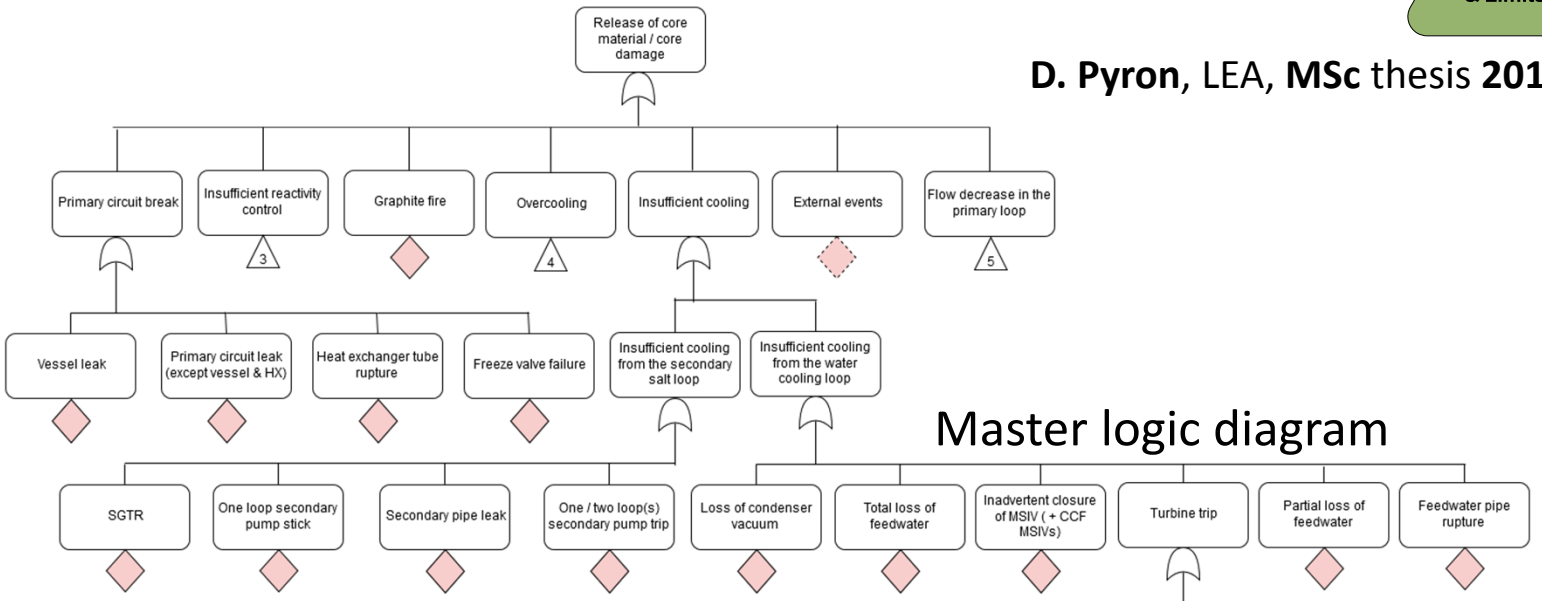
MSR safety & limits

- 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

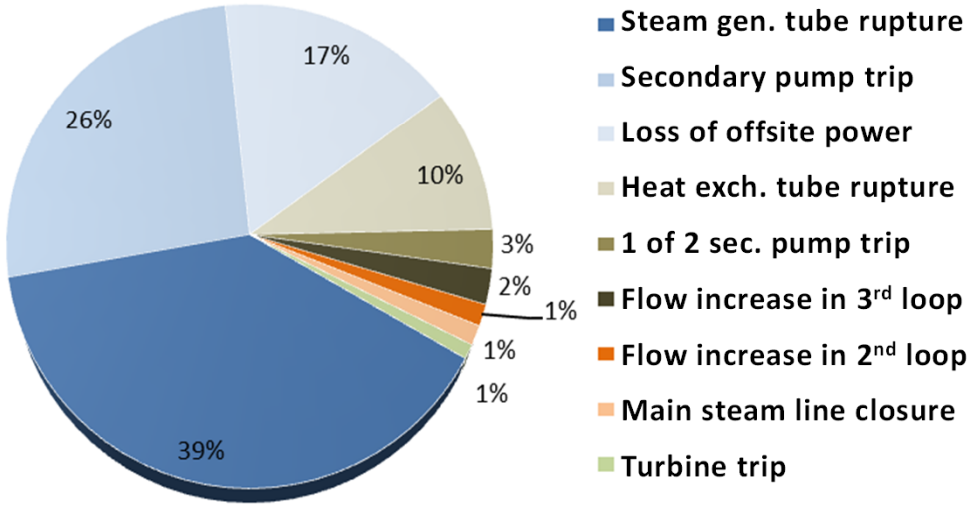
Accident scenarios & PSA 1 modeling

WP4: Safety & Limits

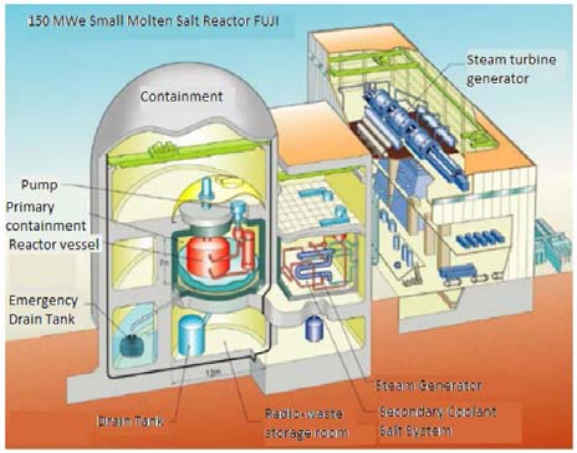
D. Pyron, LEA, **MSc** thesis **2016**



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! ☺

Invitation to MSR workshop at PSI

- 23-24 January 2017, **GIF MSR PSSC meeting** will be hosted **at PSI.**
- On 24 January 2017 afternoon, **public MSR workshop** will be hosted **at PSI**, presenting the key national programs.
- Preliminary confirmed speakers:
  - Dr. Xu – China
  - Dr. Holcomb – USA
  - Dr. Ignatiev – Russia
  - Prof. Kloosterman – EU
  - Prof. Pautz – Switzerland
  - Prof. Edwards – Australia.