# Review of the Recent FAST Project Activities Related to Gen-IV Fast Reactors

K. Mikityuk and FAST reactors group:
J. Krepel, S. Pelloni, S. Pilarski
PhDs: A. Epiney, A. Chenu, K. Sun
MSs: R. Adams, A. Pont Ribas, C. Klauser
postDoc: E. Marova

Paul Scherrer Institut

http://fast.web.psi.ch/

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# Overview

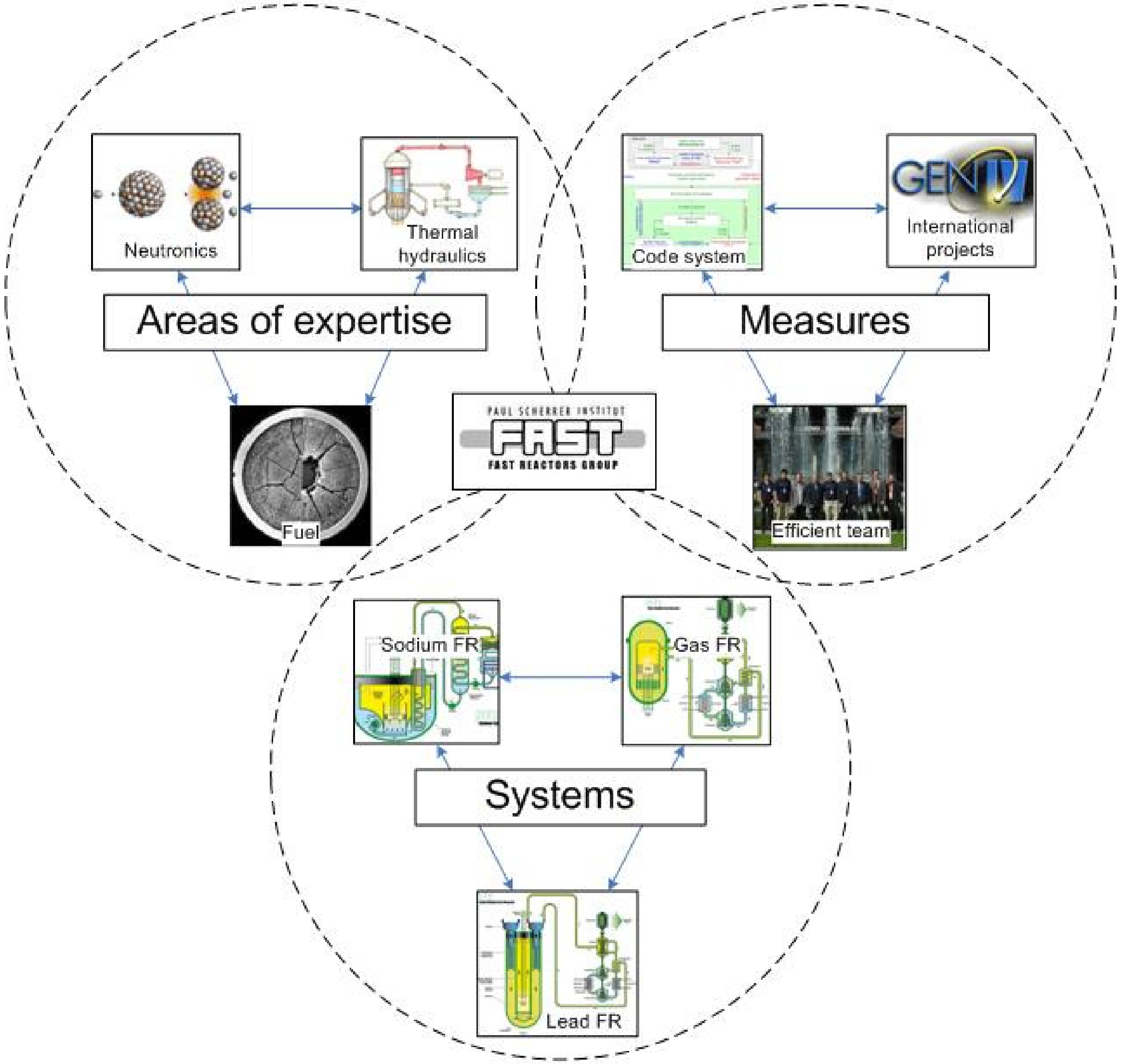
- FAST project at PSI
- International projects
- FAST code system: recent developments and applications
  - Main components of the FAST code system
  - Modelling of sodium two-phase flow with the TRACE code
  - New x-section generation procedure for the PARCS code
  - ESFR equilibrium fuel cycle analysis with the EQL3D/ERANOS procedure
  - Decomposition of reactivity effects in sodium fast reactors
  - GFR studies
  - LFR studies
- Near-future plans
  - Validation of the FAST code system
  - Multi-physics uncertainty and sensitivity analysis
  - Comparative analysis of the main Generation-IV fast-spectrum cores

# FAST project concept

K. Mikityuk

The goal of the project is to develop the ability to provide a unique expert analysis

- in neutronics, thermal hydraulics and fuel behaviour,
- with the use of a unique computational tool, integration into international programs and organization of an efficient team,
- for three Gen-IV fast-spectrum systems: sodium-, gas- and lead-cooled reactors.



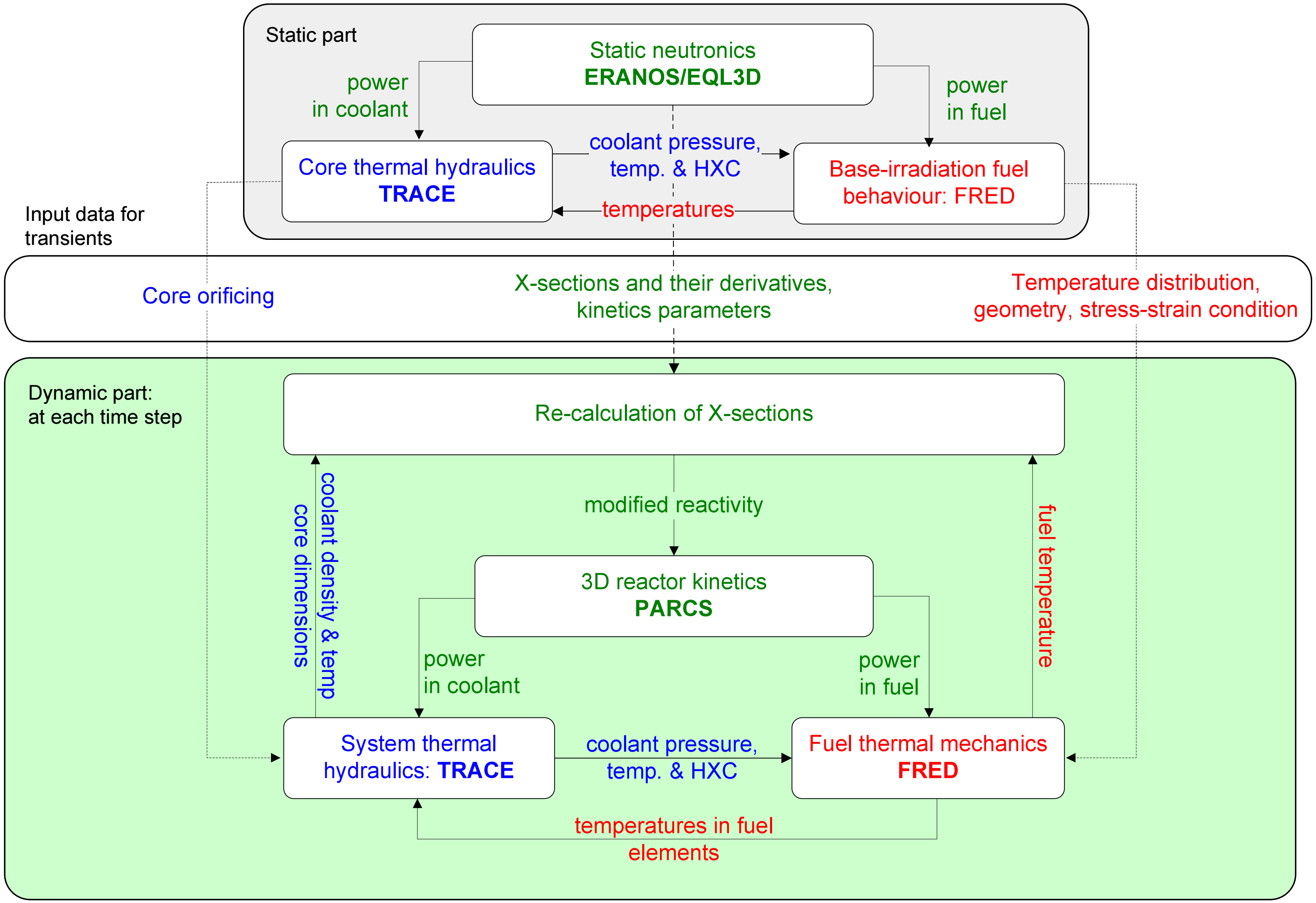
# FAST international projects



- **Gas-cooled fast reactor**
  - **EURATOM:** FP6 GCFR (finished in 2008), FP7 GoFastR (2010-2012)
  - **CEA & GIF:** cooperation in different aspects
- **Lead-cooled fast reactor**
  - **EURATOM:** FP6 EUROTRANS (2005-2009), FP6 ELSY (2006-2009), FP7 LEADER (2010-2012) – neutronics and safety analysis
- **Sodium-cooled fast reactor**
  - **EURATOM:** FP7 ESFR (2009-2012) – neutronics and safety analysis
  - **CEA:** cooperation in neutronics
  - **IAEA TWG FR:** PHENIX EOL Test Benchmarks – neutronics and thermal hydraulics

# Structure of the FAST code system





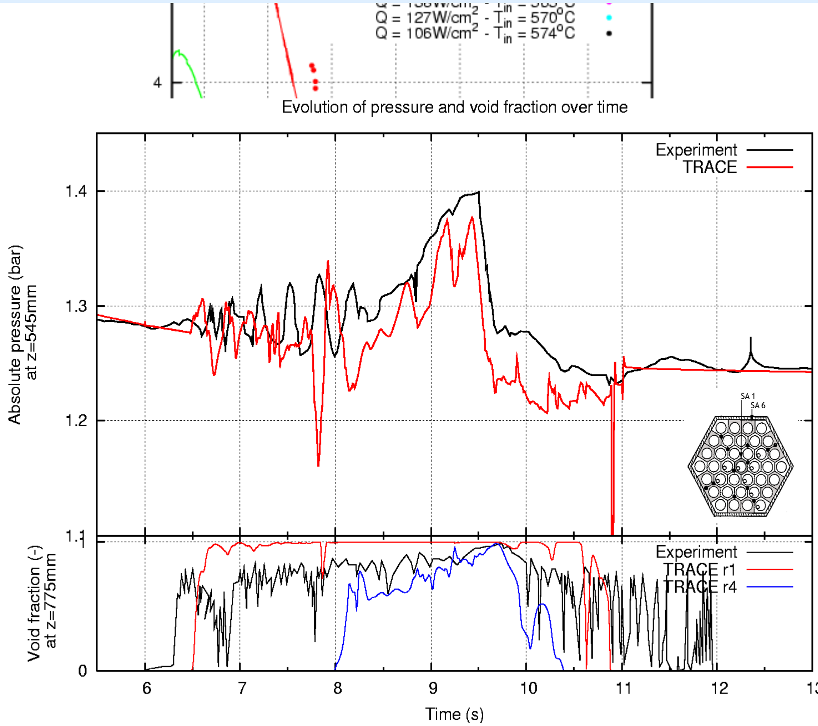
# Modelling of sodium two-phase flow with the TRACE code

- ***Purpose***: Development of an advanced computational tool for coupled neutronics thermal-hydraulics transient analysis of sodium systems
- Implementation of EOSs and physical model to simulate sodium boiling
- Benchmark against SIMMER-III
- Benchmark against experiments:
- *Next step*: Use of the FAST code system with the extended TRACE version to perform a coupled TRACE/PARCS 3D neutronics/thermal-hydraulics transient analysis of the Gen-IV SFR

Transient boiling:

simulation of a LOF in 2D pin-bundle

study of the interfacial tranfer mechanisms



# New x-section generation model for PARCS

S. Pelloni

- Motivation: to improve the x-section generation methodology in the FAST code system to take into account the interrelations between reactivity feedbacks and to prepare for implementation of the uncertainty propagation methodology.

- The main idea of the new method is to prepare a set of multi-group micro x-sections for each isotope and each core zone in the form of tables for a given range of temperatures and background cross sections (sigma-zeros) with the use of the ECCO cell code (ERANOS).

- During the transient simulation the new procedure within the PARCS code is supposed to calculate for current temperature, sigma-zero and nuclear densities for each core zone a set of macro x-sections interpolating micro x-sections from the pre-generated tables.

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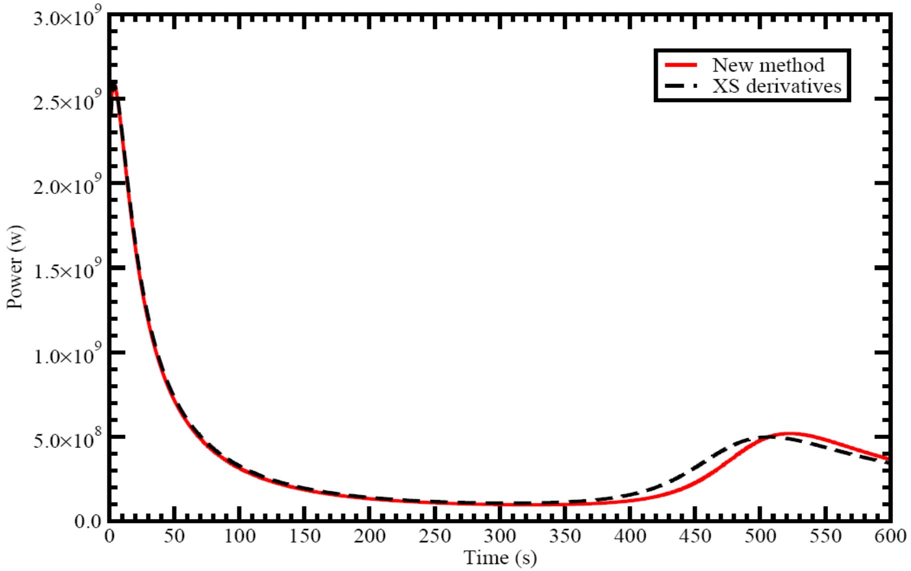
# New x-section generation model for PARCS

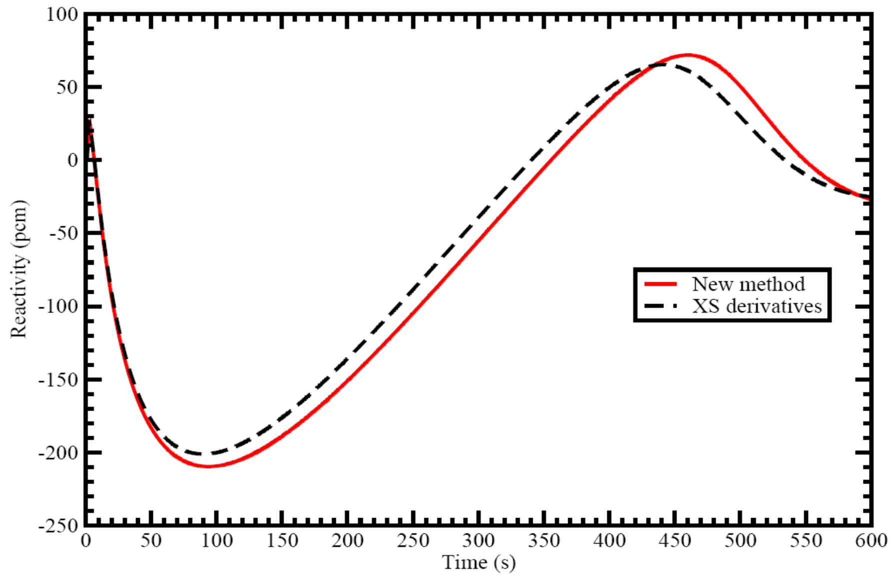
S. Pelloni

- The model was implemented in the FAST code system
- As a next step, the new model is tested against the "old" x-section calculation model based on the basic macro x-sections and their derivatives with respect to state variables (fuel temperature, coolant density, core dimensions, etc)
- Transients in which interrelations between reactivity feedbacks are weak (e.g. ULOF) were chosen – good agreement obtained

## Power in ULOF



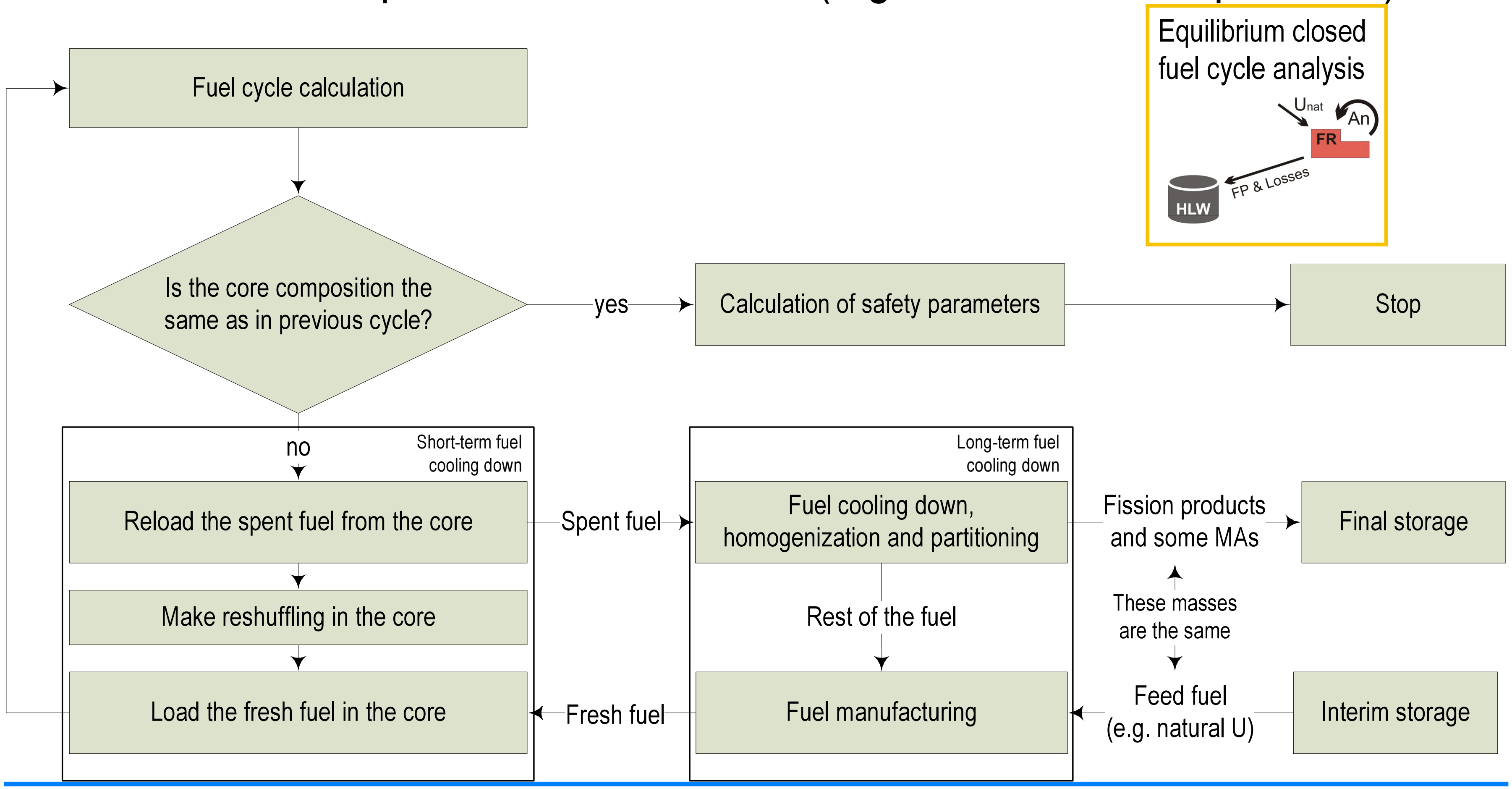

## Reactivity in ULOF



# Equilibrium closed fuel cycle simulation

J. Krepel

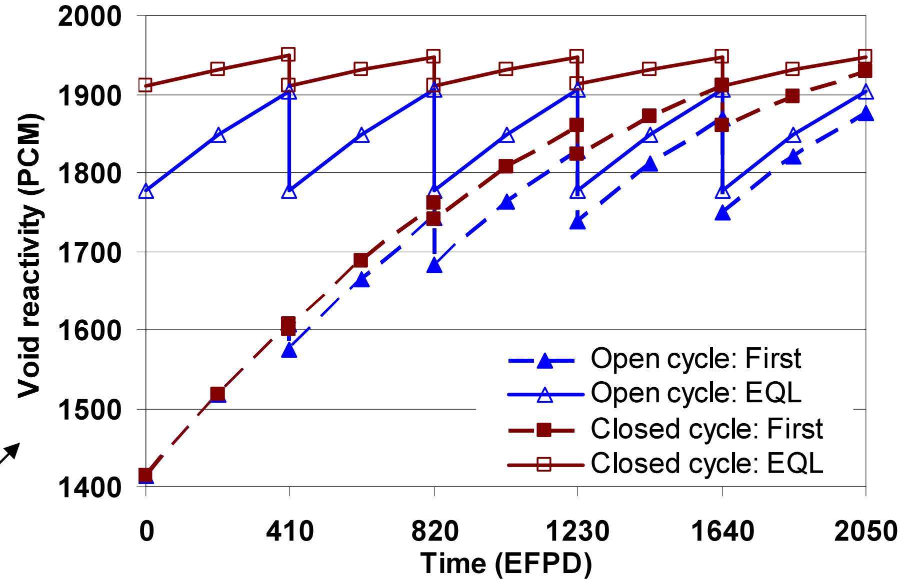
- EQL3D – ERANOS-based calculational procedure
- Multi-batch equilibrium cycles for fast-spectrum cores in 3D geometry
- Different assumptions about feed fuel (e.g. reactors' own spent fuel)

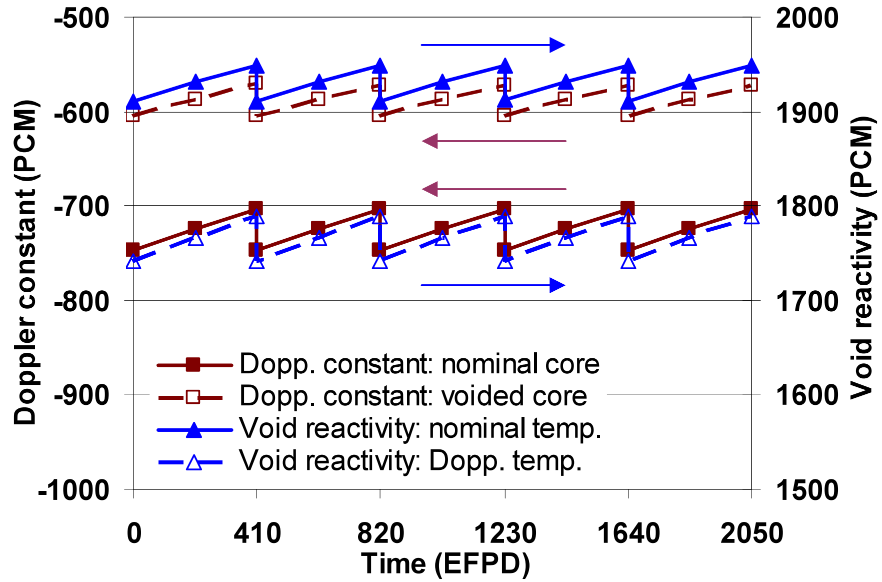


# ESFR equilibrium cycle analysis

J. Krepel

- One of the SFR preliminary oxide fuel cores designed at CEA
- The aim is to simulate and confirm the SFR capability for closed fuel cycle, and to evaluate and compare the parameters of the open and closed cycle at equilibrium
- Decomposition of the void reactivity effect to understand the deterioration of the void effect in closed cycle
- Interrelation between the Doppler and void effect → new x-section generation model
- Similar study is under way in frame of the ESFR project

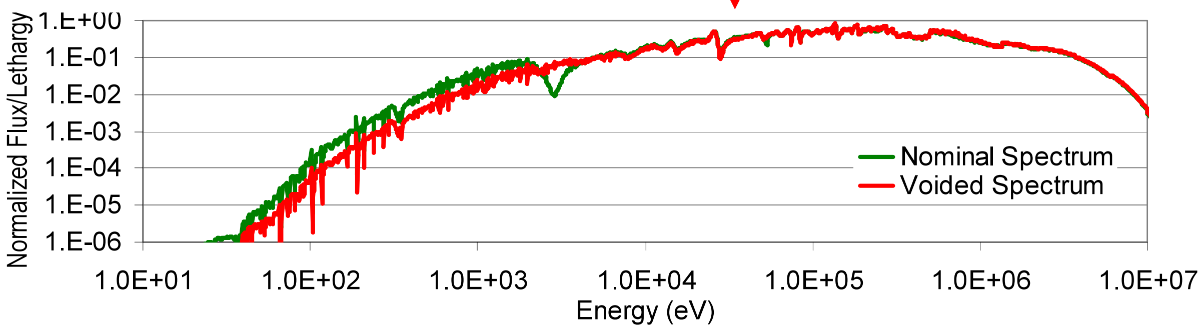


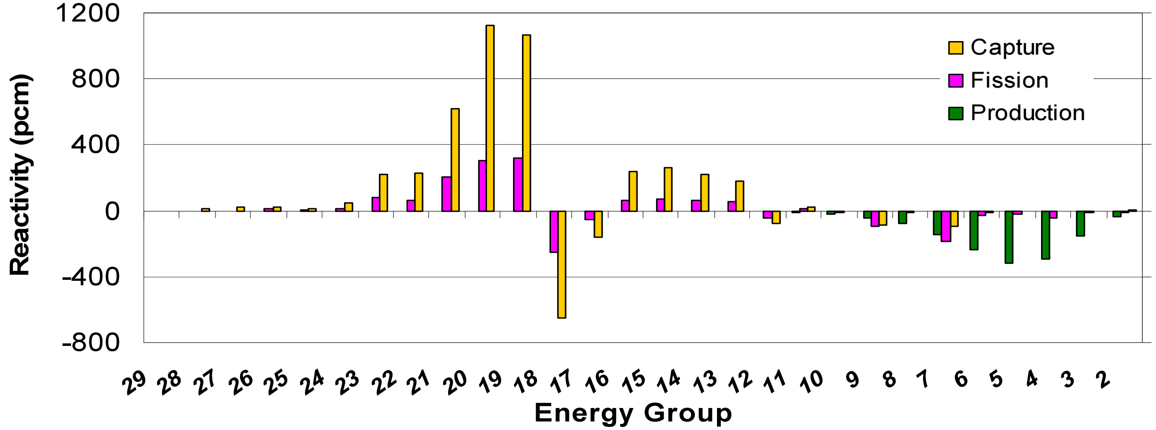



# Decomposition of reactivity effects in SFR

K. Sun

- Methodology to better understand the reasons of the positive sodium void effect
- Closed equilibrium fuel cycle conditions
- Both neutron balance method and perturbation theory algorithms
- Reaction-wise, isotope-wise, and energy-group-wise decomposition



# Gas-cooled Fast Reactor studies



- Contribution to EURATOM projects (FP6 GCFR, FP7 GoFastR) – neutronics and safety analysis

- 3D analysis of gas-cooled fast reactor core behaviour in control assembly withdrawal accidents (PhD study)

- Development and application of an advanced fuel model for the safety analysis of the Gen-IV gas-cooled fast reactor (PhD study)

- Heavy gas injection in the Gen-IV gas fast reactor to improve decay heat removal under depressurized conditions (PhD study)

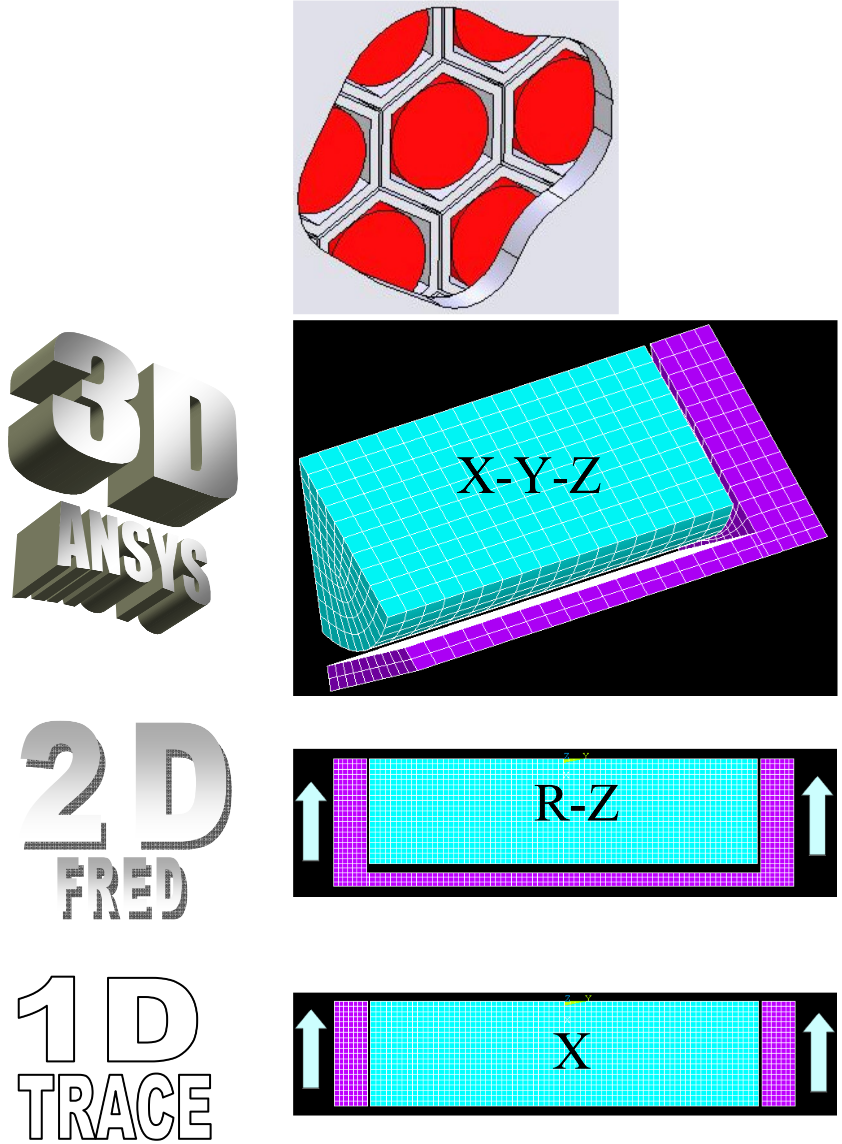
- Preliminary design of a Brayton cycle for an autonomous decay heat removal in the Gas Fast Reactor (PhD study)

- Calculational investigation in support of the low-temperature gas cooled fast reactor design (postDoc study).

# GFR fuel model

P. Petkevich, PhD

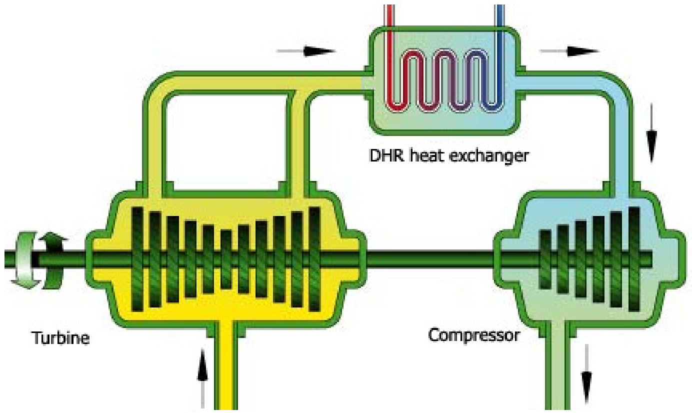
- Material properties database compiled: (U-Pu)C for fuel, SiC for matrix
- 2D thermo-mechanical model developed and validated against 3D FEM analysis
- Transient analysis performed with new model
- Limitations of the new 2D model identified
- Detailed 3D FEM analysis resulted in recommendations
  - for use of 1D models;
  - for fuel design optimization
- FAST is unique numerical tool for GFR transient analysis with links between fuel behaviour, neutron kinetics and thermal hydraulics

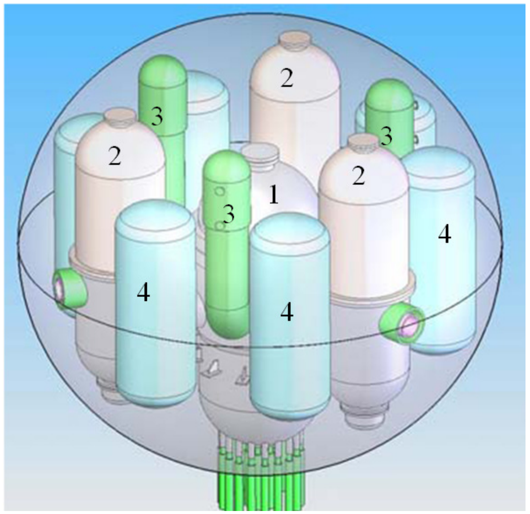


# Brayton cycle for DHR in GFR

A. Epiney, PhD

**Idea**: use of decay heat itself to evacuate it**.** As long as there is decay heat to evacuate there is energy to assure the cooling → Enhance passivity of DHR at low pressure




**Chosen design point**:

- Equilibrium at 2 bar
- 0MW power production
- He mass flow: 32 kg/s
- Turbine diameter: 1.6 m

**Pressure guard containment**

1 – reactor vessel
2 – main HX
3 – DHR HX
4 – gas reservoirs (helium / heavy gas)

# Lead-cooled Fast Reactor studies

K. Mikityuk

- Contribution to EURATOM projects (FP6 ELSY, FP7 LEADER) – neutronic and safety analysis

- Analysis of heat transfer to liquid metal

- Modelling of the oxide layer build-up on the surfaces of the structural material in the lead flow with the TRACE code

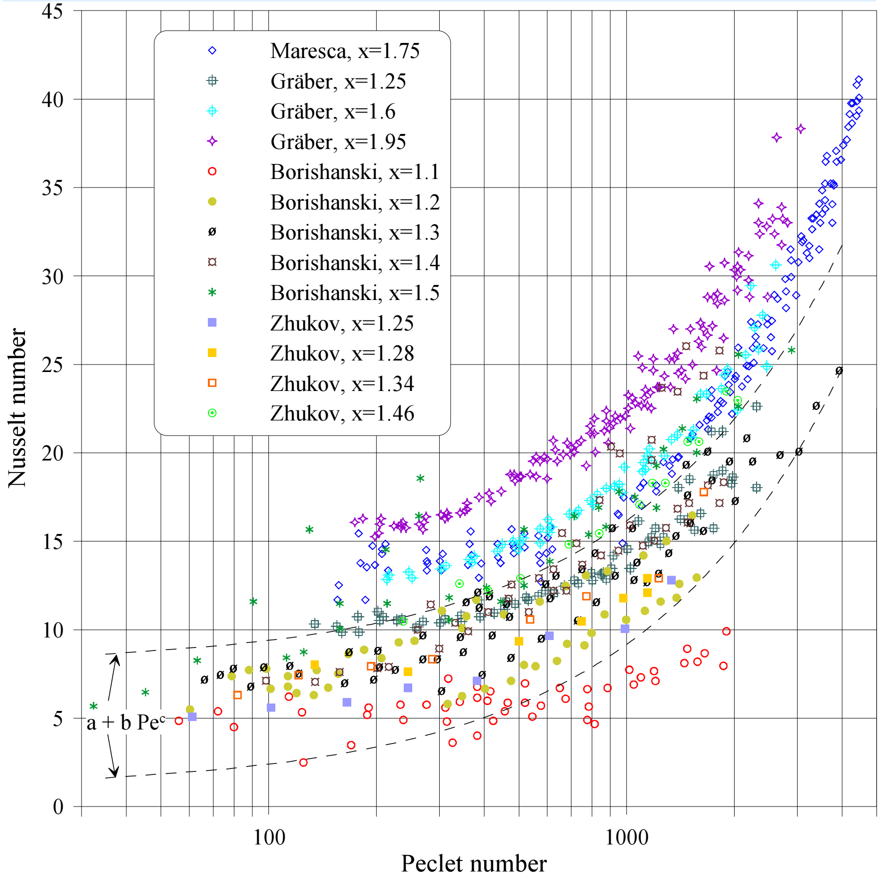
# Analysis of Heat Transfer to Liquid Metal

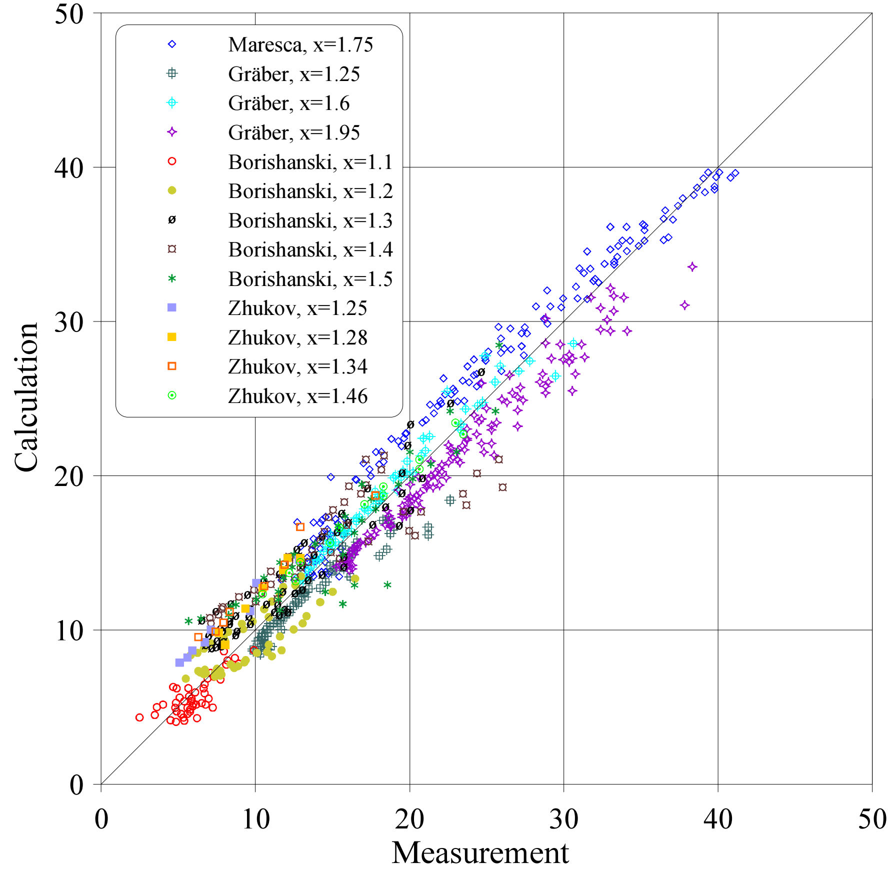
K. Mikityuk

- 658 data points for different liquid metals
- tube bundles with x = 1.1 — 1.95
- Peclet 30 to 5000

- 8 correlations analysed
- new correlation derived

$$Nu = 0.047(1-e^{-3.8(x-1)})(Pe^{0.77}+250)$$




- Recommendations for EU projects **ELSY**, **EUROTRANS** and **ESFR** produced

# Near-future plans



To focus on sodium-cooled fast reactor with preservation of activities on GFR and LFR for comparison purposes

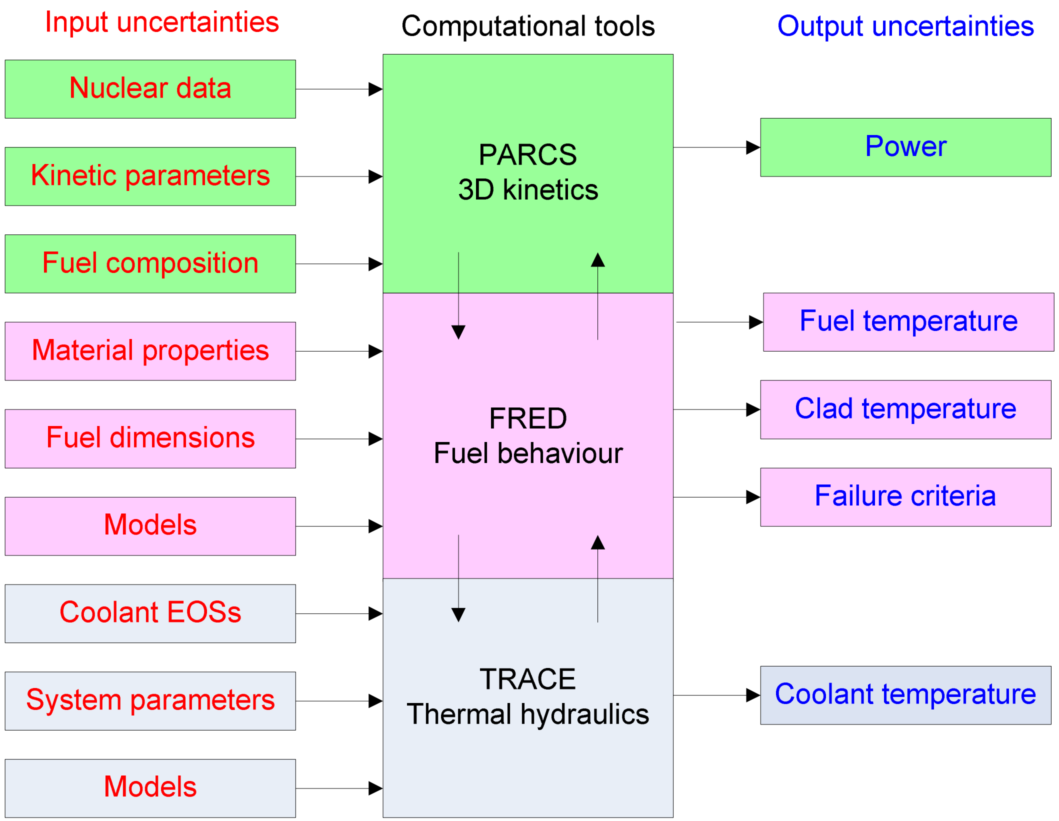
Three main directions:

- Validation of the FAST code system
  - Static neutronics: validation of ERANOS,,e.g. against PHENIX-EOL/control rod withdrawal test data and against BFS/BN-600 data.
  - Thermal-hydraulics: validation of TRACE, e.g. against PHENIX-EOL/natural circulation test data and against sodium boiling data (KNK/FzK, ISPRA, CABRI/SCARABEE).
  - Fuel behaviour: validation of FRED, e.g. against HALDEN UO2 base-irradiation data and against CABRI/SCARABEE fast transient data.
  - Coupled transient simulation: validation of ERANOS/PARCS/TRACE/FRED, e.g. against first phase of the PHENIX-EOL/natural circulation test data and against EBR-II LOF WS and LOHS WS tests.
- Multi-physics uncertainty and sensitivity analysis
- Comparative analysis of the main Generation-IV fast-spectrum cores

# Uncertainty propagation methodology



- To develop uncertainty propagation methodology in frame of the FAST code system
- for comparative evaluation of the uncertainties of different natures (in neutron data, material properties, models, etc.)
- for steady-state and transient analysis of the Gen-IV systems (SFR first)



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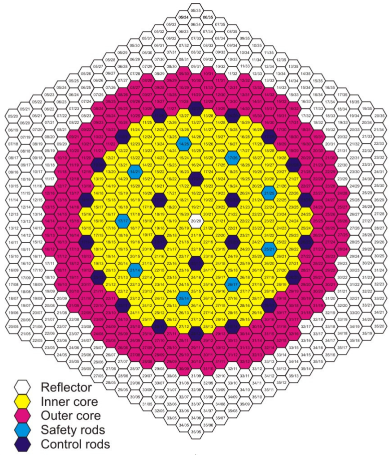
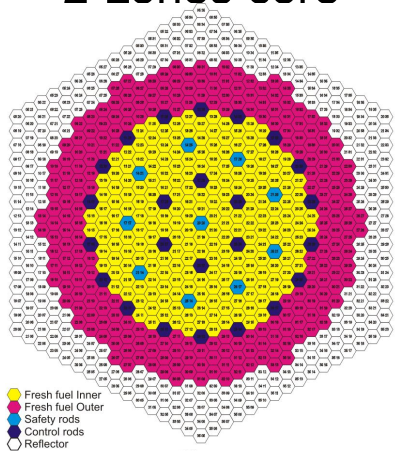
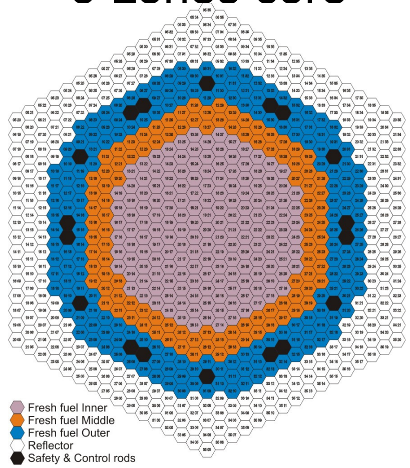
# Three Gen-IV systems – multibatch schemes

J. Krepel

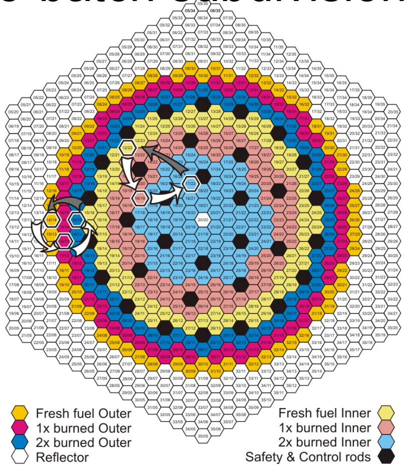
| SFR | GFR | LFR |
|---|---|---|
| 3600MWth | 2400MWth | 1500MWth |
| 2-zones core | 2-zones core | 3-zones core |



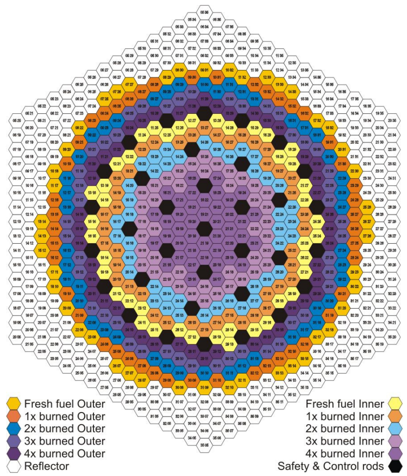



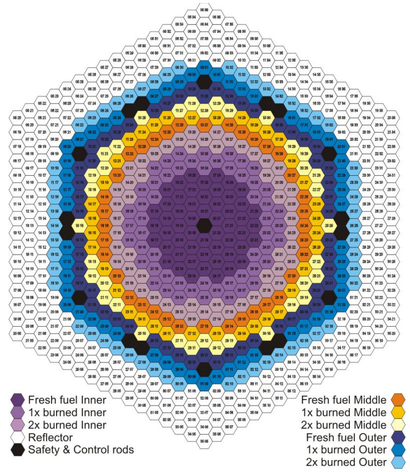

5-batch subdivision




3-batch subdivision




3-batch subdivision

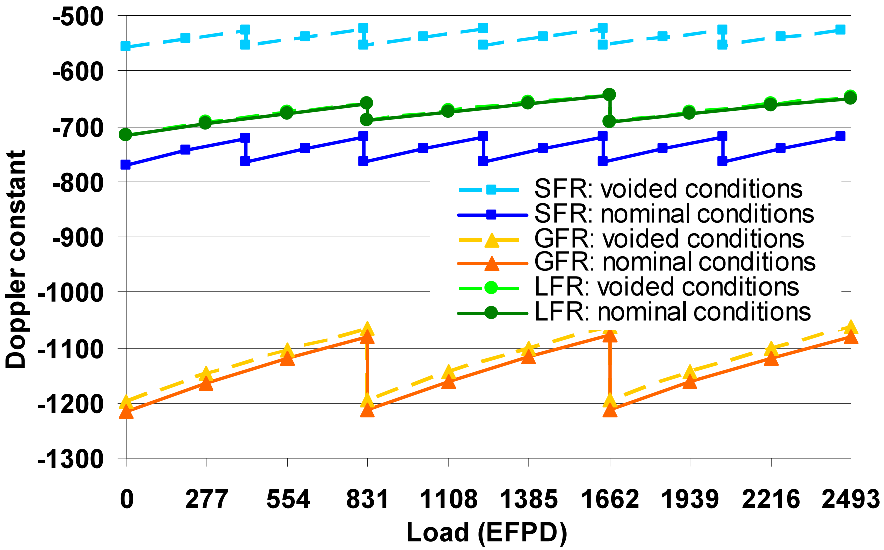


# Comparison of equilibrium safety parameters

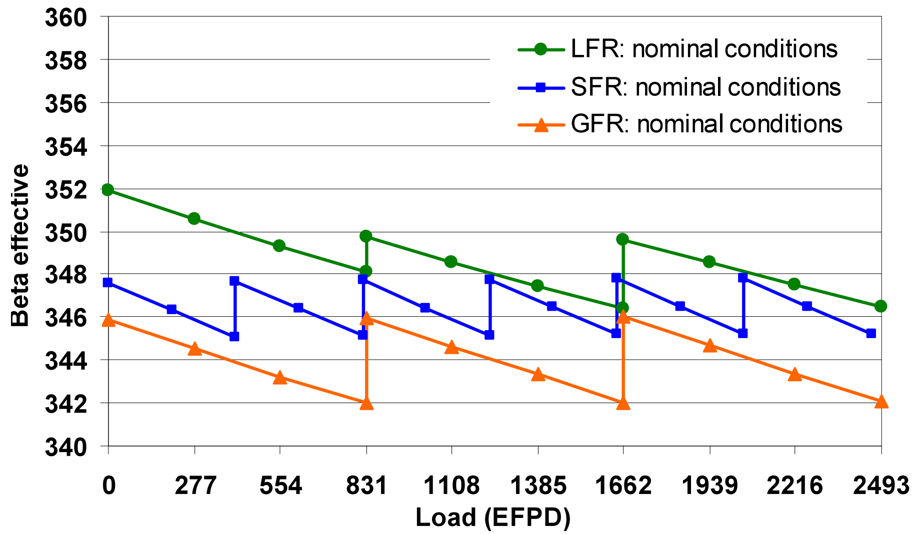
J. Krepel

- SFR – strong dependence of Doppler on void conditions
- GFR – the best Doppler
- Beta effective very close for all systems

Doppler constant, pcm




Beta effective, pcm



# Comparison of equilibrium safety parameters

J. Krepel

| Core: | SFR | | GFR | | LFR | |
|---|---|---|---|---|---|---|
| Strategy | open cycle | closed cycle * | open cycle | closed cycle * | open cycle | closed cycle * |
| Residence time (EFPD) | 5 X 410 =2050 | 5 X 410 =2050 | 3 X 831 =2493 | 3 X 831 =2493 | 3 X 831 =2493 | 3 X 831 =2493 |
| Reactivity swing | 773 | 642 | 3139 | 1265 | 1134 | 580 |
| Pu content (w%) | 17.7 | **17.9** | 18.1 | **18.8** | 16.5 | **16.9** |
| MA content (w%) | 0.5 | **1.0** | 0.3 | **1.3** | 0.3 | **1.2** |
| Doppler constant | -898 | **-15%** | -1326 | **-9%** | -851 | **-15%** |
| Void reactivity | 1775 | **+6%** | 215 | **+23%** | 253 | **-6%** |
| $\beta$ | 370 | **-6%** | 368 | **-6%** | 370 | **-6%** |
| $\Lambda$ (ms) | 0.41 | **-10%** | 0.98 | **-10%** | 0.86 | **-15%** |

* *closed cycle = 100% Actinides recycling by reprocessing & using of natural uranium feed*

*Void reactivity is calculated assuming the voidage of the fuel region only*

# Conclusions

- The FAST code system is a computational tool that gives us unique opportunity to compare the breeding and safety parameters for the main Gen-IV fast-spectrum system in equilibrium open and closed cycle

- The one of the important current R&D directions is the coupled 3D neutron kinetics/thermal-hydraulic analysis of the SFR transients with sodium boiling

- The important future directions include further validation of the code system, continuation of the SFR/GFR/LFR comparison study and implementation of the multi-physics uncertainty/sensitivity methodology for static and transient analysis


Thank you! Any questions?