PAUL SCHERRER INSTITUT

PSI

H. Ferroukhi :: Paul Scherrer Institut

Laboratory for Reactor Physics and Systems Behaviour

NES Kompetenzen und Highlights, October 18, 2016, PSI

The Lab in a Nutshell

- Home of **Nuclear Data, Reactor Physics and Integral Safety Analyses**
  - **Thermal** and **Fast** Reactor Systems
  - **Multi-Physics Multi-Scale** Simulations
  - **Uncertainty** Quantification **and Sensitivity Analyses**

Develop and Qualify Simulation Methodologies for Current and Advanced Reactors

Perform conceptual studies on innovative reactors for waste reduction as well as safety enhancements

- Home of **Technical and Scientific Support** to
  - **Nuclear Safety Authorities** (ENSI, STUK)
  - **Industry** (swissnuclear, E.ON, Areva)
  - **Swiss Nuclear Waste Management Organization** (NAGRA)
  - **National Institutes and Universities** (e.g. Criticality Safety)

Support safe operation of current and future nuclear power plants

- Home of **Experimental Reactor Physics**
  - *Until 2011*, **at PSI Zero-Power PROTEUS Research Reactor**
  - *Since then*, **at EPFL Zero-Power CROCUS Reactor**

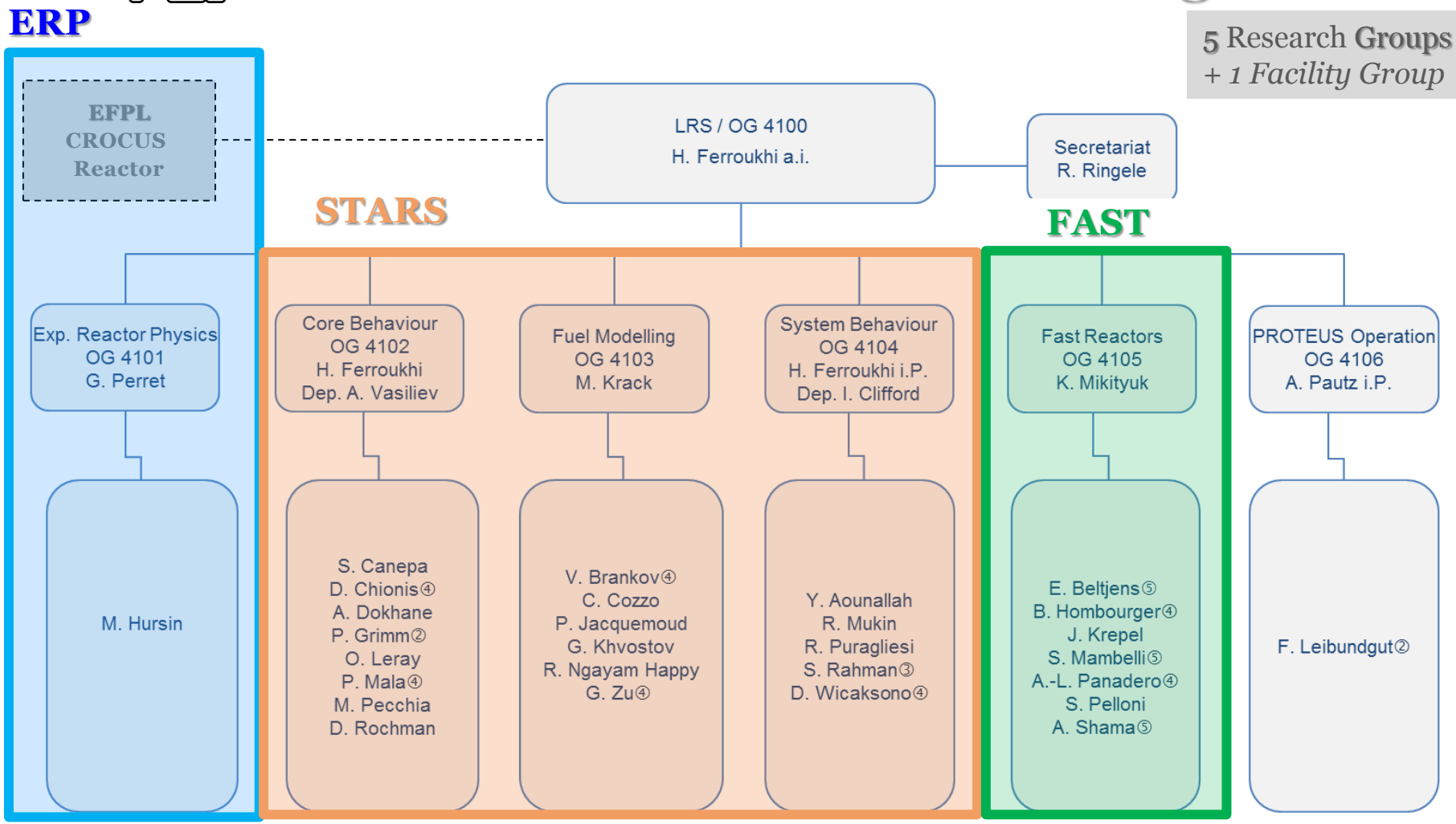
Design, conduct and interpret measurements to validate reactor physics codes and nuclear data

- Home of **Education and Teaching Programs**
  - **Neutronics, Special Topics on Reactor Physics, Nuclear Computation Lab @EPFL/ETHZ**
  - Supervision of **Post-Docs**, **PhDs** and **Semester/Master Students**
  - Supervision of **Practicums and Guest Scientists**

Contribute to the education of the future generation of nuclear engineers and scientists

LRS Organization

5 Research Groups
+ 1 Facility Group



3 Research Programs: ERP, STARS, FAST

21 Scientific Staff + **3** Administrative Staff + **1** Post-Docs + **7** PhDs + **3** Master Students

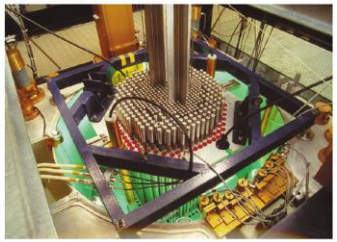
Panorama RND Programs

ERP
Home of *Experimental Reactor Physics and Measurement Techniques*

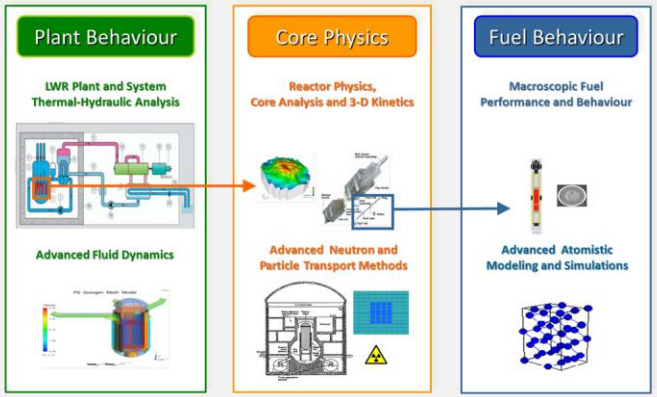
PROTEUS Zero Power Facility at PSI (now being decommissioned)

PROTEUS Shutdown in 2011
Now under preparation for Decommissioning

CROCUS Reactor at EPFL



STARS
Home of *Multi-Physics Multi-Scale Modelling* for Integral LWR Safety Analyses



- Research
- *Scientific Support*
- *Education*

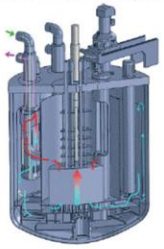
FAST
Home of *Multi-Physics Analyses* of FAST Spectrum and Molten Salt Reactors

Goals	• Evaluation of performance and safety of Gen-IV SFR • Search for design solutions for Gen-IV MSR • Representation of Switzerland internationally • Teaching
International	• Generation IV International Forum; • OECD WP on International Nuclear Data Evaluation; • IAEA Technical Working Group on Fast Reactors

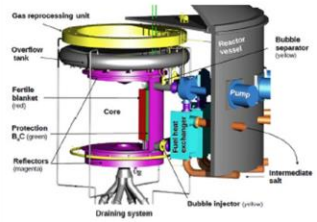
- **GCFR** (EU) — Gas-Cooled Fast Reactor (FP6 & FP7)
- **GFR** (GIF) — Gas-cooled Fast Reactor (cooperation with CEA)
- **EUROTRANS** (EU) — LBE-cooled ADS (FP6)
- **ELSY** (EU) — European Lead fast reactor SYstem (FP 6)
- **ESFR** (EU) — European Sodium-cooled Fast Reactor (FP7)
- **SFR** (GIF) — Sodium-cooled Fast Reactor (cooperation with CEA)

Today, Focus of FAST Activities mainly on SFR and MSFR

Sodium Fast Reactors (ASTRID)



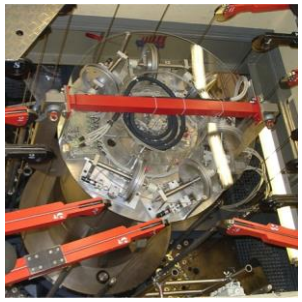
Molten Salt Fast Reactors (MSFR)



Validation on reactivity effects of spent fuel with uncertainty quantifications

LWR-II spent fuel samples

40-cm long UO_2 and MOX samples with burn-up up to 120 and 70 GWd/t



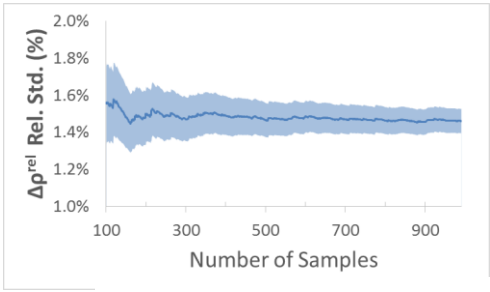
Past Reactivity effect measurements @ PROTEUS

- Central test tank of PROTEUS
- 3 moderation conditions

$$\Delta\rho^{rel} = \frac{\Delta\rho\left(\text{fresh U 3.5\%} \rightarrow \text{burnt}\right)}{\Delta\rho\left(\text{fresh U 3.5\%} \rightarrow \text{natural U}\right)}$$

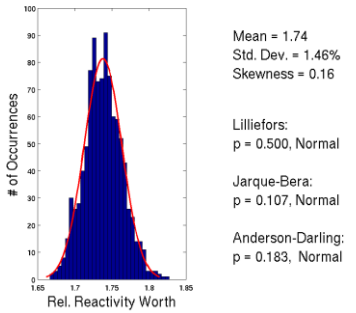
Uncertainty methods for CASMO-5: SHARK-X

- Consider nuclear data XS uncertainty (SCALE-6.0)
- Consider spent fuel composition uncertainty (Mst)
- Direct perturbation (DP) and statistical sampling (SS) methods

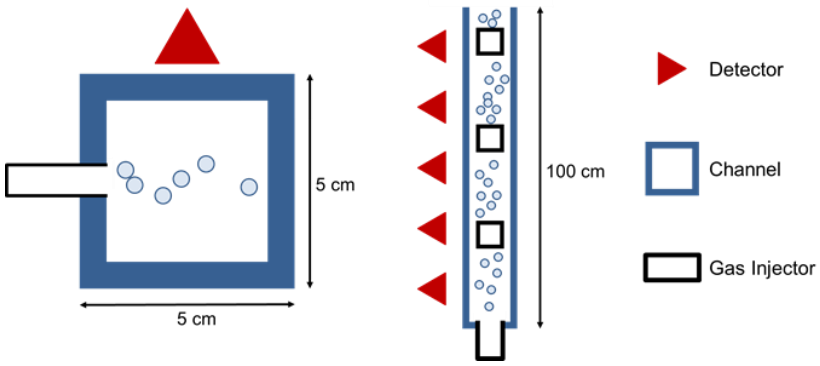


Results

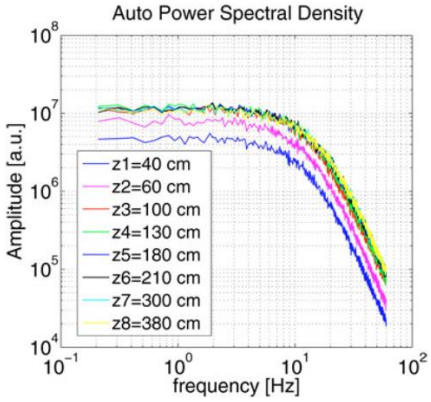
- SS and DP methods agree and give consistent uncertainty
- Future work to propagate nuclear data uncertainty through improved irradiation history (QUASAR)

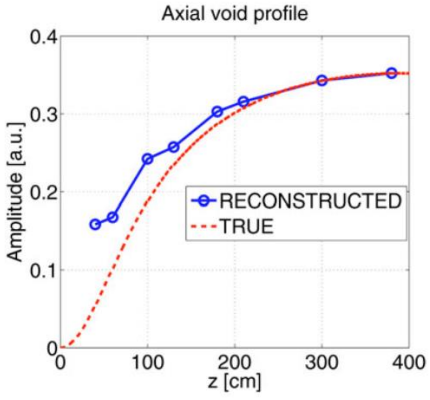


Void profile measurements at CROCUS through neutron noise



In-core neutron noise setup



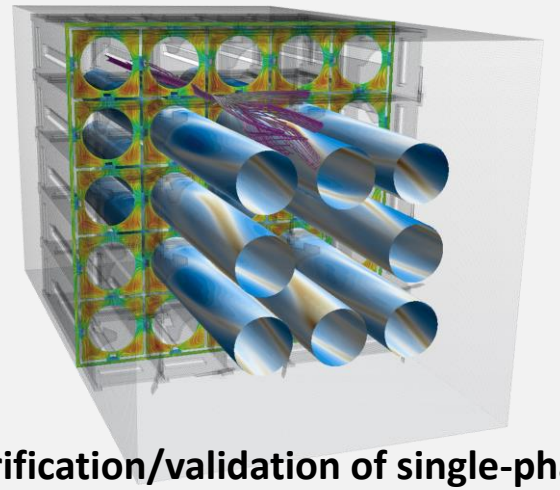


Development of an experimental setup to **reconstruct axial void profile in BWR** through **neutron noise** measurements of in-core detectors

- A **theoretical method**[1] to reconstruct the void profile within a BWR channel using in-core neutron noise has been developed at Chalmers University
  - Transit time of the bubbles is measured by correlations in detector signals at discrete locations
  - Relationship between void and transit time is known
  - Third order polynomial fit of void profile
- The method will be tested **in clean conditions in CROCUS** with a channel containing a two-phase flow with known void distribution
- **Separate characterisation** of the bubble distribution using **existing visualization techniques.**

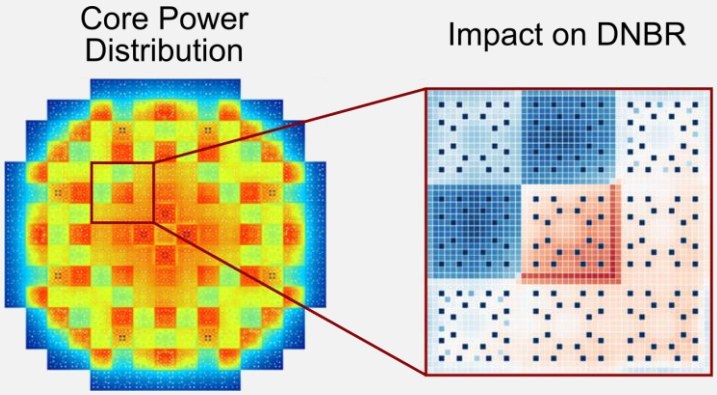
[1] V. Dykin and I. Pazsit, "Simulation of in-core neutron noise measurements for axial void profile reconstruction in boiling water reactors," *Nucl. Technol.*, vol. 183, 2013.

STARS/Plant Behaviour Samples 2016



Verification/validation of single-phase RANS CFD models for full-length PWR fuel assembly

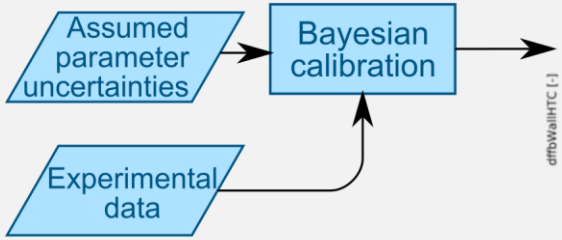
- Largest CFD model in LRS to date
- 122 Mio cells, 4032 CPUs
- Swiss National Supercomputing Centre (CSCS)

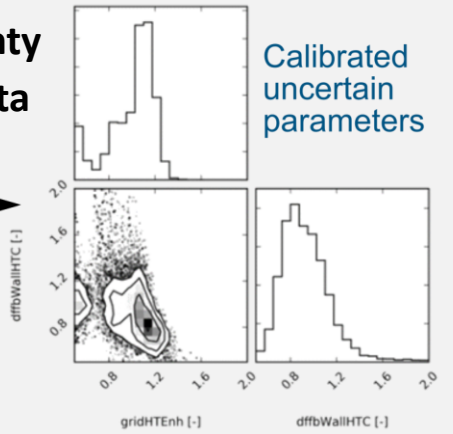


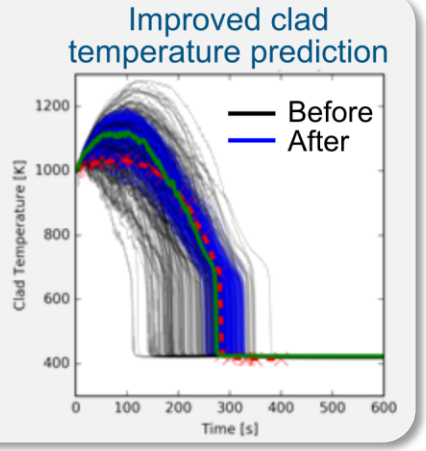
Studies of PWR fuel assembly bowing effects using subchannel codes

- Fuel rods may bow (bend) due to non-uniform power distribution
- Local power peaking and flow distortion impacts major safety parameters

Bayesian calibration of statistical uncertainty in reflood model parameters using SET data







Core Analyses with Uncertainty Quantification

Upgrade of the PSI Swiss Core Model Platform CMSYS

Nuclear Data Uncertainty *"from CASMO to Disposal"*

Preliminary Pilot Study conducted for KKB1

0.63 0.8	0.36 0.6	2-D Power Std (%)	
1.32 0.8	1.26 1.7	0.41 0.8	
1.15 0.6	1.09 0.3	1.25 1.7	0.36 0.7
1.33 1.1	1.15 0.6	1.32 0.9	0.63 0.9

Major Challenge:

Statistical Convergence

⇔ 1 UQ Analysis

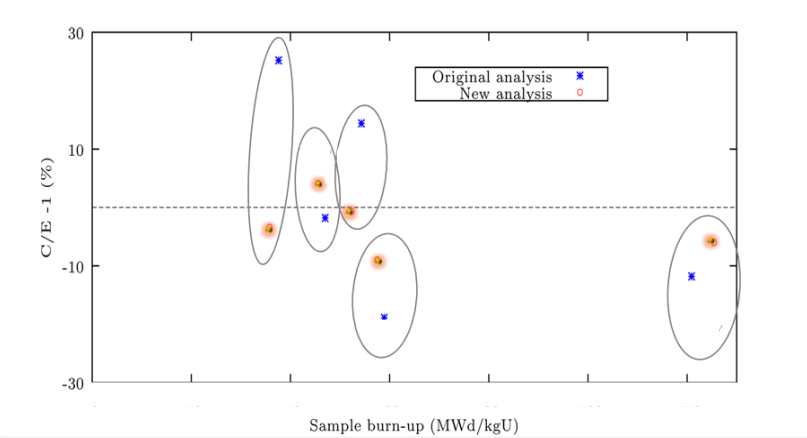
⇔~ 400 000 CPU*hours

1 TB Storage

BOHR Method for Spent Fuel Characterization

Reconstruction of Pin-Wise Nuclides from Core Models

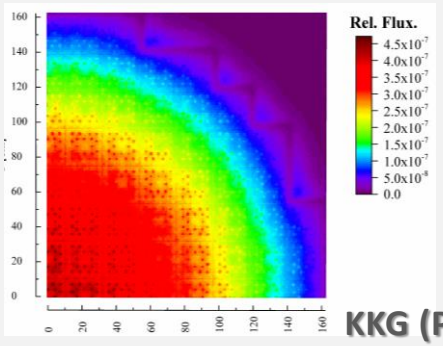
Significant Enhancement of Cm244 Predictions



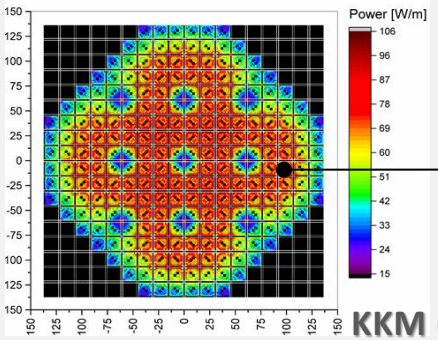
Full Core Monte-Carlo Modelling with MCNP for the Swiss Reactors

Development of Methodology for Initialization of Pin-Wise Nuclide Compositions of Burned Cores

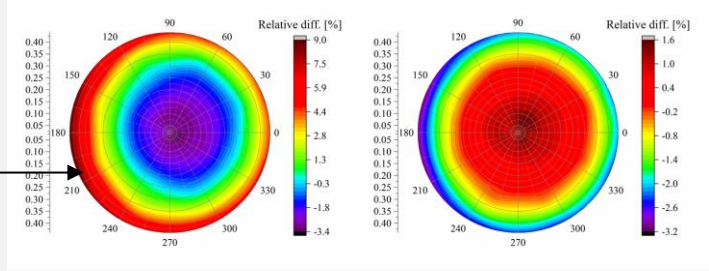
Model Optimization for High-Resolution Calculations of Intra-Pin Azimuthal Flux/Power and Nuclide Distributions



KKG (PWR)



KKM (BWR)



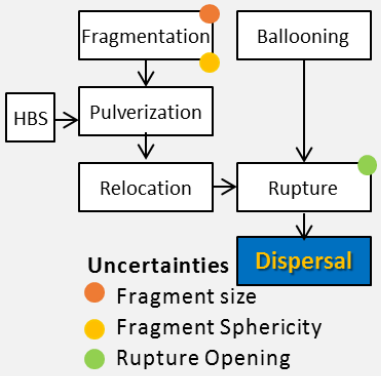
Thermal flux

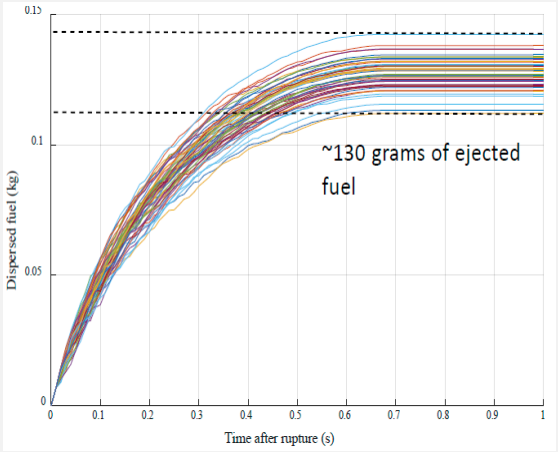
Fast flux

STARS/Fuel Behaviour Samples 2016

LOCA Fuel Behaviour

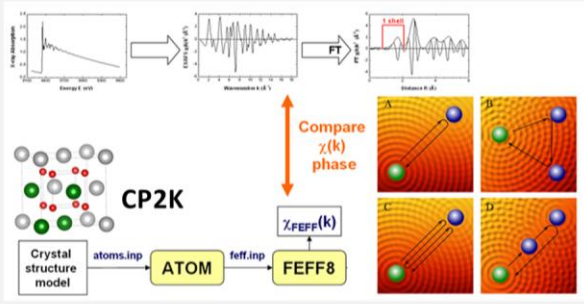
Development of Fuel Dispersal Model with coupled mass flow rate equations for solid-gas discharge



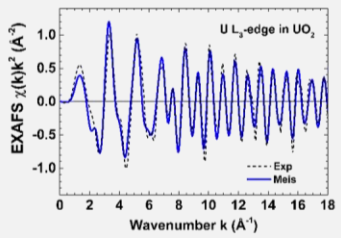


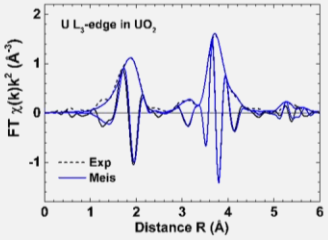
Multi-Scale Fuel Modelling

Validation of XAFS spectra simulation for UO_2



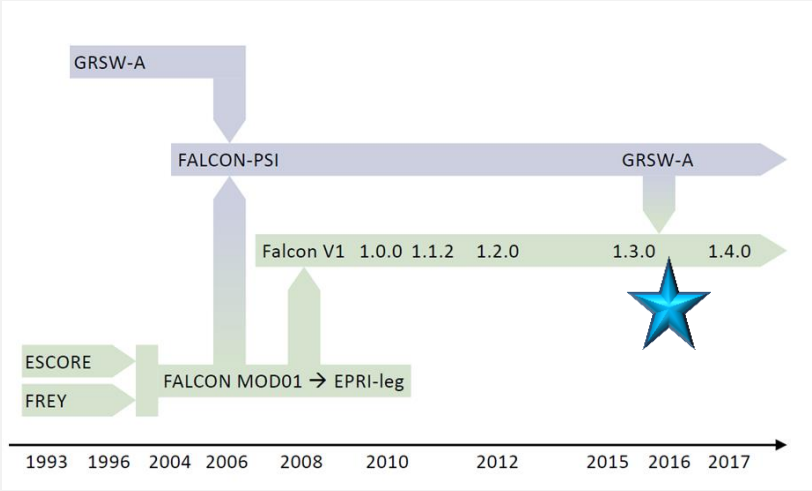
Collaboration:
- LRS
- AHL
- LNM
- ISSP (Latvia)





FALCON Code Development (Coll. EPRI/PSI/ANATECH/Objexx)

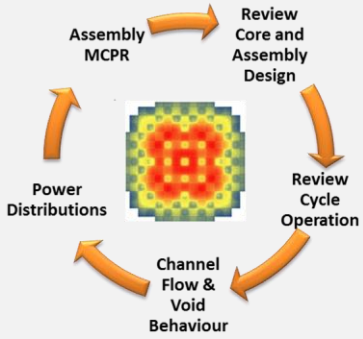
- PSI/GRSW-A model integration close to completion
- Plan for official release with Falcon V.1.4 (2017)
- Preliminary V&V completed:
  (basic regression, KKL_AEB rod, FUMEX, SuperRamps)
- Next Phase: Analysis of full V&V GRSW-A matrix



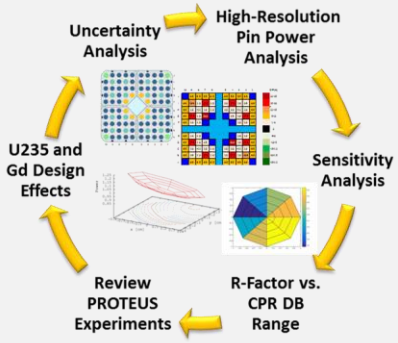
Dryout in modern BWR Fuel Designs

Hypothesis Testing and Cause Analysis with Multi-Physics Studies

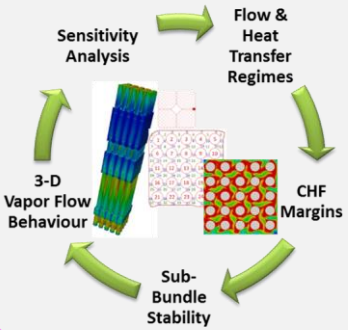
CORE ANALYSIS
CMSYS (CASMO/SIMULATE)



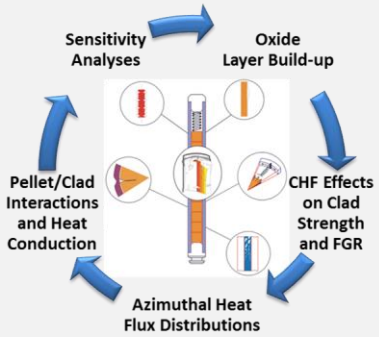
REACTOR PHYSICS
CASMO5 / MCNP6



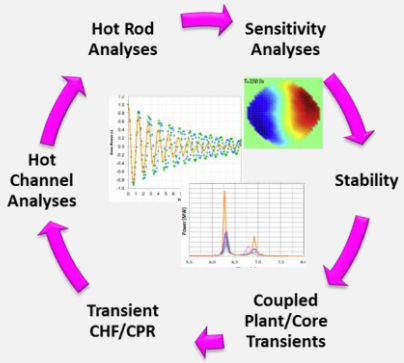
THERMAL-HYDRAULICS
COBRA-TF / TRACE / CFD



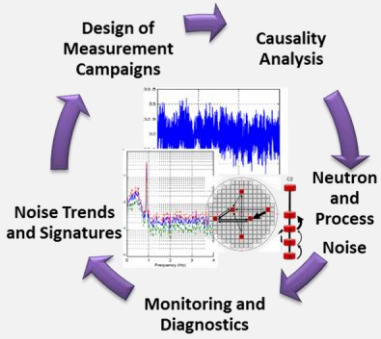
FUEL BEHAVIOUR
FALCON/GRSW-A



STABILITY AND TRANSIENTS
S3K / TRACE-S3K

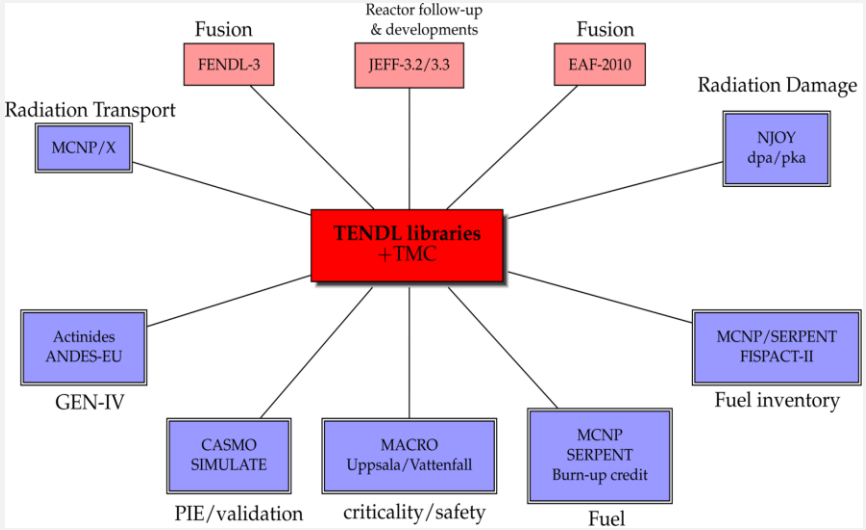


SIGNAL ANALYSIS
PSI TSA Methodology



Nuclear Data - TENDL Library

- "**T**ALYS **E**valuated **N**uclear **D**ata **L**ibrary"
- *Combines theoretical calculations and measurements into a single library for general applications,*
- *Launched in 2008 with releases every year*
- **Development now at LRS/STARS** (tendl.web.psi.ch/home.html)



Partnership with US.DOE/CASL

- VERA Platform for High-Fidelity High-Resolution Multi-Physics LWR Core Simulations
  - Full Core Sub-Pin Resolved 3-D Neutron Transport
  - Full Core Sub-Channel resolved 3-D thermal-hydraulics
  - Full Core pin resolved 2-D/3-D thermo-mechanics
  - Coupling to chemistry and structural material modules

Prediction of CRUD Build-up and Power Shift with VERA

http://www.casl.gov

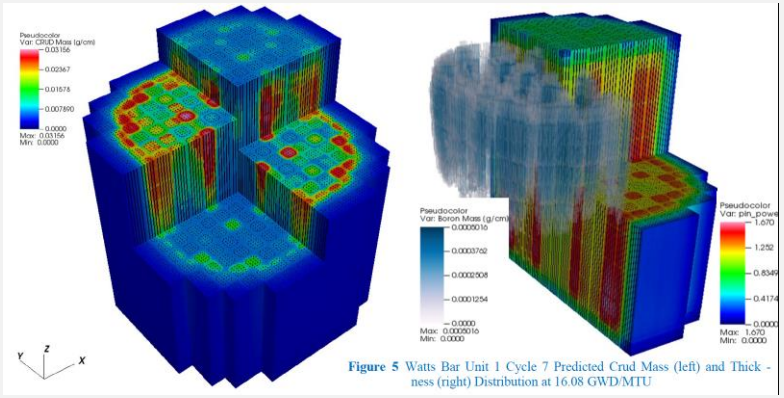


Figure 5 Watts Bar Unit 1 Cycle 7 Predicted Crud Mass (left) and Thick - ness (right) Distribution at 16.08 GWD/MTU

- LRS/STARS as first international associated partner
- Collaboration on further development and validation of VERA for Swiss applications
  - Experiments, fuel/core designs, reactor operation
  - Steady-State/Transient analyses
  - Advanced Audit Tool for BWR Safety Analyses

MSR Neutronics & fuel cycle:

Tools: EQL0D & EQL3D equilibrium cycle routines based on SERPENT and ERANOS codes.

Aim: fuel cycle safety and performance characteristics.

MSR safety evaluation:

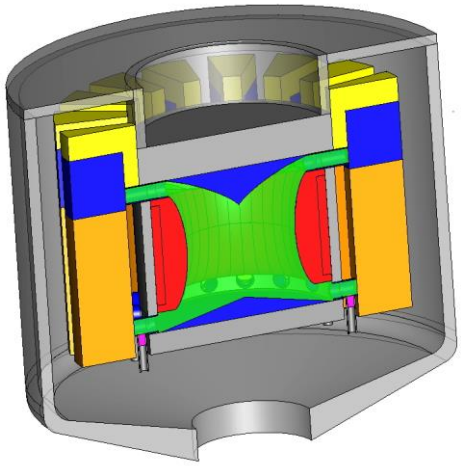
Tools: TRACE-PARCS, TRACE-point-kinetics, GeN-Foam (Open-FOAM).

Validation: based on available reactor data from MSRE (ORNL) and. MSFR benchmark.

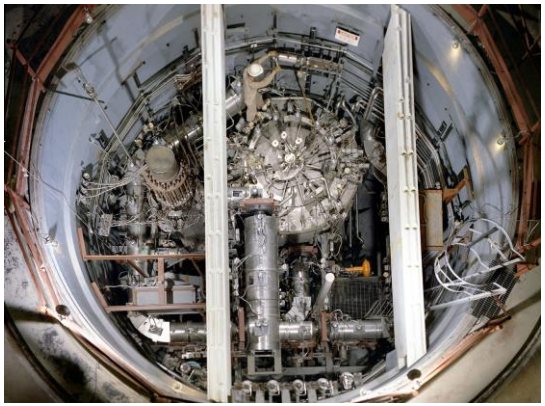
MSR design studies:

Aim: waste minimization and high fuel utilization.

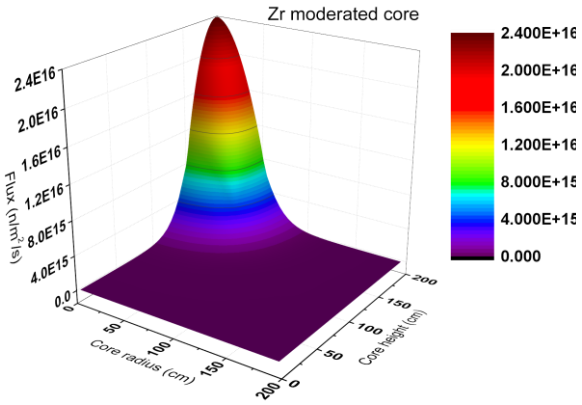
Cases: Moderation level, hybrid spectrum core, refueling strategies, reprocessing strategies, breed-and-burn mode.



Molten Salt Fast Reactor Concept



Molten Salt Reactor Experiment



Hybrid spectrum MSR

Lead Coordinator of Major European SFR Project Proposal for H2020

ESFR-SMART

European Sodium Fast Reactor Safety Measures Assessment and Research Tools

proposal submitted to H2020 framework program; budget ~10 MEUR (5 MEUR from EU)

Coordinator-- Dr. K. Mikityuk (PSI)

PSI /CH	AFW /UK	AREVA /FR	CEA /FR	CIEMAT /SP	CHALMERS /SW	
EDF /FR	ENEA /IT	GRS /DE	HZDR /DE	IPUL /LV	IRSN /FR	
JRC /EU	KIT /DE	LEMTA /FR	LGI /BE	NNL /UK	UCAM /UK	UPM /SP

Use legacy experiments
-- SFR operational data (SPX1/CEA)
-- sodium boiling (KNS-37/KIT)
-- molten fuel ejection (CABRI/IRSN)
-- molten pool behaviour (SCARABEE/IRSN)
-- aerosols in containment (FAUST/KIT)
-- aerosols in containment (NALA/KIT)
-- aerosols from sodium fire (FANAL/CEA)

Calibrate and validate codes

Assess new safety measures for ESFR
-- low void effect core design
-- corium discharge tubes
-- passive decay heat removal
-- large-inertia and passive pumps
-- improved natural circulation, *etc*

Conduct new experiments
-- MOX fuel properties (CEA → ITU)
-- forced-to-natural convection (KASOLA/KIT)
-- sodium boiling (SOLTEC/KIT)
-- chugging boiling (CHUG/PSI)
-- corium jet/catcher (JOLO/LEMTA)
-- corium/catcher (LIVE/KIT)
-- corium jet/concrete (MOCKA/KIT)

Develop new instrumentations
-- eddy current flowmeter (HZDR)

Establish new networks
-- students mobility grants to work at EU Na facilities
-- workshops and summer school

Demonstrate new reactor concept features
-- iso-breeder (produces fissile fuel for own needs)
-- safer than LWRs (no core meltdown in Fukushima-like accident)
-- safer than SFRs (low void effect)

Schwerpunkte 2017

ERP

- **Remove fuel from PROTEUS building** and transfer facility dismantling to PSI/LOG
- Launch **"PROTEUS Legacy Project"** for knowledge preservation and validation center
- Perform **spent fuel neutron source measurements** at HotLab
- Conduct **new experiments at CROCUS** (e.g. VOID, Colibri)

STARS

- Methodologies for **CFD Fuel Assembly Flow Analyses**
- **H-Uptake modelling for fuel behavior** during operation and towards dry storage (LNM Coll.)
- **Multi-physics research on BWR dryout** and new **high resolution simulation** methods (CASL)
- **Spent fuel analyses** methods and new ILL **measurement of Nd147 cross-section** (LRC Coll.)
- Development of **advanced PSI Fluence/Activation scheme** for decommissioning (GFA coll.)

FAST

- Development of MRS **burnup calculation method for moving fuel** (CROSS)
- Launch EU/H2020 **ESFR-SMART project**
- Consolidate **nuclear data uncertainty** methods in collaboration with STARS

PAUL SCHERRER INSTITUT

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Thank You !