PAUL SCHERRER INSTITUT

Wir schaffen Wissen – heute für morgen

Paul Scherrer Institut

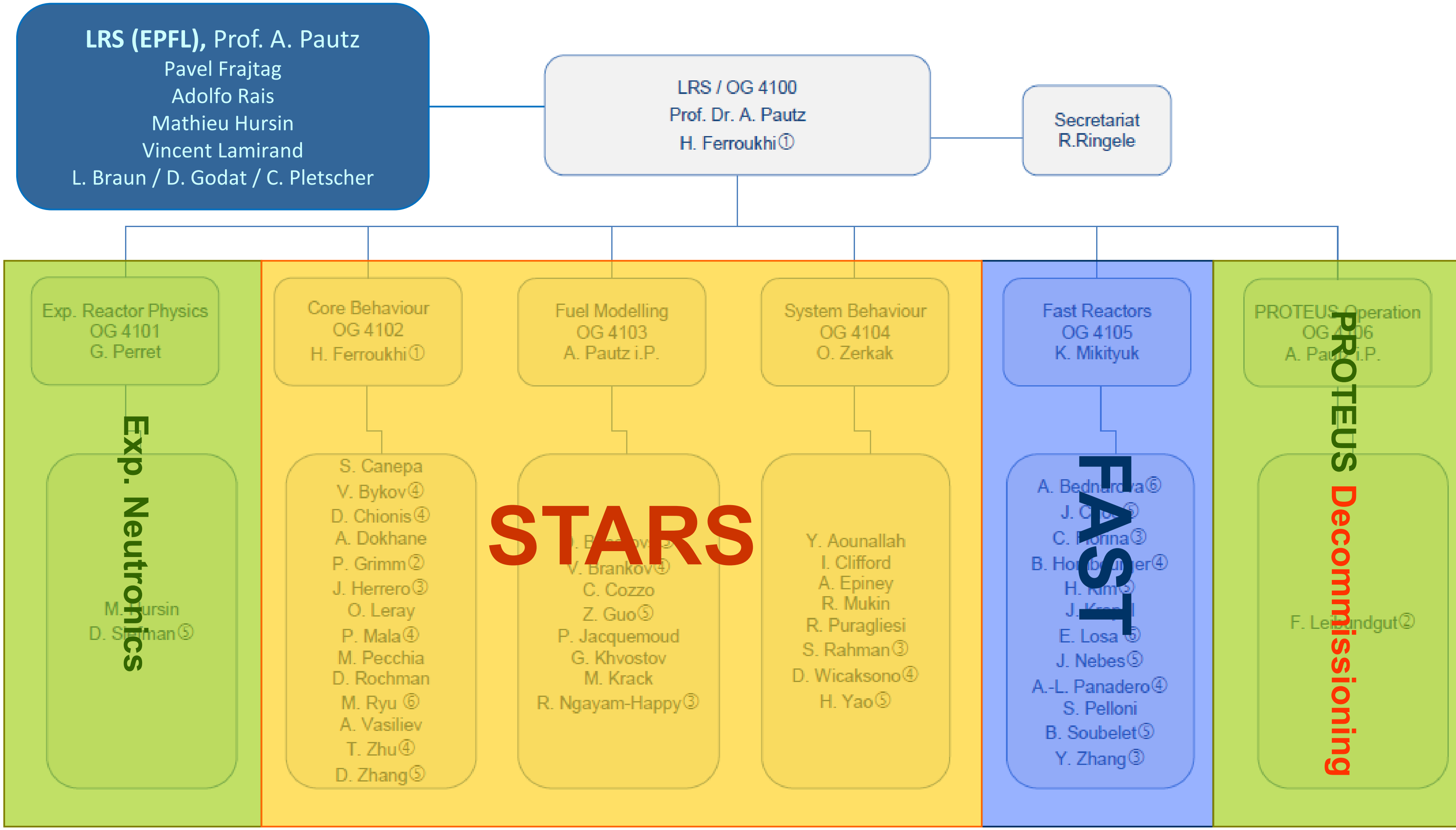
H. Ferroukhi (stv. LL)

LRS - Laboratorium für Reaktorphysik und Systemverhalten

Organization, Mission, Strategic Goals and Projects Highlights 2014

NES "Kompetenzen und Highlights", March 18, 2015, PSI

Organization (as of February 2015)



5 Research **Groups** + 1 Facility Group ⇔ **3** Research **Projects** + 1 Decommissioning Project

40 Staff ⇔ 60 % Scientists and 40 % [Post-Docs & PhDs]

+ 11 Master Students & Praktikants

Mission

- Develop and qualify simulation methodologies for integrated safety assessments for current and advanced reactors
- Act as a scientific support and TSO unit for national and international partners for the safe operation of current and advanced Nuclear Power Plants
- Design, carry out and interpret reactor experiments and fuel characterization measurements to validate reactor physics codes and improve nuclear data
- Perform conceptual design studies on innovative reactors for waste reduction and incineration as well as safety enhancement and risk minimization
- Contribute to the education of the future generation of nuclear engineers and scientists, with focus on reactor physics, integrated reactor analysis and reactor experiments

Strategic Goals

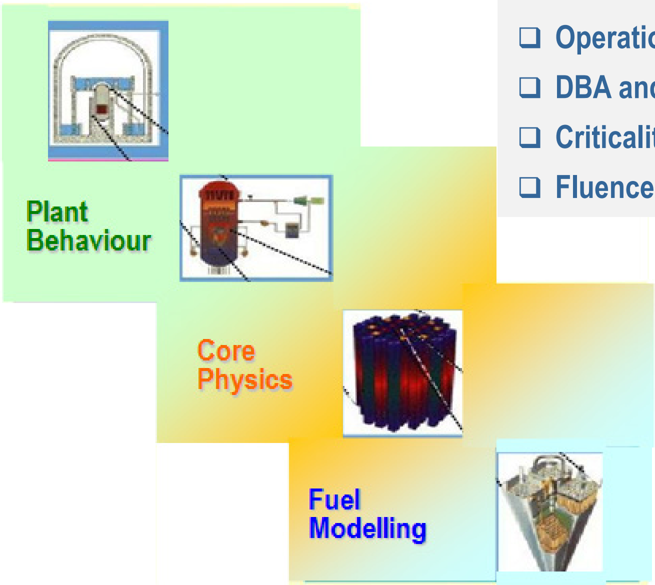
- Build and maintain a High-Fidelity simulation platform for LWR cores (Higher-Order Deterministic Neutron Transport, Full-Core Subchannel Analysis, 3D Thermal-Mechanical Fuel Modelling)
- Development of computational tools (including Open Source CFD) for Uranium and Thorium Closed Fuel Cycle and Safety Analysis of SFR and MSR
- Consolidation of an Integrated Methodology for the Treatment of Uncertainties and Sensitivities in all Modelling Areas
- Build up Knowledge in Component Activation, Storage and Transport Safety, and the relevant Nuclear Safety Regulations for Decommissioning of Nuclear Installations
- Advanced fuel modelling during base irradiation and transients (LOCA, RIA, PC(M)I)
- Establish an experimental "home base" at CROCUS, foster cooperation with the Hot Laboratory at PSI, and take benefit of the huge PROTEUS experimental data base
- Expansion of the Teaching Activities of LRS within the Nuclear Master Program of EPFL/ETHZ, but also establishing new educational schemes for non-university partners

LRS Highlights

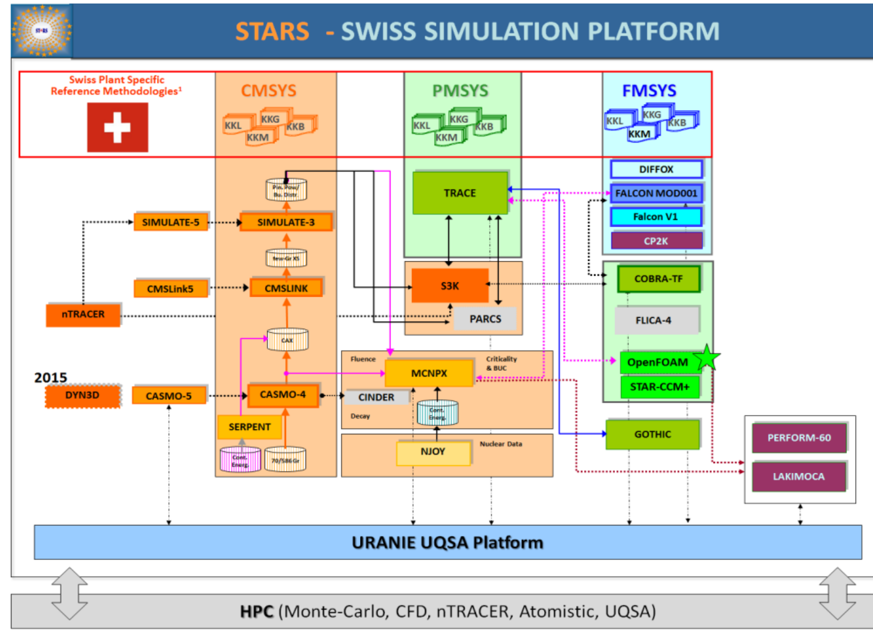
STARS

Multi-Disciplinary LWR Safety Analyses

- Normal Operation
- Operational Transients
- DBA and Beyond DBA
- Criticality Safety
- Fluence, Dosimetry



Multi-Physics Multi-Scale Code System



Multi-Scope TSO Mission

SCIENTIFIC SUPPORT

- **Maintain Reference Validated Models**
  for all Swiss Reactors and Cycles
- **Regulatory Support** (ENSI, STUK EPR)
  e.g. Fuel/Core Reload Licensing,
  Period Safety Reviews, New Reactor Designs
- **Utility Support** (National NPPs)
  e.g. advanced applications and R&D studies
  for operational, ageing and back-end

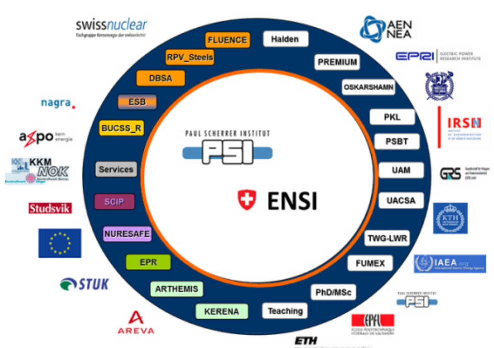
"Act as leading **national TSO Unit** for LWR safety analysis in Switzerland"

RESEARCH AND DEVELOPMENT

- **Code Assessment and Validation**
  of state-of-the-art simulation codes
- **Multi-Physics** Coupled Methodologies
  for integrated safety simulations
- **Multi-Scale** Numerical Schemes
  for high-fidelity Reference solutions
- **Uncertainty and Sensitivity** Analysis
  for best-estimate safety assessments
- **Education and Teaching**
  for academic projects and know-ho transfer

"Conduct R&D aimed at **Best-Estimate Integrated LWR Safety Analyses**"

Multi-Partner Program



ISO-9001

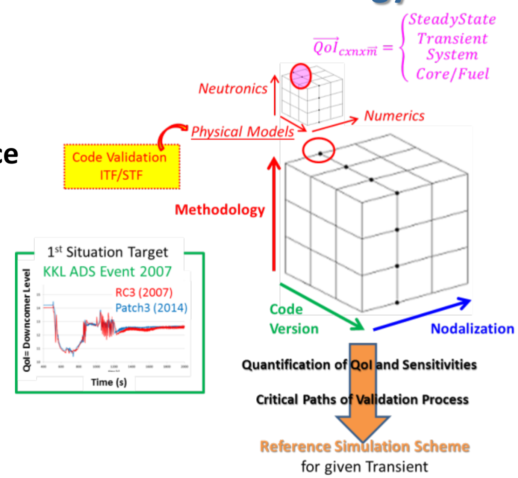
ETSON
EUROPEAN TECHNICAL SAFETY ORGANISATIONS NETWORK

STARS — RND Samples 2014 – Plant Behaviour

TRACE Modelling of the Swiss Reactors

Research towards Consolidated V&V Strategy

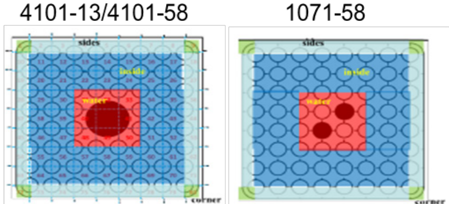
Systematic Tracking of QoIs Evolution over M-Dimensional Space <u>for each Transient</u>



Sub-Channel Modelling with COBRA-TF

Validation for OECD/NEA BFBT Void/CHF Experiments

BFBT
4101-13/4101-58 — 1071-58

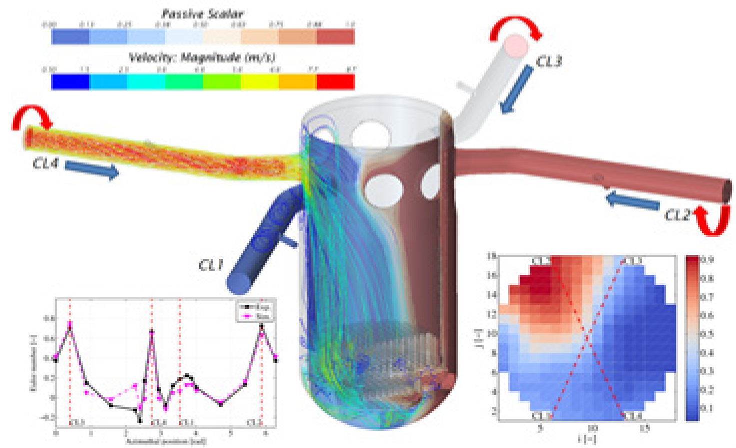


Coverage Ratios (Fraction of C/E within σ_{exp})

test	corner	sides	inside	water	average	max
4101-13	0.11	0.99	1.00	0.22	0.99	0.99
1071-58	0.79	0.99	0.03	0.00	0.31	0.99
4101-58	0.24	1.00	0.45	0.00	0.51	1.00

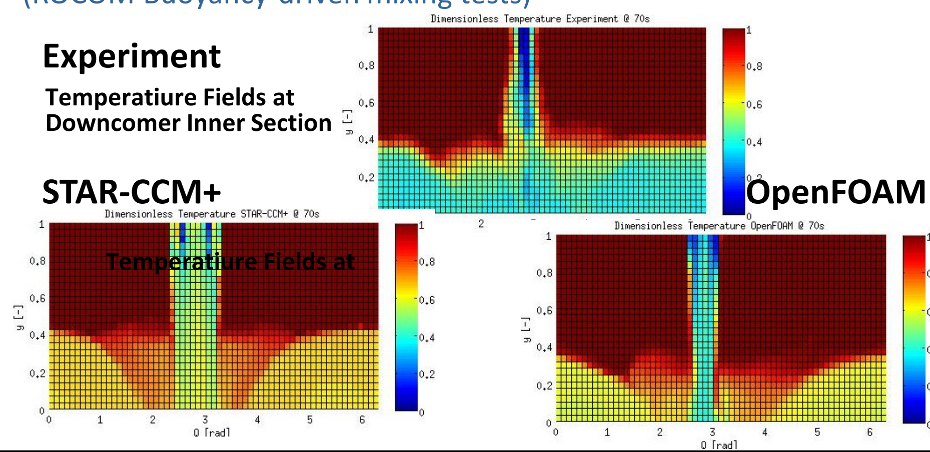
CFD Modelling for Multi-Physics Safety

Validation of STAR-CCM+ for MSLB Applications (Juliette Coolant Mixing Experiments)



First Assessment of OpenFOAM for LWR Applications

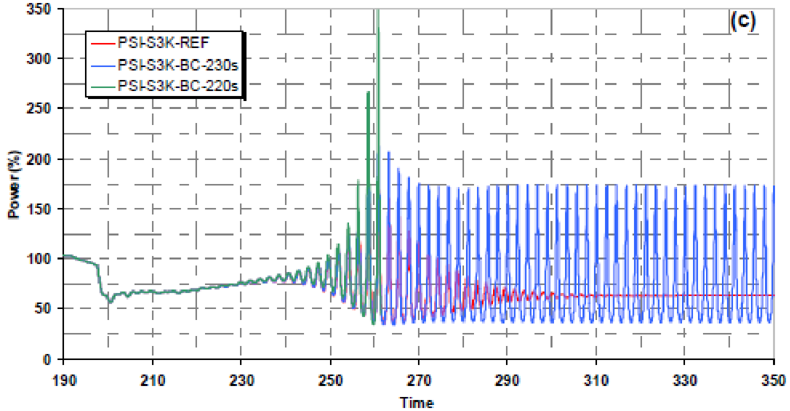
(ROCOM Buoyancy-driven mixing tests)



STARS — RND Samples 2014 – Core Physics

Reactor Dynamics and BWR Stability

Validation of SIMULATE-3K and TRACE/S3K
(Oskarshamn-2 Feedwater Transient and Stability Event))

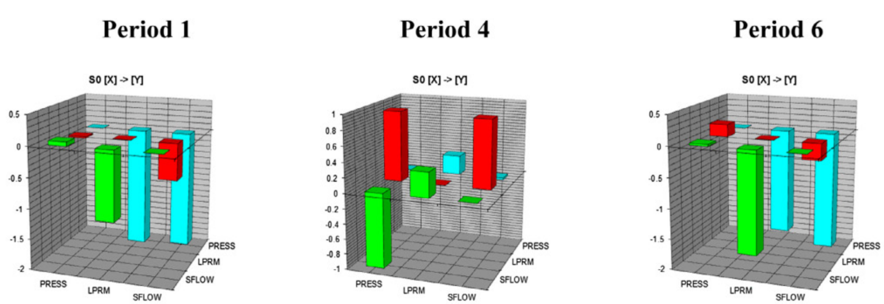


Signal and Noise-Analysis Methods

Development of Continuous-Structural ARMA Method for Plant Diagnostics and Causality Analysis

Application to KKL C20 Start-Up Stability Event

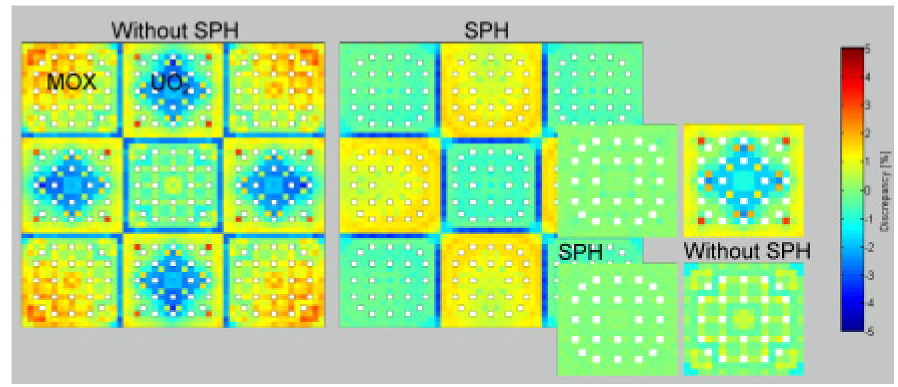
Steam Flow → Neutron Flux Causality indicated by CSARMA



Full-Core Pin-by-Pin 3-D Transport

Development of CASMO/SPH Algorithm for Pin-Cell Homogenized 3-D Solvers

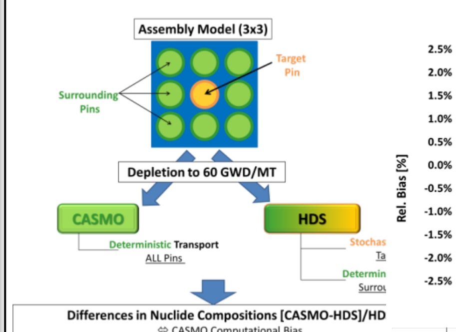
Comparison CASMO vs nTRACER w/o SPH for UO2/MOX Cluster

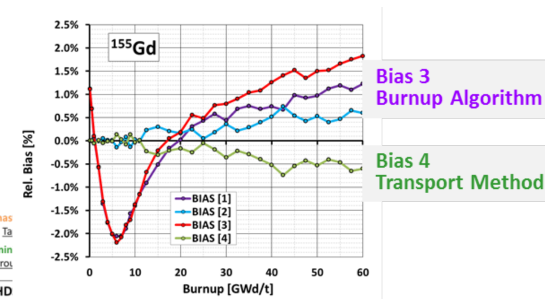


Hybrid Stochastic/Deterministic Methods

Development of Coupled CASMO/Serpent Depletion Scheme

Evaluation of CASMO Numerical Biases in SNF Isotopics

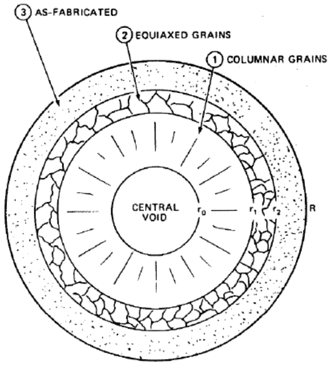


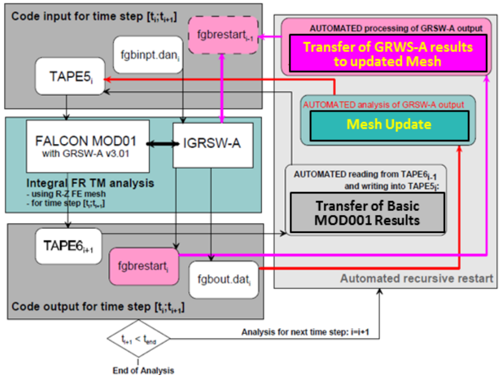


RND Samples 2014 – Fuel Modelling

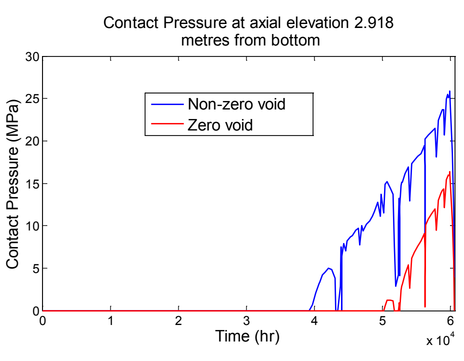
Advanced Fuel Behaviour Models for FALCON

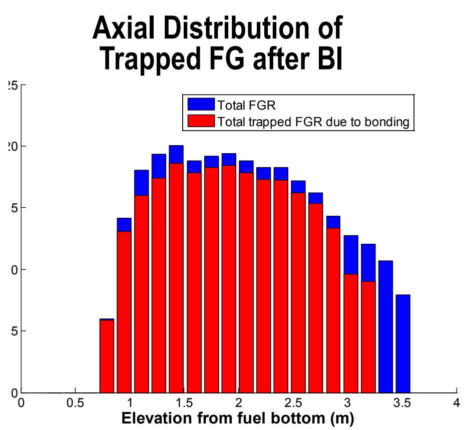
New methodology to account for "Fuel Restructuring" during LWR Fuel Base Irradiation (BI) at very High T





Development of BWR "Fission Gas Trapping Model" due to Pellet-Clad Bonding

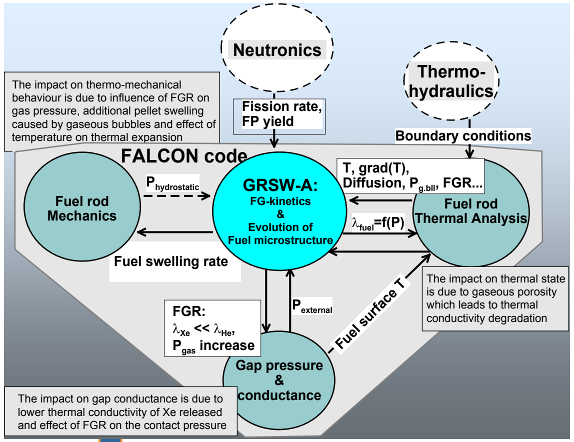


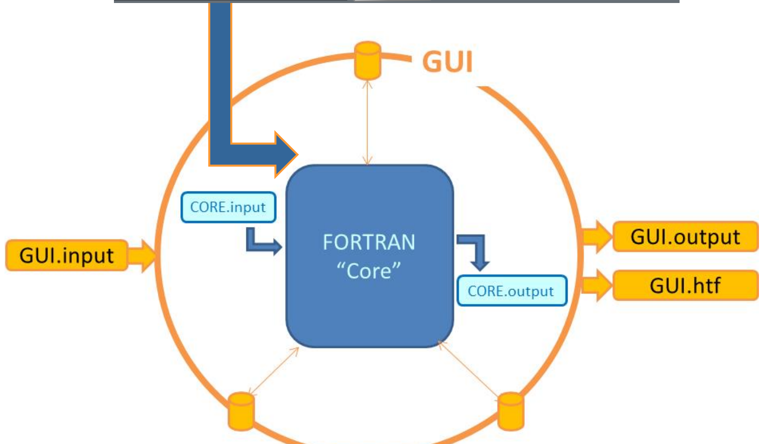


Falcon V1 Code Development

August 2014 - LRS/STARS becomes member of EPRI Falcon Development Team

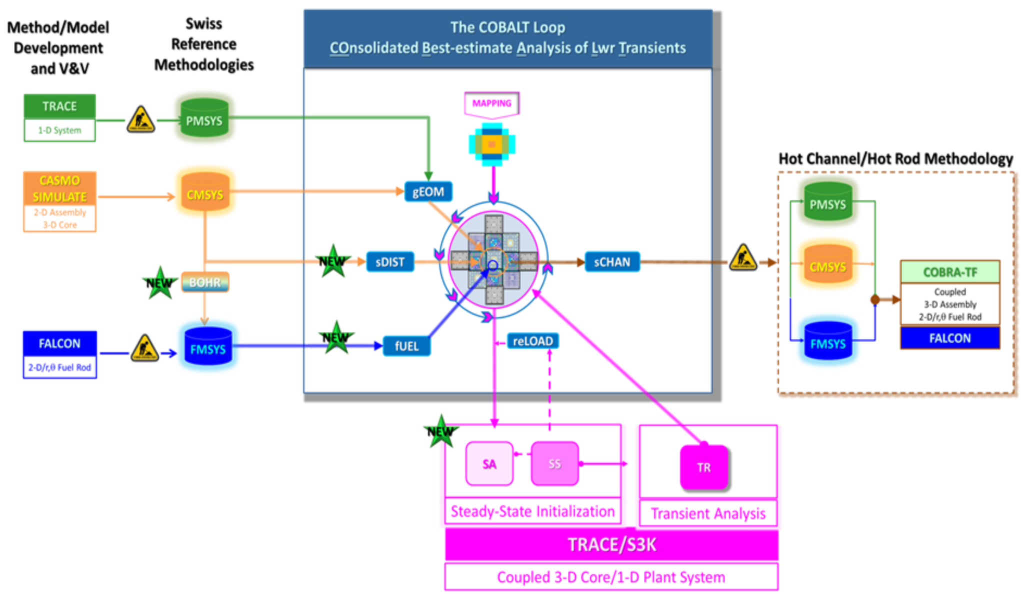
PSI Advanced Gas Release and Swelling Model (GRSW-A) integration in Falcon V1.3 Release





STARS — RND Samples 2014 – Multi-Physics

Development of the "COBALT Loop" for Coupled Plant/Core/Fuel Safety Analyses of the Swiss Reactors

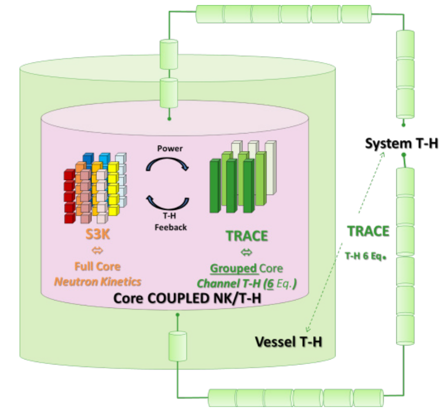


Motivation 1:
Reference **Best-Estimate** Transient Analysis Methodologies

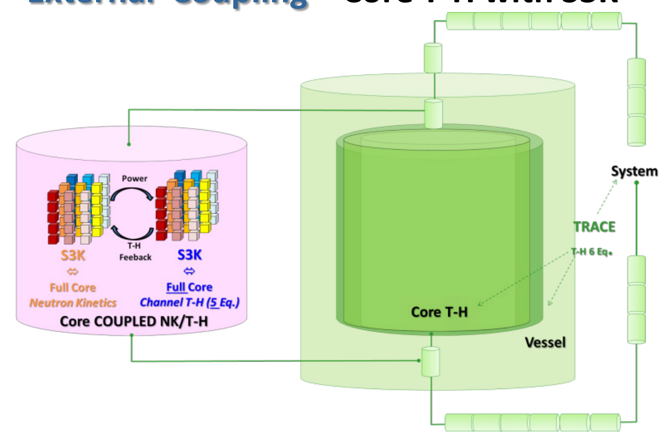
Motivation 2:
Automated and Integrated Scheme for
Multi-Physics Uncertainty Propagation

Development of new "External Coupling Scheme" for TRACE/S3K Coupled Plant/Core Analyses

Internal Coupling – All T-H with TRACE

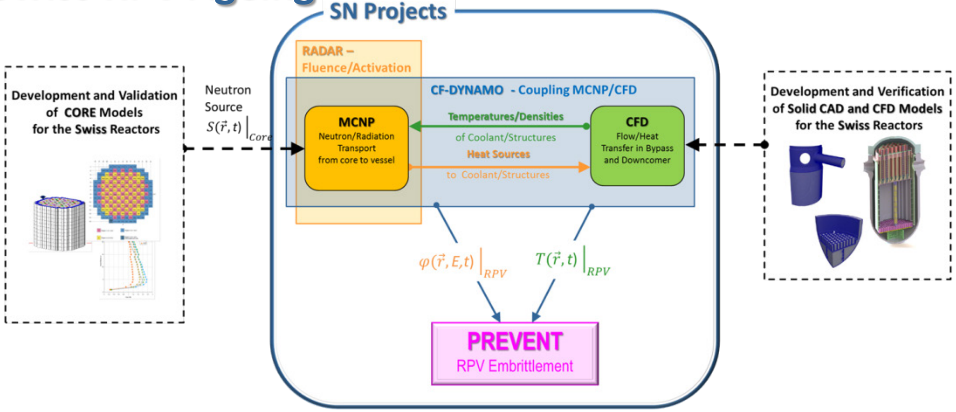


External Coupling – Core T-H with S3K



STARS — RND Samples 2014 – Multi-Physics

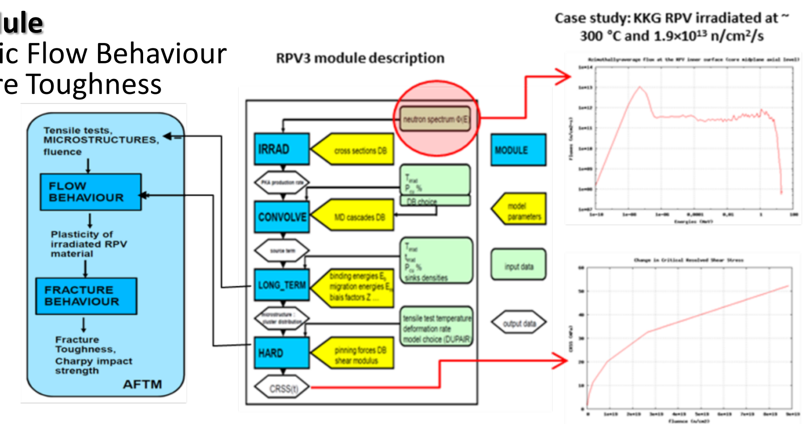
Multi-Physics Multi-Scale Integrated Methodology for Swiss RPV Ageing



Establishment of PERFORM-60 for Microscopic and Macroscopic Modelling of RPV Embrittlement

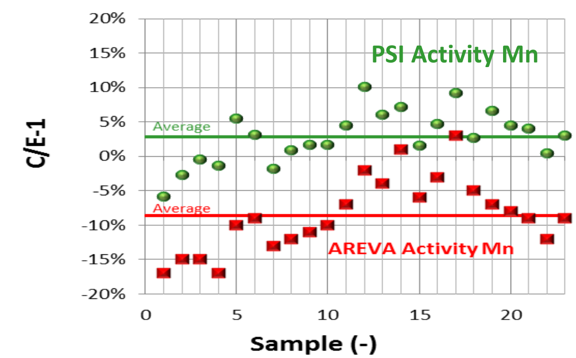
RPV3 Module – Microstructure Evolution and Estimations of ΔDBTT for Swiss Conditions

AFTM Module
Macroscopic Flow Behaviour and Fracture Toughness
Coll. LNM

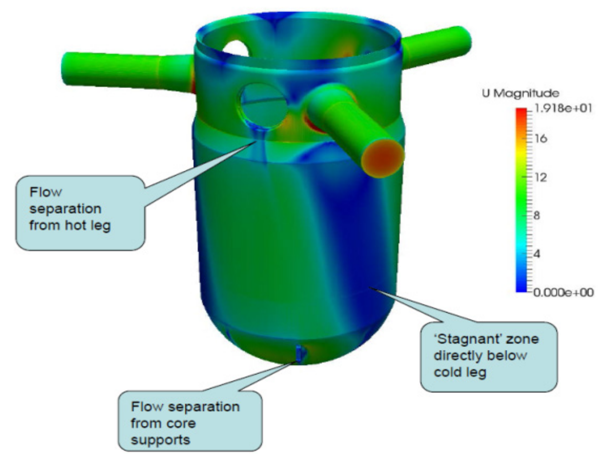


Enlarged Validation of STARS/MCNPX Fluence Scheme

KKG C27 Scrapping Tests (C vs E for Mn Activity)



Studies with CFD (OpenFOAM) of KKG Vessel Coolant Conditions



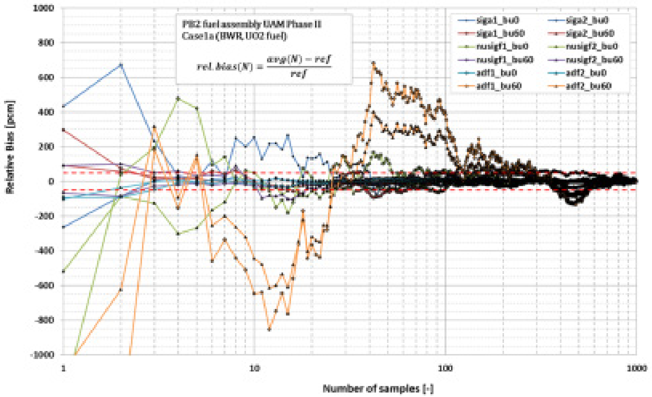
STARS — RND Samples 2014 – Uncertainty Analysis

Nuclear Data Uncertainty/Sensitivity Analysis

ND Propagation in CASMO/SIMULATE Swiss Core Analyses

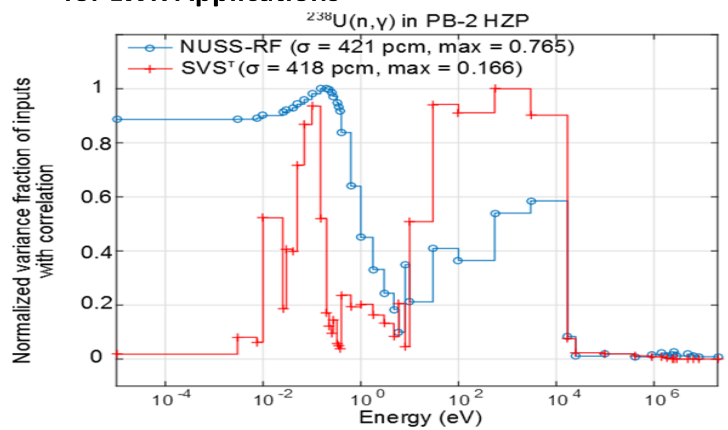
Convergence Studies for Optimal # Samples

(Main Challenge: 1 Core Sample ~ 5-10 GB Model)



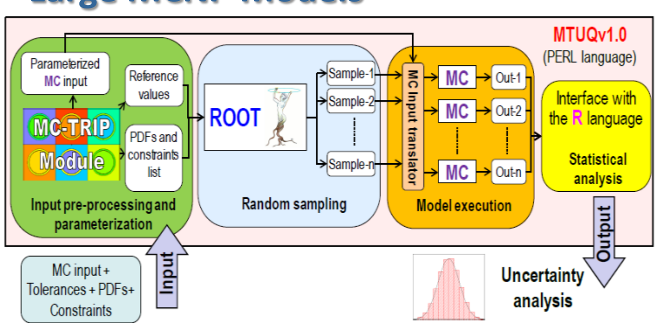
ND Propagation in MCNP Analyses

Assessment of new Global Sensitivity Analysis Method for LWR Applications



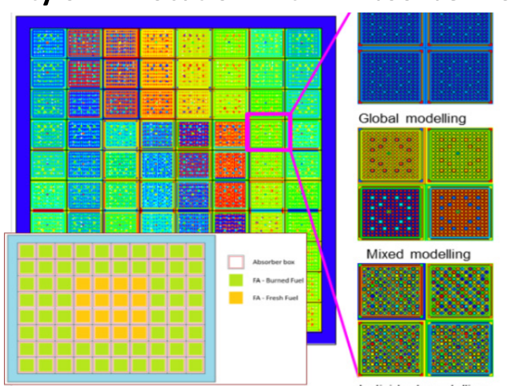
Manufacturing and Technological Uncertainty Quantification

PSI MTUQ Methodology for Arbitrary Perturbations of Large MCNP Models



Application to KKB Wet Storage Pool CSE+BUC

(Uncertainty of FA Location within Absorber Box)



Test study with an absorber box dimension:

MTUQ-Global: Kef σ=388pcm

MTUQ-Individual: Kef σ=88pcm

Convention OFAT: ΔKef =409pcm; ΔKef/SQRT(N)=46pcm

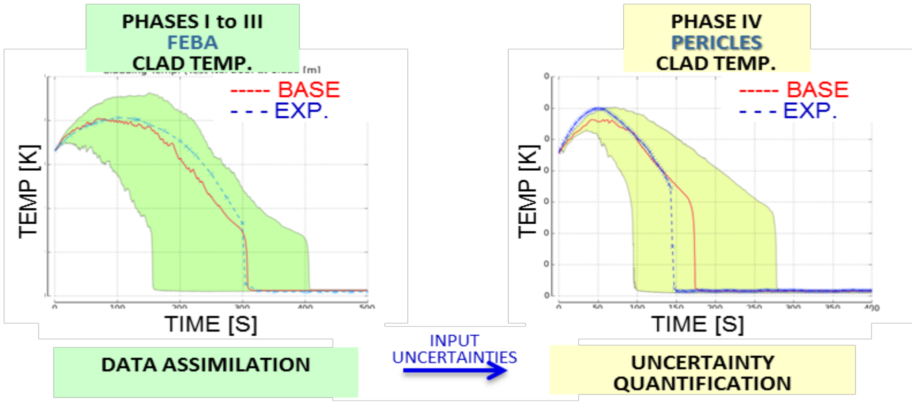
- **With conventional "global" methods (SUSA), uncertainties overestimated**
- **Low Effects of Intra-assembly Individual Perturbations**

STARS RND Samples 2014 – Uncertainty Analysis

Thermal-Hydraulic Physical Model Uncertainties

Participation to OECD/NEA/CSNI PREMIUM

(Reflood Model Uncertainties during LOCA)



- **Phases I and II:** Participants to select uncertain input parameters relevant to **core reflooding after LB-LOCA**
- **Open Phase III**: Participants to calibrate the PDFs of uncertain input parameters using **FEBA** exp. data (6 tests)
- **Blind Phase IV:** Participants to quantify output uncertainty for 6 **PERICLES** tests
- Evaluation of results based on C/E errors for PERICLES:
  Clad temperature evolutions at different elevations
  Quenching Time (Tquench)
- **PSI current methodology using TRACE code**
  Phases I & II: **Expert judgement**
  Phases III and IV: **Monte-Carlo propagation**
- PSI ranked 5th in top category: blind results "**well bounded**"
- PSI methodology being improved as part of PhD
  Multi-variate data assimilation + Bayesian framework

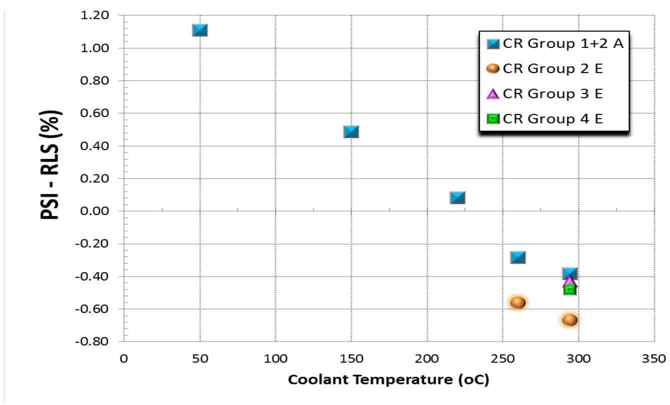
General Results PHASES III AND IV	Participant (Code)	Width of uncertainty band	Parameters (FEBA) (PERICLES)
FEBA & PERICLES data **well bounded**	IRSN (CATHARE	Very wide	3 3
	VTT (APROS)	Wide	6 6
	UNIPI (RELAP5)	Rather wide	4 4
	SJTU (RELAP5)	Wide	4 4
	PSI (TRACE)	**Wide**	**26 34**
FEBA **roughly** bounded PERICLES **not always**	Tractebel (RELAP5)	Wide to rather wide	8 8
	CVRez (RELAP5)	Average	2 2
	OKBM (KORSAR)	Rather narrow to average	2 2
FEBA Tquench **not bounded** PERICLES **not bounded**	UPC (RELAP5)	Narrow to rather narrow	3 3
	OKBM (RELAP5)	Very narrow to narrow	3 3
	CEA (CATHARE)	Rather narrow to average	3 3
	GRS (ATHLET)	Wide	6 8
	Bel V (CATHARE)	Very narrow to average	3 3
FEBA **not bounded** PERICLES **not bounded**	KAERI (COBRA)	Very narrow to narrow	4 4
	KINS (MARS-KS)	Very narrow	2 2

STARS Scientific Support 2014

Core Reload Licensing

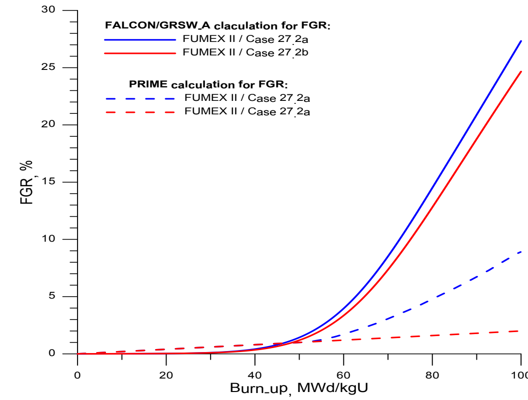
1st Time "Blind-Mode" Verification for ALL Reactors

Comparison PSI/Vendor Results for KKG Cycle 36 Critical Boron



Code Licensing

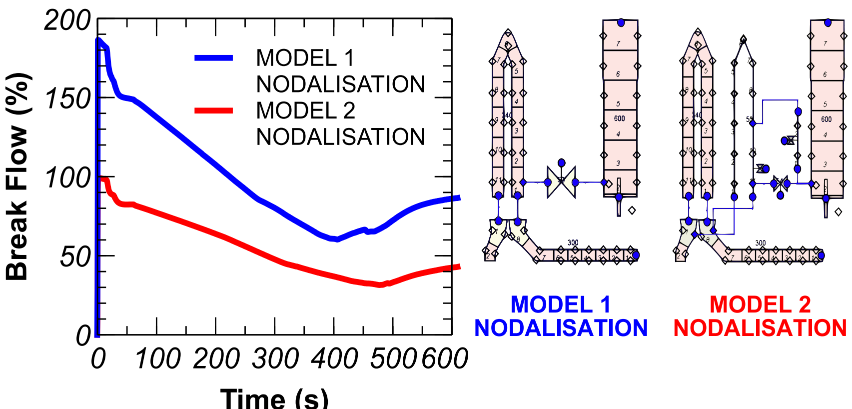
Review of KKM PRIME Fuel Performance Code with Benchmarking against Falcon/GRSW-A



Periodic Safety Reviews

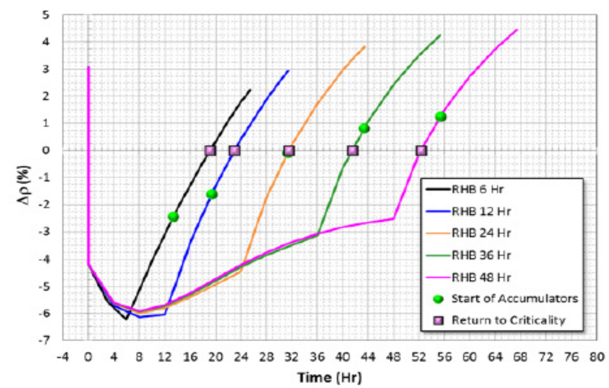
TRACE Modelling and Analyses of KKG SGTR Scenarios

Effect of Wall Fraction through Ruptured Tube on Releases



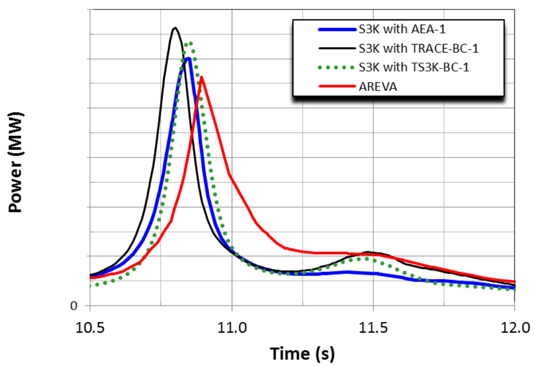
SAM Procedures

SIMULATE-3 Evaluation of Return-to-Criticality during Depressurization for KKG Cycle 36

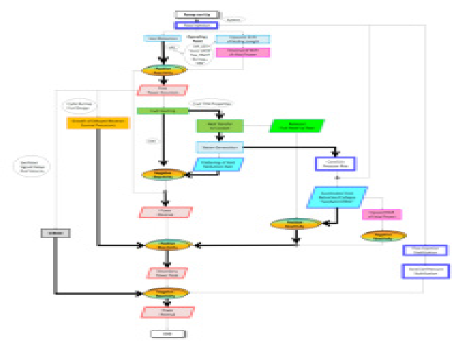


Plant Modernization – Multi-Physics Analysis of KKL Fast Pump-Run-Up Transients

Comparison
PSI/S3K vs AREVA/S-Relap/RAMONA

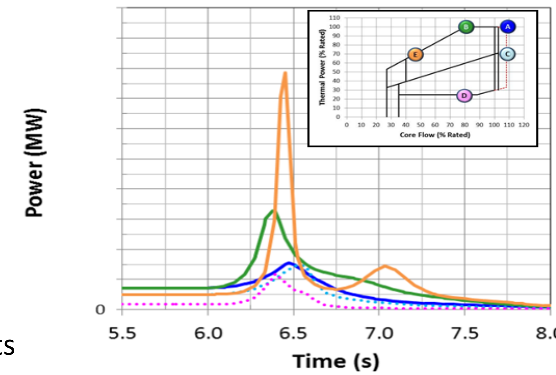


In-depth Study of
Transient Phenomenology



Very tight and Fast NK/T-H Dynamical effects

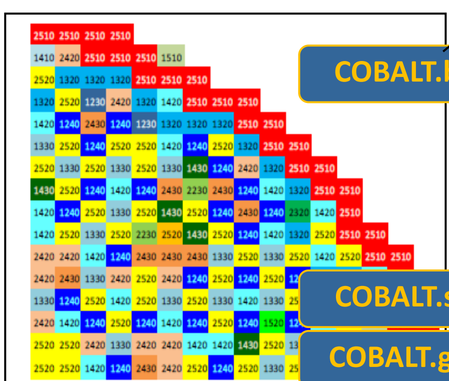
PSI t Evaluation of
Transient Response in
Entire KKL Operating Domain



Fuel Safety Criteria – Core-Wide Estimates of Fuel Rupture/Dispersal (Coll. ENSI/NRC/PSI)

Development of "COBALT Loop" Modules for BWR Multi-Physics "FULL CORE LOCA" Analyses

KKC Cycle 30 – Assembly Bins

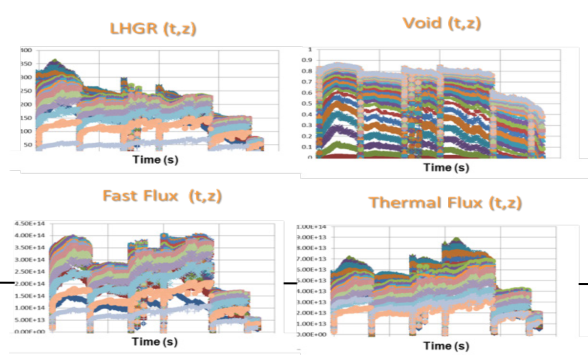


COBALT.bohr

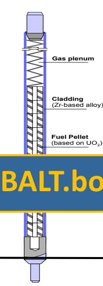
COBALT.sdist

COBALT.geom

Rod-by-Rod SIMULATE-3
Reconstructed Bundle Operating History

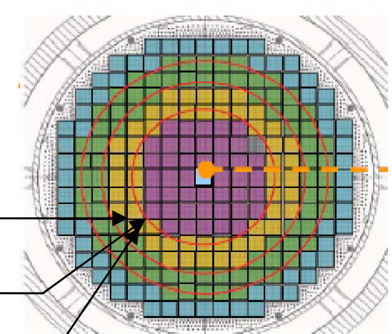


FALCON/GRSW-A
Base Irradiation



COBALT.bohr

TRACE System +
Full Core Model



STARS — Education 2014

Post-Docs

- **Criticality Safety of Spent Nuclear Fuel Geological Repositories** - NAGRA Collaboration
- **Deterministic (TRACE) / Probabilistic Dynamics** – LEA Collaboration
- **Physics-based Modelling of RPV embrittlement** –SN/ LNM collaboration
- **Atomistic modelling of Chromium doped fuel** – Sciex Program / LNM Collaboration

PhDs

- **Nuclear Data Uncertainty Propagation in MCNP Calculations** (Compl. March 2015)
- **Physical Model Uncertainties in Thermal-Hydraulics Codes** (Feb. 2013)
- **Fuel Fragmentation, Relocation and Dispersal** during LWR LOCAs (March. 2013)
- **Methodologies for Pin-Cell Homogenization** in Next Generation Reactor Core Simulators (August 2013)
- **Development of High Fidelity Depletion Solver for Spent Fuel Characterization (Oct. 2014)**
- **Advanced Methodologies for PWR Neutron Noise Modelling (Nov. 2014)**

SNF Proposals (for new Post-Docs/Phds)

- **Derivation and Assessment of CFD Anisotropic URANS Closure Models** (Submitted October 2014)
- **Nuclear Data Enhancements via Simulation-Experimental Studies (under preparation)**

Master Projects

- **Batch 2013-2014 – Realization of 4 Master Projects**
  - Validation of PSI Fluence Scheme for KKG Axial Gradient Probes
  - Hybrid Deterministic/Stochastic Transport Depletion Scheme
  - Development and Assessment of Monte-Carlo Codes for Nuclear Data Homogenization
  - Assessment of Open Source CFD Code for OECD/NEA PKL Turbulent Flow Experiments
- **Batch 2014-2015 – Start of 3 Master Projects**
  - **Direct generation of TRACE plant system models using CAD geometry**
  - **Basement of nTRACER for direct-core PWR cycle depletion calculations**
  - **Atomistic simulations of irradiation damage in doped fuel**

Teaching (EPFL/ETHZ)

- **Special Topics in Reactor Physics**
- **Nuclear Computations Laboratory Course**

LRS Highlights

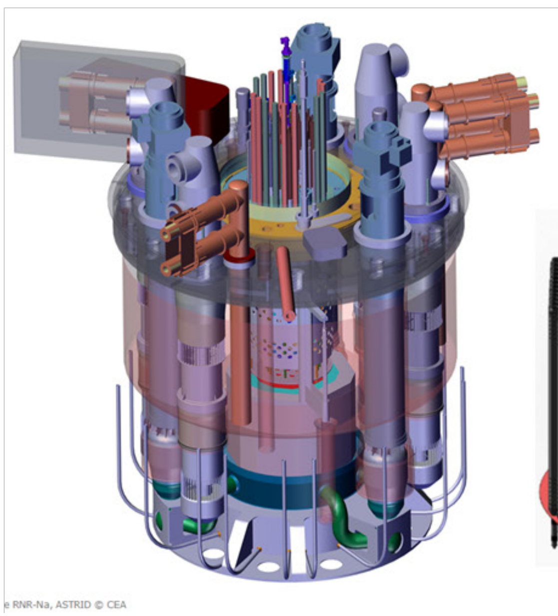
FAST

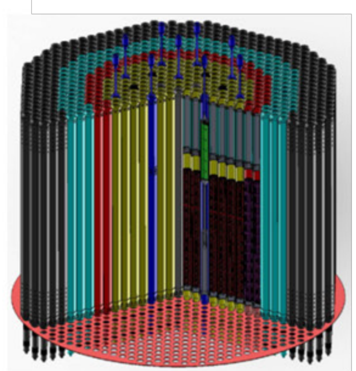
FAST reactors group @ PSI

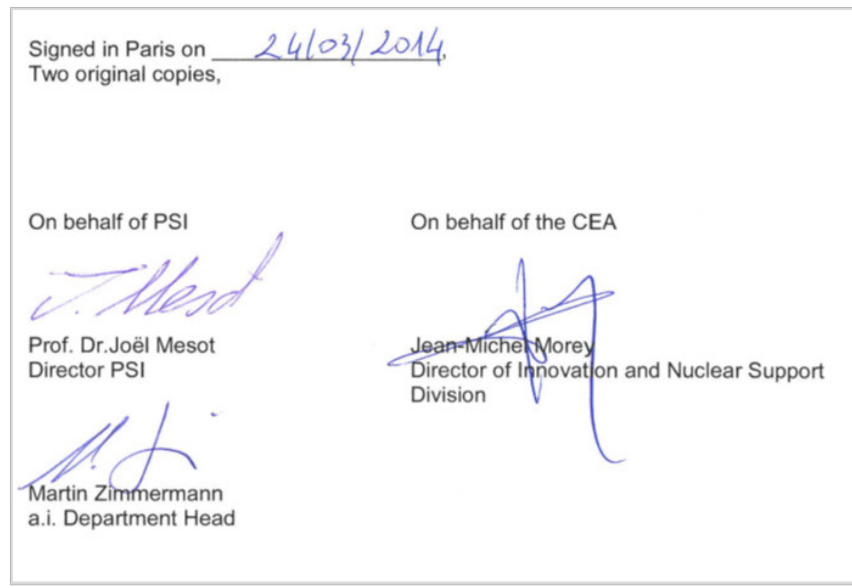
Goals	• Evaluation of performance and safety of Gen-IV SFR • Search for design solutions for Gen-IV MSR • Representation of Switzerland internationally • Teaching
International	• Generation IV International Forum; • OECD WP on International Nuclear Data Evaluation; • IAEA Technical Working Group on Fast Reactors
Teaching	• EPFL / ETHZ NE MS: lectures for compulsory course • 5 PhD and 13 MS completed • 2 PhD and 4 MS on-going
Publications	• 52 peer-reviewed journal papers • 103 conference papers • 1 international patent

- Collaboration agreement with CEA on R&D and technological development in support to the conceptual and basic design for the ASTRID prototype was signed in March 2014

- PhD co-financed by CEA started in October 2014 on static and transient neutronic, TH and TM modeling of core and primary system of ASTRID.







Signed in Paris on 24/03/2014,
Two original copies,

On behalf of PSI

Prof. Dr.Joël Mesot
Director PSI

Martin Zimmermann
a.i. Department Head

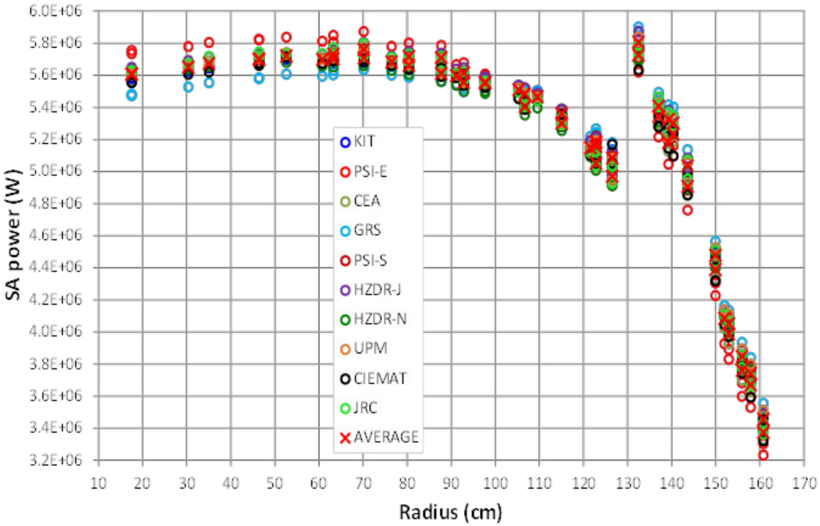
On behalf of the CEA

Jean-Michel Morey
Director of Innovation and Nuclear Support Division

- Sep 2013 – Sep 2014 was the first year of ESNII+ EURATOM project ("Preparing ESNII for Horizon 2020").
- We coordinated the work of WP6 "Core safety" with 16 European organizations and in particular a neutronic benchmark.
- The first result will be presented at the ICAPP conference in Nice.

ESNII+ meeting at PSI

Radial power distribution in the ASTRID core



Experimental Breeder Reactor-II (EBR-II) designed, built and operated by Argonne National Laboratory in Idaho (1961-1994).

In 1986 pumps and all active safety systems were intentionally turned off with the reactor at full power. The reactor shut itself down.

IAEA Coordinated Research Project focuses on analysis of *reactor data* on

- Core static neutronics
- Protected Loss of Flow (SHRT-17)
- Unprotected Loss of Flow (SHRT-45R)

1D transient analysis revealed deficiencies and 3D analysis started.

The first result will be presented at the ICAPP conference in Nice.

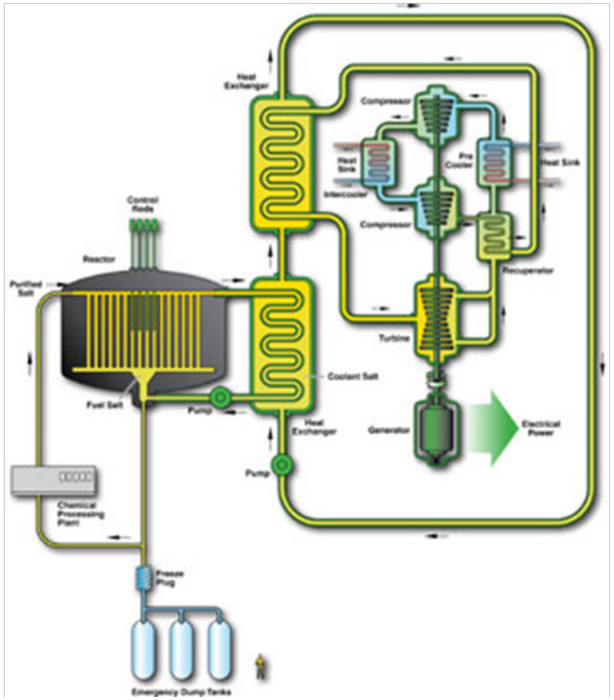
The MSR Task Force was launched in 2014 at the level of NES.

Dr. Krepel from the FAST group is a coordinator and a responsible for system design.

The activity is ongoing and the foreseen project should be generally dedicated to the MSR safety.

Focus on selected design-independent features of MSR (all safety relevant):

- salt phase changes,
- off-gas system layout,
- volumetrically heated liquids, etc.



SAMOFAR: framework for the new project

- Title: A Paradigm Shift in Nuclear Reactor Safety with the Molten Salt Fast Reactor
- Prepared for the first call of Horizon2020 (NFRP 3: Innovative approaches to reactor safety.
- 11 participants: TU Delft, CNRS, JRC, CIRTEN, IRSN, CINVESTAV, AREVA, CEA, EdF, PSI, KIT
- NES participation (financing additional to EU to be found):

NES lab	Task	MM
LRS	FPs neutronics simulation	1.5
	Simplified transient model (TRACE)	4.5
	Coupled NK/TH/TM transient model (OpenFOAM)	6.0
	Salt freezing with OpenFOAM	6.0
LEA	Simplified PSA-3	8.0
AHL	PuF3 behaviour	6.0
LTH	Aerosols formation and migration	6.0

Molten Salt Reactor project: SNF PhD

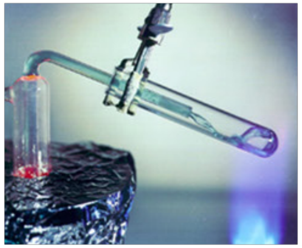
FNSNF

In 2014 the PhD study application "Small modular Molten Salt Fast Reactor design for closed fuel cycle" was approved by Swiss National Science Foundation.

The PhD plan as well as the first results was approved by EPFL Committee:

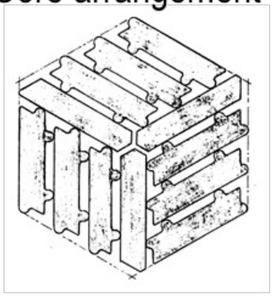
- Initial fuel criticality and breeding
- Equilibrium fuel criticality and breeding
- Breed-and-burn operation mode
- Leakage utilization
- Fuel cycle strategy
- Recycling scheme
- Thermal-hydraulics options

Salt selection



Moderator selection

Core arrangement



Materials selection

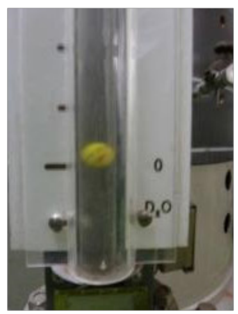
LRS Highlights

Experimental Neutronics

PROTEUS Decommissioning

- The safety report, rules of operation, decommissioning project document and post-operation plan were submitted in the second half of 2014.
- All documents were accepted by ENSI in 2014.
- The post-operation phase started in 2015
  - The reactor instrumentation is currently being shutdown







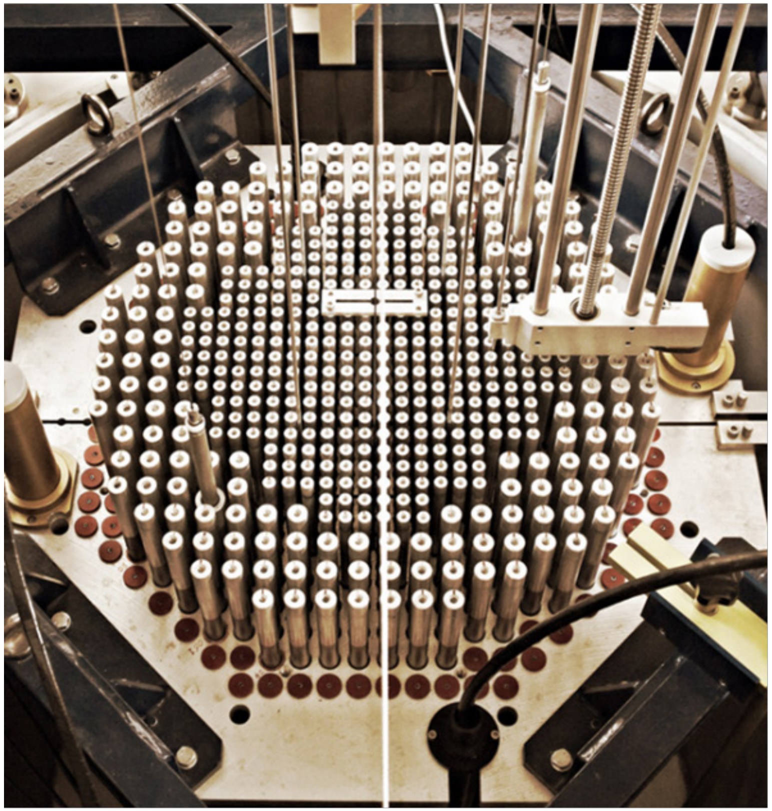
PROTEUS to CROCUS

- **PROTEUS personal decreased slightly**
  - A reactor manager and its depute
  - 5 reactor physicists involved with PROTEUS Pikett

- **CROCUS manpower and licensed personnel increased significantly**
  - New reactor manager and scientific collaborator in 2014
  - Relocation of PSI employee to EFPL
  - 2 new licensees as reactor physicist

- **LRS/EPFL main tasks are to**
  - Renew the safety report of CROCUS,
  - Design new experiments for CROCUS and LOTUS
  - Reinforce the teaching activities

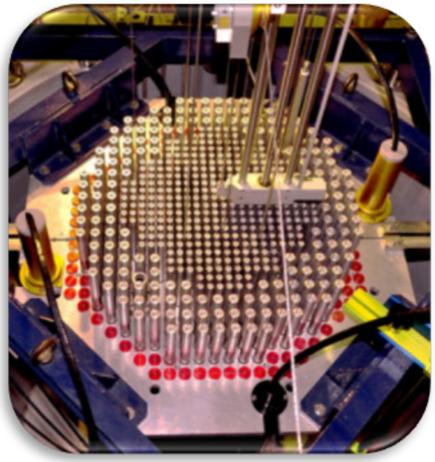
CROCUS Reactor

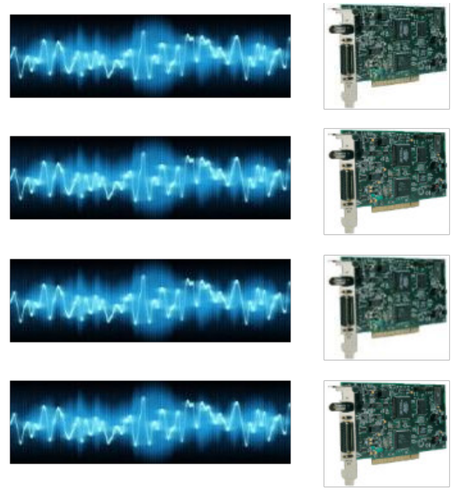


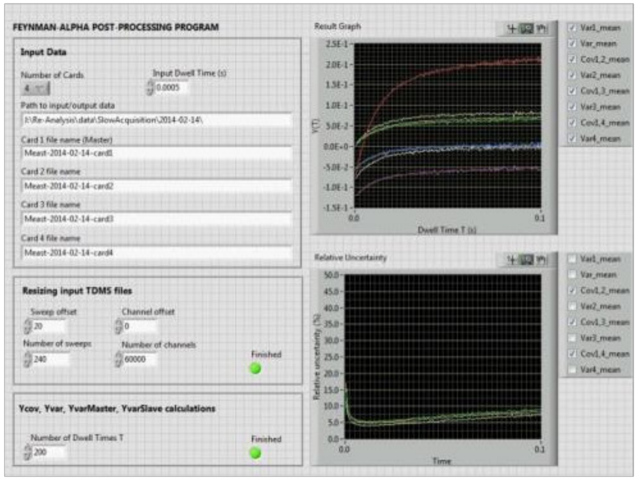
- Reactor type
  - LWR with core partially submerged in light water
  - Atmospheric P and room T
  - Forced convection
- Power lower than100W
- Flux lower than $6.8.10^8$ $cm^{-2}.s^{-1}$
- Controlled by water level or rods
- Core dimensions
  - ⌀60 cm/100 cm
- Fuel lattices
  - 2-zone: 336/176 rods actually
  - Inner: UO_2 1.806 wt% 1.837 cm
  - Outer: Umet 0.947 wt% 2.917 cm

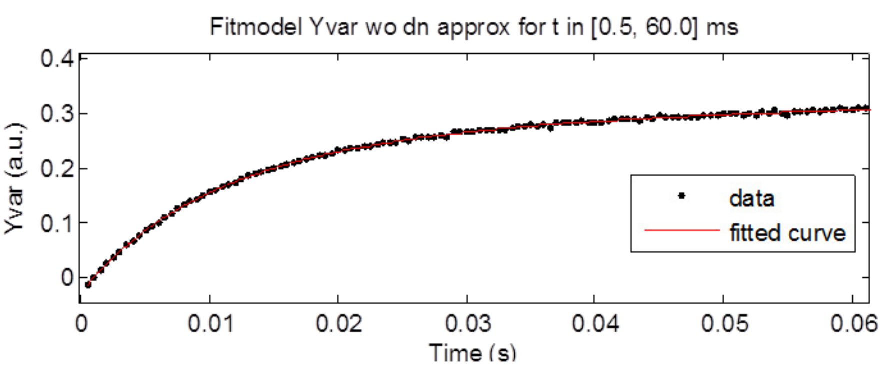
Highlight 2014: CROCUS neutron noise

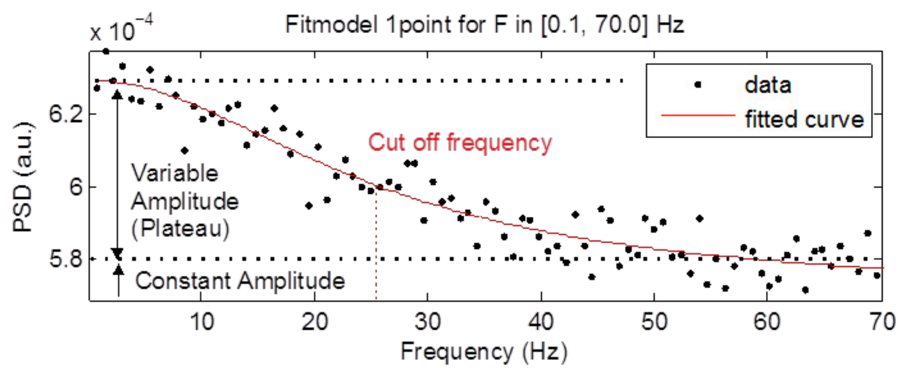
Laboratory for Reactor Physics and Systems Behaviour
Nuclear Energy and Safety Department









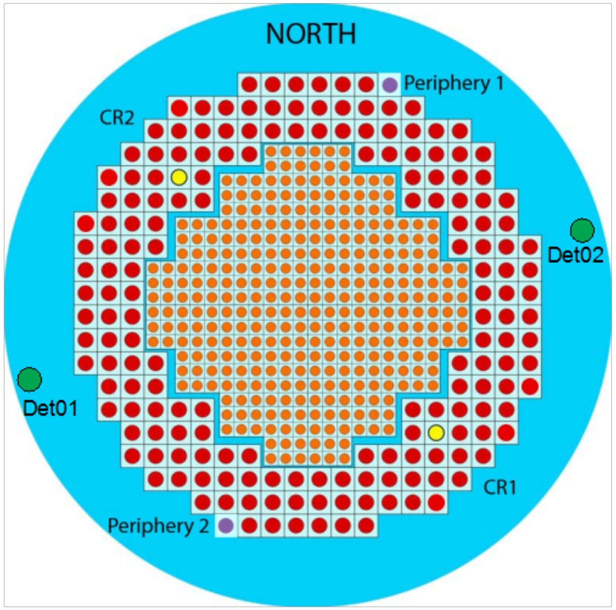


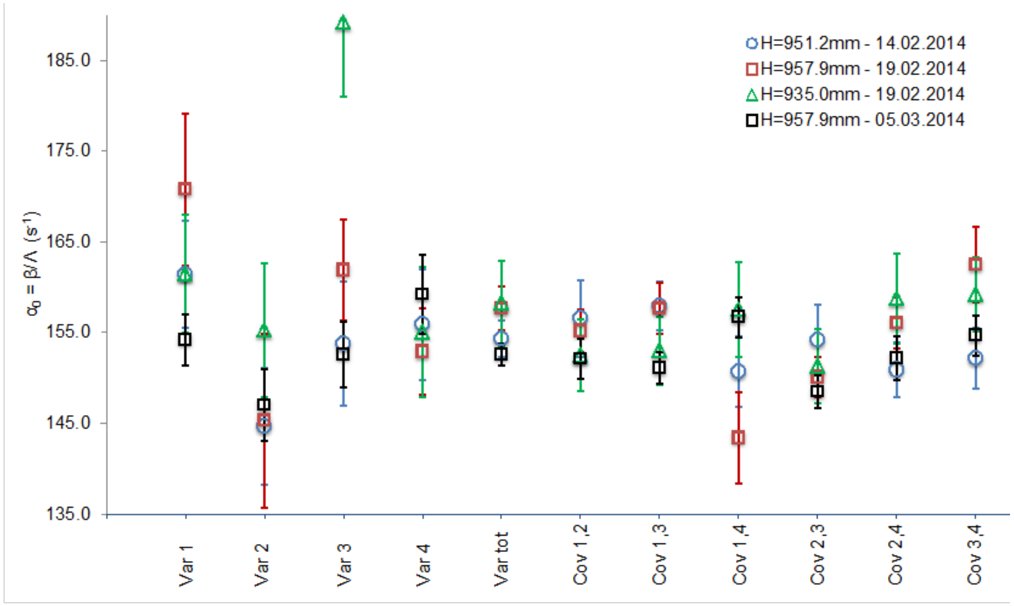
$$Y_{ij}(T) = \frac{\sqrt{R_i R_j} D}{F \beta^2 (1+\rho_\$)^2} \left(1 - \frac{1 - e^{-\alpha T}}{\alpha T}\right)$$

$$CPSD(\omega) = \frac{R_i R_j D}{F \beta^2 (1+\rho_\$)^2} \frac{1}{1 + \left(\omega / \alpha\right)^2}$$

$$\alpha = (1+\rho_\$)\, \beta / \Lambda$$

Highlight 2014: CROCUS neutron noise





- Consistent β/Λ results for different subcritical levels and detectors
- Good agreement with MCNP predictions for β (e.g. 756 ± 20 pcm vs. 759 ± 7 pcm) and Λ.
- Measurement station now used in a new experimental class for the Master of Nuclear Engineering at EPFL
- Project helped start collaboration on measurement technique with CEA and to define new experiments in CROCUS.

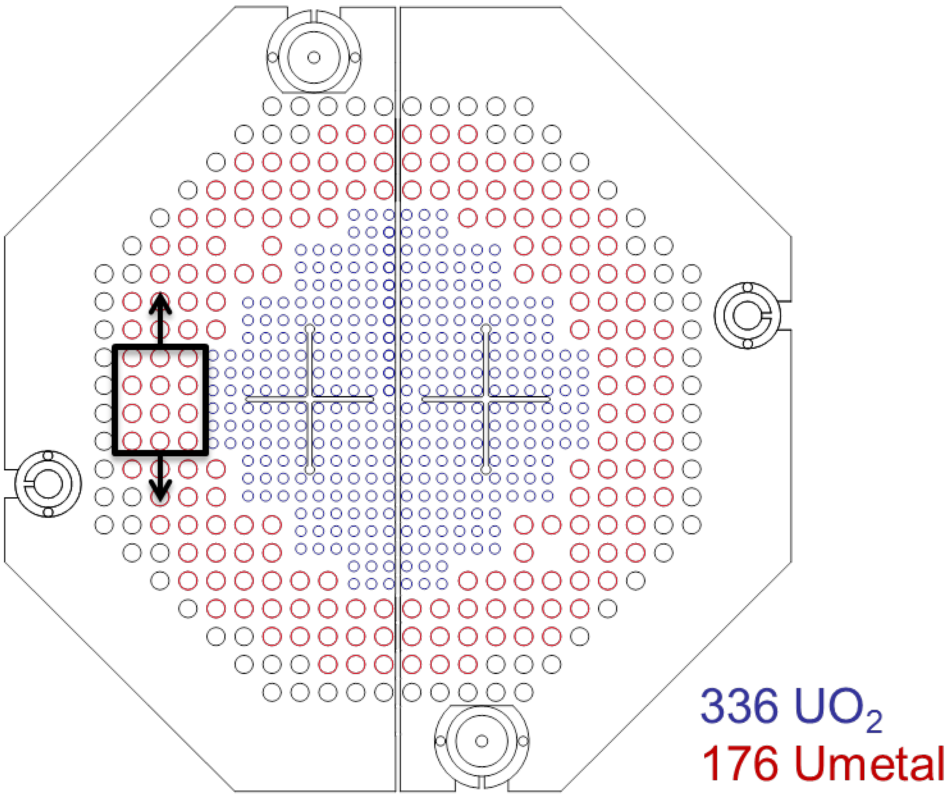
List of experiments on CROCUS

- PhD project on safety analysis for research reactor (A. Rais)
- Characterization of CROCUS spectrum
- Optical fibres scintillators
  - small non-intrusive for core mapping
  - used as tagged-source for safeguard purposes
- Hydrogen scattering cross sections above 100 keV
- Reflector materials qualifications (Fe, Cr, Ni, MgO)
- Pile oscillation methods (e.g. Hf_{nat})
- Kinetic parameter measurements by noise techniques
- Control rod position measurement by noise techniques
- BWR void fraction determination by noise techniques
- Mechanical noise induced by fuel rod oscillations

Mechanical noise by fuel rod oscillations

- Power fluctuations are observed in Swiss PWR reactors
- Suspected cause is vibration of fuel assemblies
- PhD on Modelling D. Chionis started within STARS on the topic
- Collaboration with CROCUS - Provide experiments for code validation

- Frequency:
  0.1 to 5 Hz every 0.1Hz
- Amplitude:
  1 to 3mm every 0.5mm
- Number of pins:
  At least 12, at best1 to 25
- Signal
  At least sinusoids
- Reproducibility



THANK YOU …