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Wir schaffen Wissen – heute für morgen

Paul Scherrer Institut

Andreas Pautz

NES “Kompetenzen und Highlights”: Laboratorium für Reaktorphysik und Systemverhalten (LRS)

Content

LRS Organization

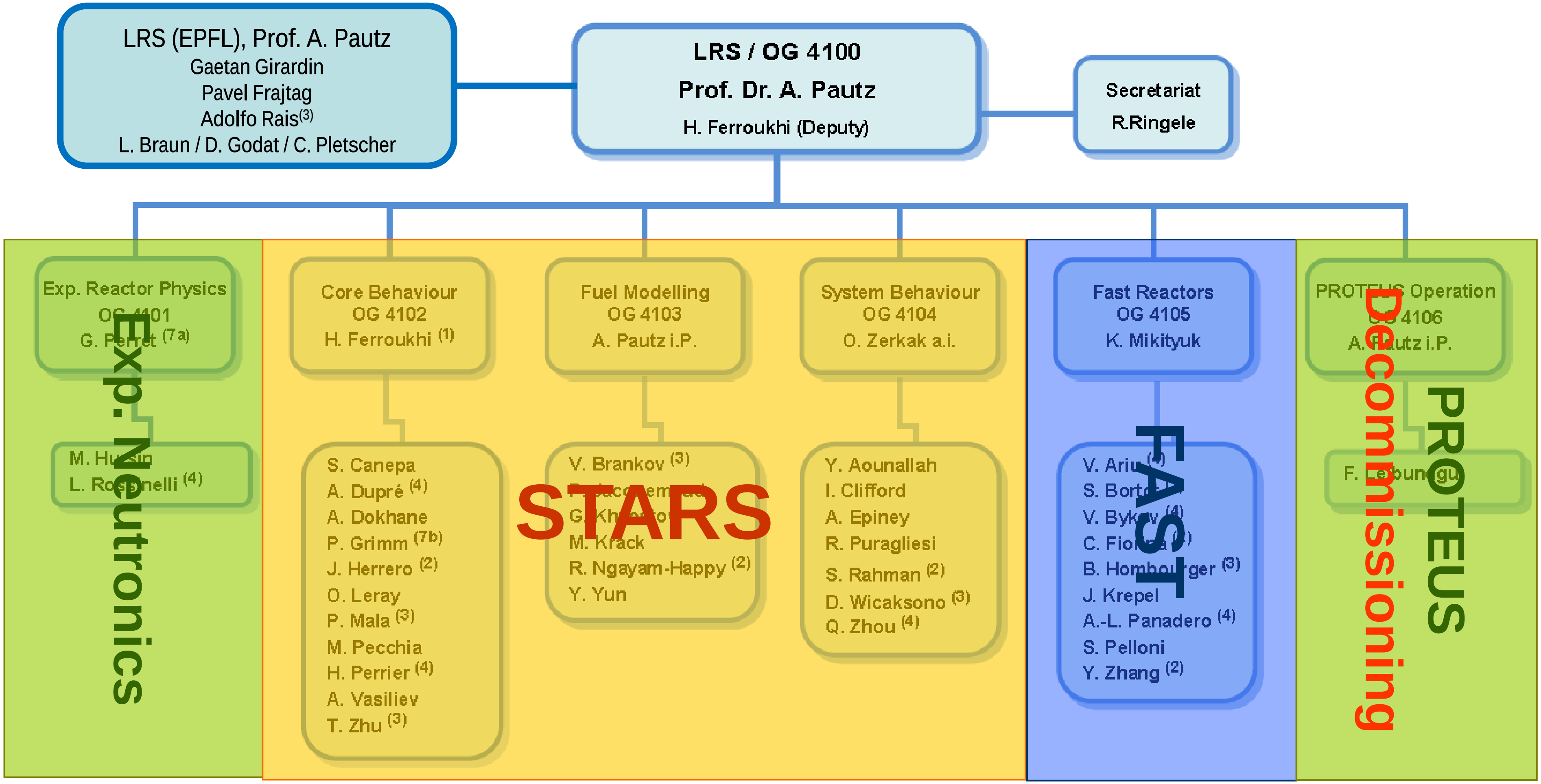
LRS Mission and Strategic Goals

LRS Projects & Highlights: STARS
- Core Physics
- Plant Behavior
- Fuel Behavior

LRS Projects & Highlights: FAST
- Sodium Fast Reactor Studies
- Molten Salt Reactor

LRS Projects & Highlights: Experimental Neutronics
- Decommissioning PROTEUS
- CROCUS Utilization

Organization of LRS (as of 1st of March, 2014)



(1) Lab Head Deputy (2) Post Doc (3) PhD Student (4) Master Student (5) Intern (6) Guest Scientist (7a) Proteus Facility Manager; (7b) Deputy

LRS Mission and Strategy

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Laboratory for Reactor Physics and System Behavior: Our 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 of LRS

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

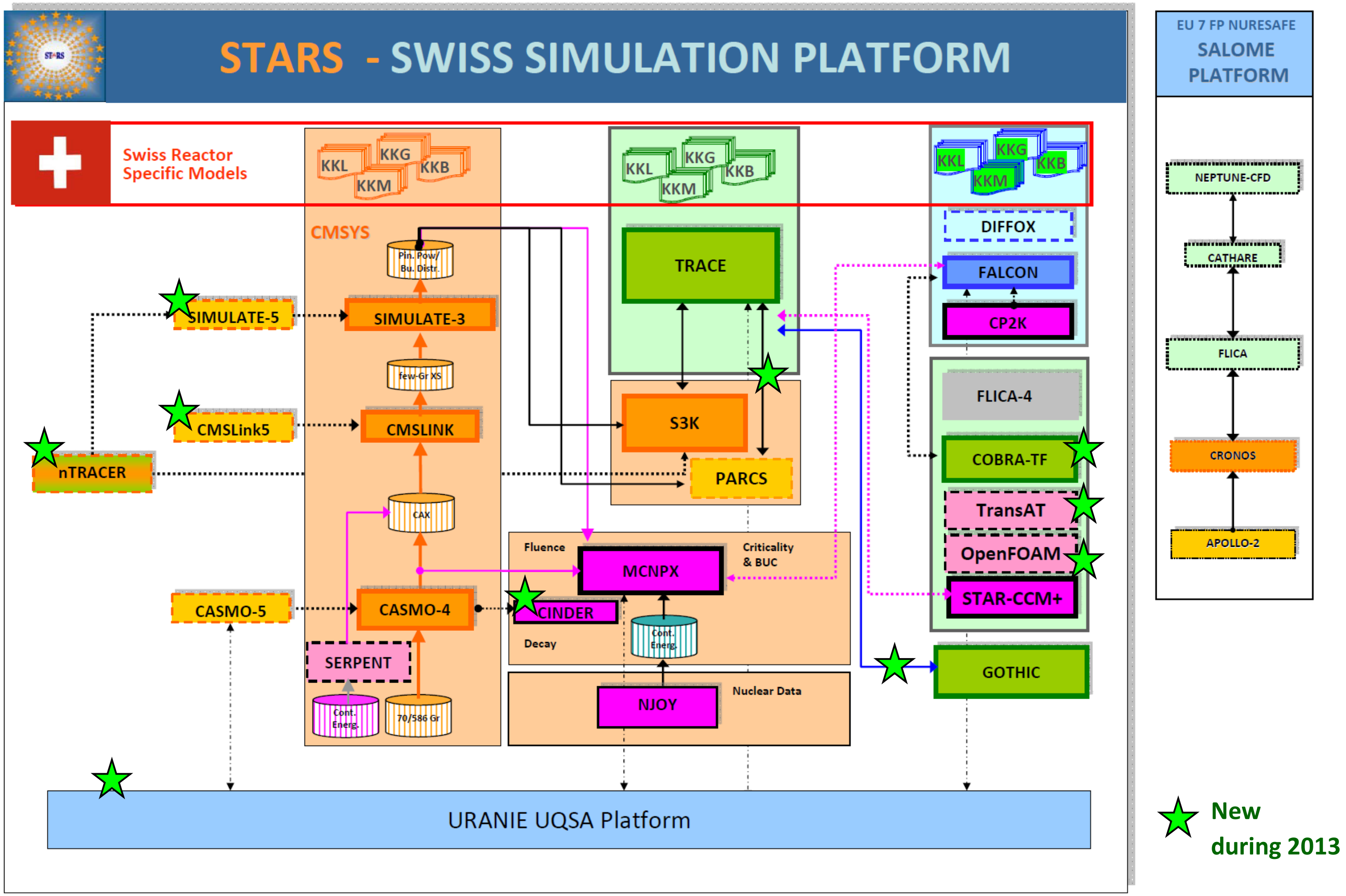
LRS Highlights: STARS

LWR Analytical Facility

Essence of STARS
Maintain and Further Develop the
the "Swiss Simulation Platform"

⟺

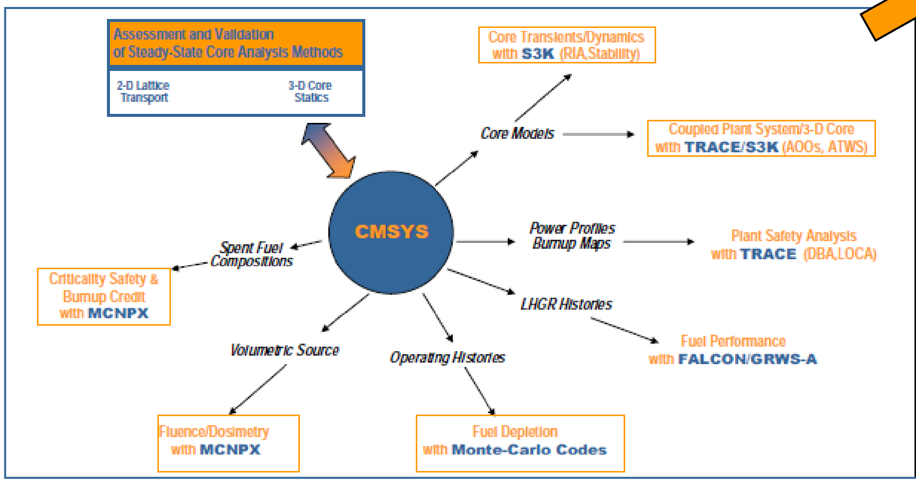
Analytical Facility for
Integrated Multi-physics Multi-scale
LWR safety Analyses



Scientific Support for Swiss Core Licensing

PSI Core Management System CMSYS

- Validated Reference Reactor Fuel and Core Models for All Swiss Reactors and All Operated Cycles
- Basis for Development of Advanced Safety analyses Methodologies
- Unique capability for research organization

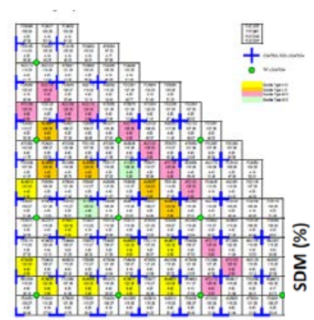


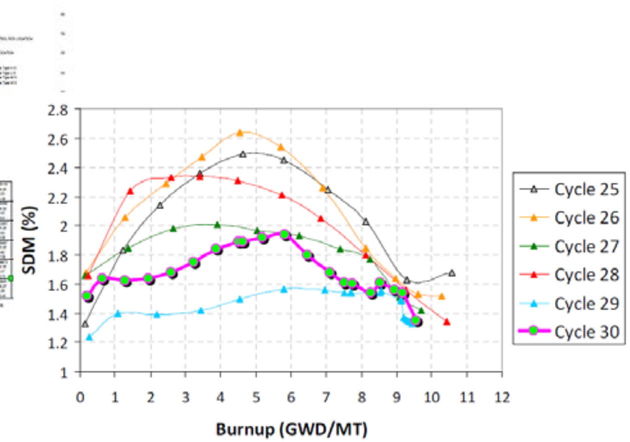
New Activity for Regulatory Support

- Independent Safety Verifications of Cores Designs to be Operated in the Swiss Reactors

During 2013, Verification for Leibstadt conducted

- Very short licensing period → Less than 3 weeks in August!
- PSI verification of utility analyses analyses confirmed adequacy of new core design → new Core Approved and now Operated





ENSI Feedback

"…first time that ENSI gives the Freigabe for KKL not only based on our checks but also based on analyses by our experts which … is a major improvement of ENSI`s regulatory work. …

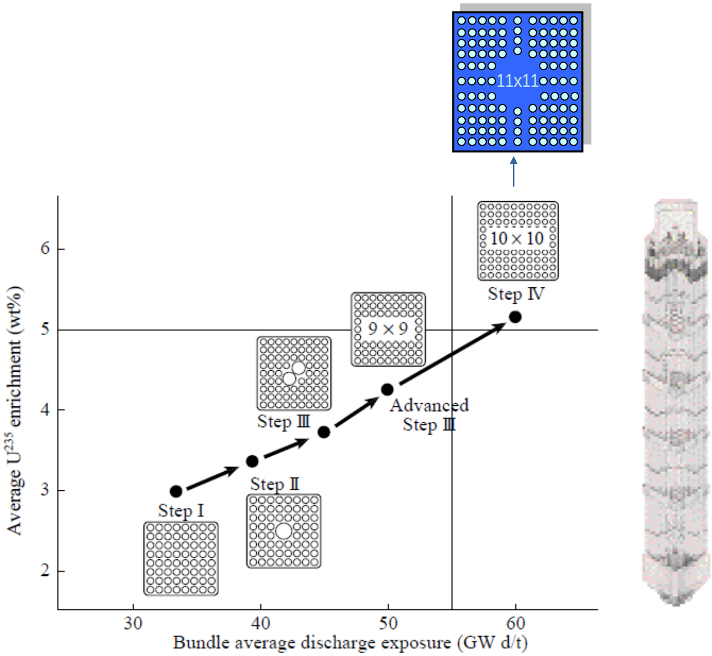
From 2014 PSI Core Licensing Verifications for **ALL** Reactors

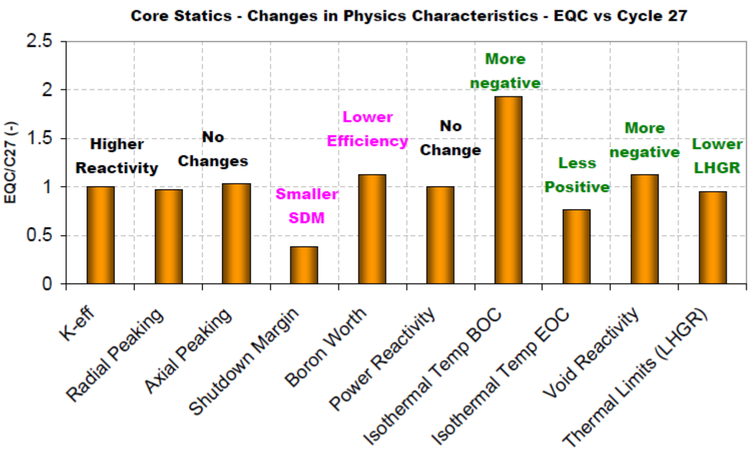
PLANT	Outage		PSI Core Licensing		
	Start	End	Receipt of RLS data	Completion of Analyses and Report/Letter	Who
KKB1 (1.Stillstand)	01.04.2014	13.04.2014	01.03.2014	24.03.2014	LO41
KKB1 (2.Stillstand)	15.08.2014	08.12.2014	[redacted]		
KKB2	17.06.2014	29.06.2014	17.05.2014	07.06.2014	LO41
KKG	08.06.2014	06.07.2014	08.05.2014	29.05.2014	FH41
KKL	04.08.2014	28.08.2014	04.07.2014	25.07.2014	CS41
KKM	10.08.2014	04.09.2014	10.07.2014	31.07.2014	DH41

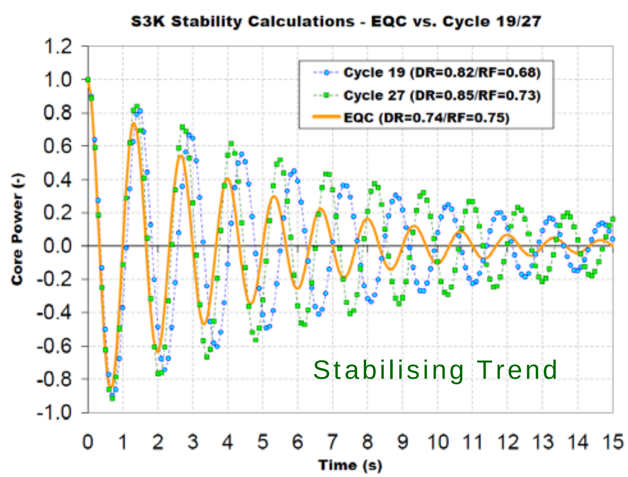
Regulatory Support for Licensing of new BWR Fuel Design

Equilibrium Core Cycle (EQC) Analyses
with 3-D Neutronics/Thermal-Hydraulics

Fuel Assembly Design 11x11



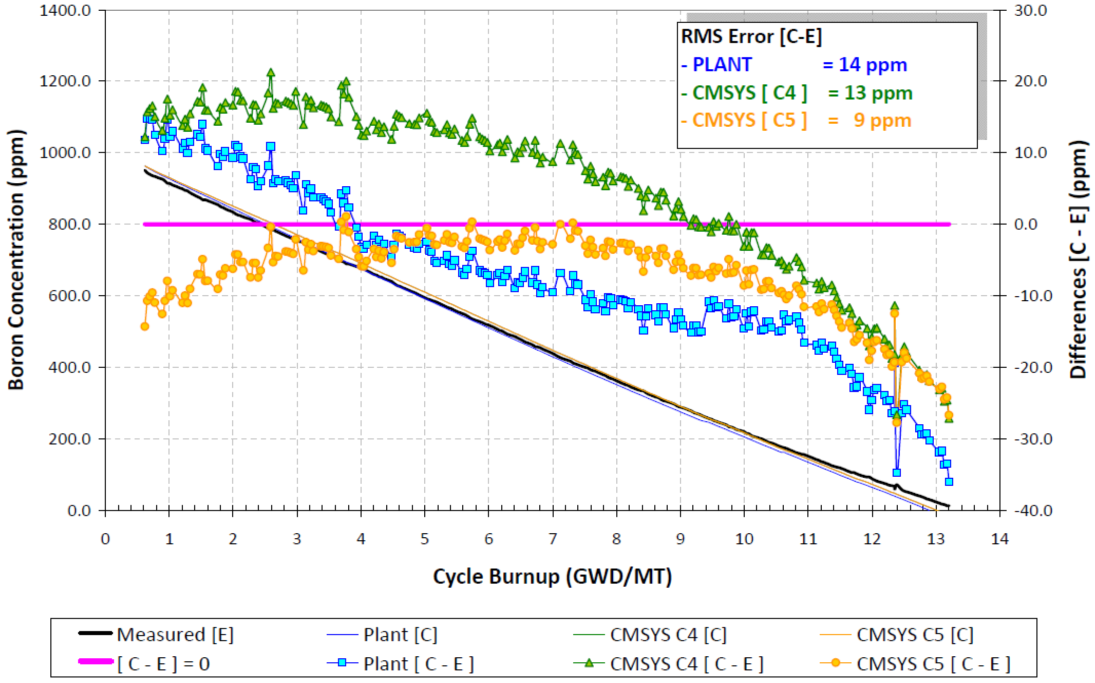




Assessment of Swiss Core Analysis Methods

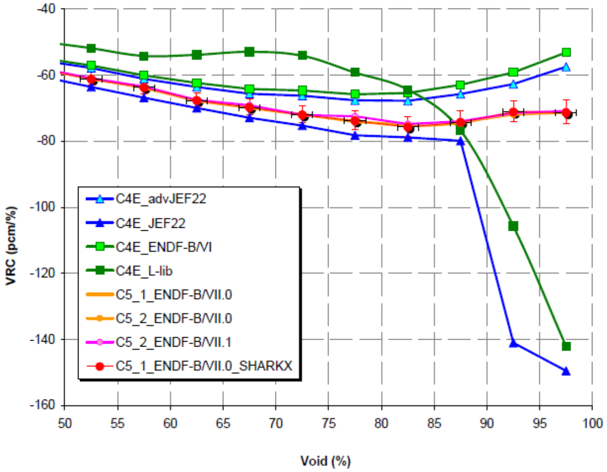
Update of KKG Core Modelling Methodology and Transition to CASMO-5

Predicted vs Measured Boron Concentration for Cycle 32

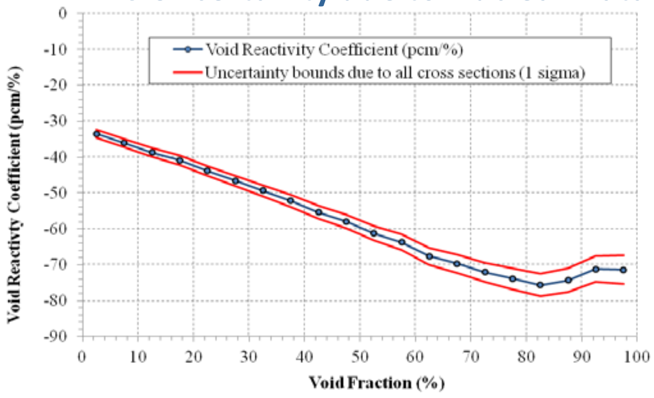


BWR Void Reactivity Coefficient

VRC Range of Variation from Code/Library Updates

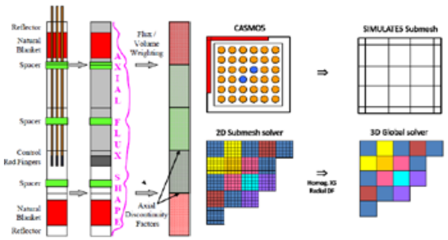


Towards Quantification of VRC Uncertainty due to Nuclear Data



Core Physics — Higher-Order Deterministic Core Analysis

Transition to SIMULATE-5
Next-Generation Core Simulator

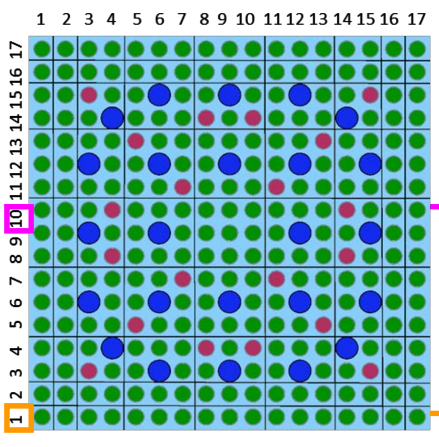


Neutronics
Multi-Group Simplified Transport
Axial/Radial Sub-Mesh Homogenised ND
Microscopic Fuel Depletion

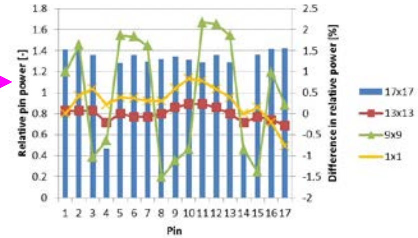
Thermal-Hydraulics
Assembly/Sub-Assembly 2-D (Axial/Radial) Flow

Assessment of
Radial Sub-Mesh Method for PPR

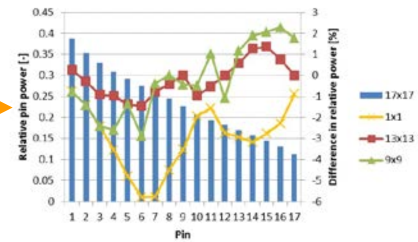
S5 Radial Sub-Meshing
UO2 Gd with 9x9 Sub-mesh



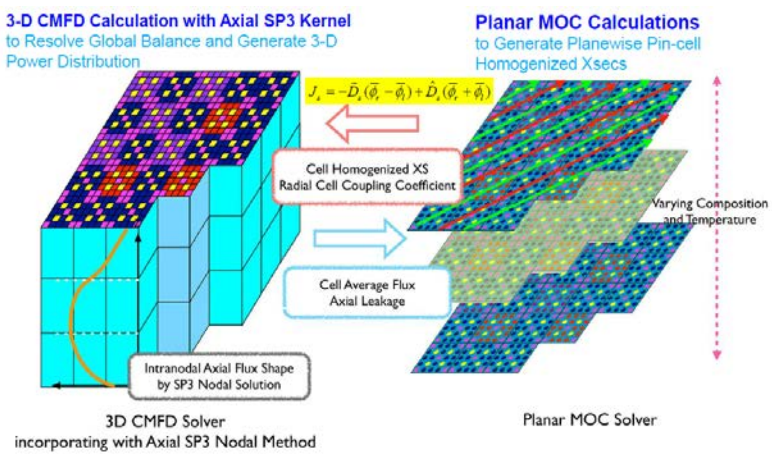
S5 Pin-Power Comparisons
Central Assembly BOC



Peripheral Assembly EOC



Development/Validation of nTRACER
(Coll. Seoul University)



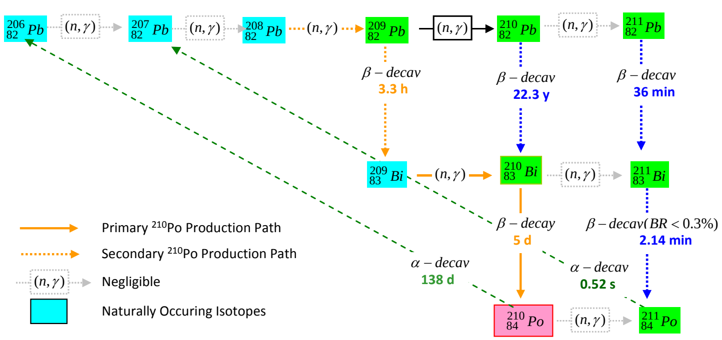
Neutronics
Multi-Group 2-D Integral Transport /1-D SPn
Microscopic Fuel Depletion

Thermal-Hydraulics
Sub-Channel 3-D Flow

Assessment of ORIGEN-2.2 for Inventory Calculations

- **Used for national inventory calculations (PSI, Genf Forschungsreaktor, Basel Forschungsreactor)**
- **Assessment of code for "non-standard" application (Collaboration with Lausanne)**
  Estimations of ^{210}Pb/^{210}Po mass and activity profiles in Bismuth/Lead Materials irradiated in Nuclear Reactors

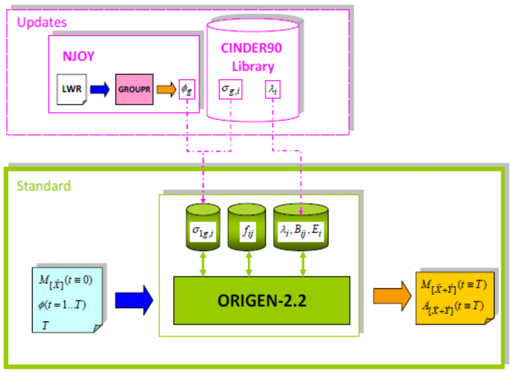
Review of Po Production Paths → Assessment of ORIGEN-2.2 with LWR 1-g XS Library (IAEA Benchmark) → Modelling and Analysis with Updated Libraries



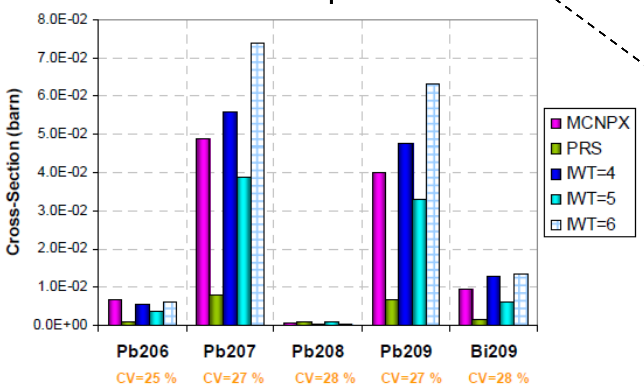
Assessment of ORIGEN-2.2 with LWR 1-g XS Library (IAEA Benchmark)

Multiple Library Errors and Deficiencies/Gaps Detected

Modelling and Analysis with Updated Libraries



Sensitivity of Pb/Bi 1-g XS to assumed LWR Spectrum



Quantification of Uncertainties

1. Nuclear data evaluations;
2. Spectrum for cross-section collapsing;
3. Nuclear data uncertainties;
4. Flux Level;
5. Target Material Compositions.

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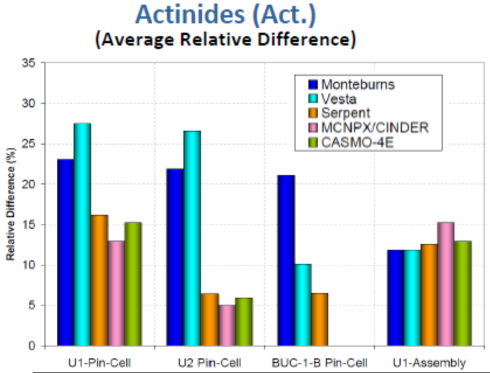
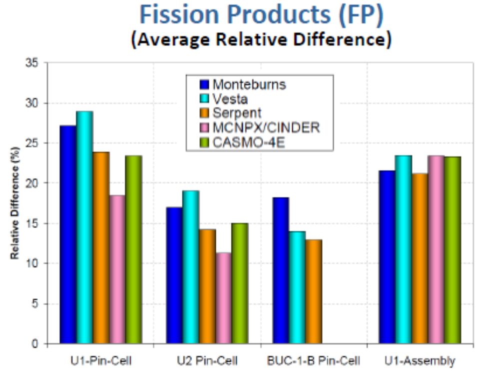
Core Physics — High-Fidelity Fuel Depletion

Assessment of Monte-Carlo based Depletion Codes
Verification and Validation (PROTEUS-II Sample)





- For U1/U2, Relative Differences to Experimental Results (C/E)
- For BUC-1.B, Relative Differences to Average Benchmark Results

- Slightly better performance of Monteburns both for Act. And FPs
- MCNPX/CINDER superior MC-code for Pin-Cells but not Assembly Models
- Serpent overall superior MC code
- Moderate but systematic enhancement compared to CASMO-4E (~ 1-2% for Act. And 3-5% for FPs).

Serpent adopted as main MC Depletion Solver

Parallelization and Scaling Performance (2.5 M Histories)

U1 Pin-Cell

Number of Cores	1 walltime [hrs]	2 walltime [hrs]	2 speedup [-]	4 walltime [hrs]	4 speedup [-]	8 walltime [hrs]	8 speedup [-]	16 walltime [hrs]	16 speedup [-]
Monteburns	170.47	81.87	2.08	40.83	4.18	20.24	8.42	11.04	15.44
Vesta	209.59	118.26	1.77	57.44	3.65	27.82	7.53	12.69	16.51
Serpent	23.56	18.67	1.26	9.43	2.50	4.48	5.26	#N/A	#N/A

U1 Assembly

No. of Procs	1 walltime [hrs]	2 walltime [hrs]	2 speedup [-]	4 walltime [hrs]	4 speedup [-]	8 walltime [hrs]	8 speedup [-]	16 walltime [hrs]	16 speedup [-]
Monteburns	192.10	99.07	1.94	48.03	4.00	22.80	8.43	12.87	14.93
Vesta	205.52	104.71	1.96	58.22	3.53	28.27	7.27	18.45	11.14
Serpent	88.99	19.30	4.61	9.81	9.07	6.15	14.48	#N/A	#N/A

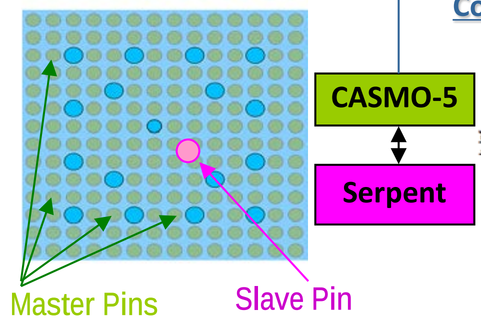
Scaling performance

- **Pin-cells** - better with Monteburns/Vesta
- **Assembly** better with Serpent

Wall-time

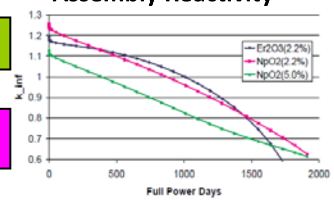
- **Systematically substantially lower with SERPENT**

Development of Hybrid Neutronic CASMO/Serpent Assembly/Multi-Assembly Depletion Scheme

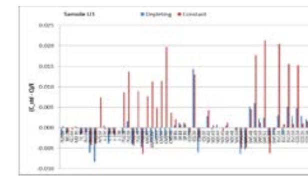


Evaluation of CASMO Computational Biases (BUC)

Assembly Reactivity

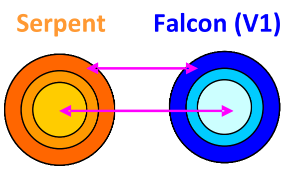


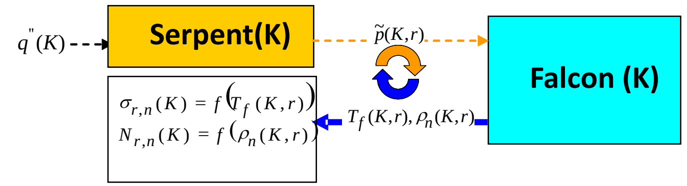
Slave Pin Fuel Compositions



On-Going MSc Project

Development of Coupled Neutronic/Thermo-Mechanics Fuel Rod Depletion

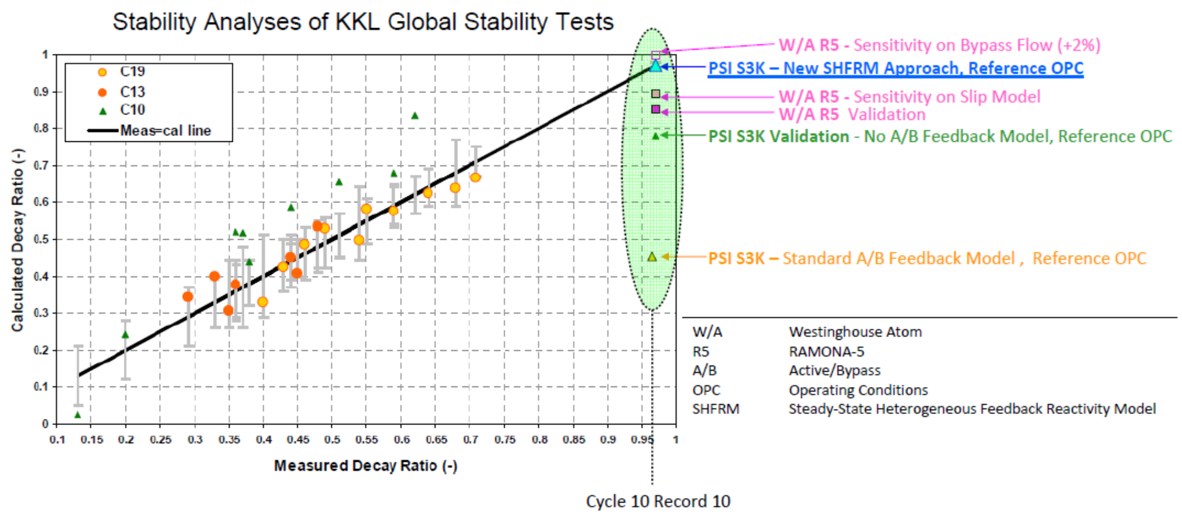




Development of S3K 3-D Coupled Neutronics/T-H Stability Methodology for the Swiss BWRs

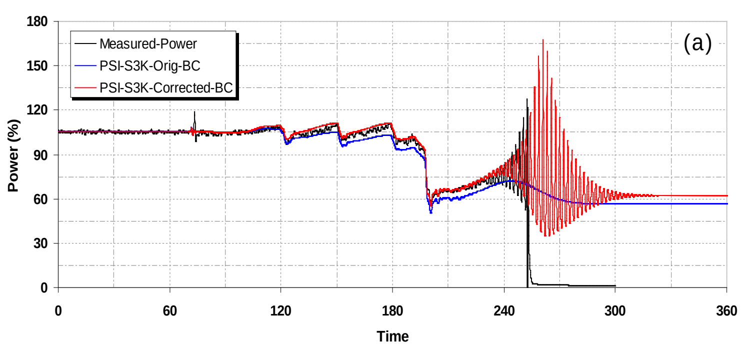
Comprehensive Sensitivity Analyses to establish “Systematic” and “Generic” Methodology

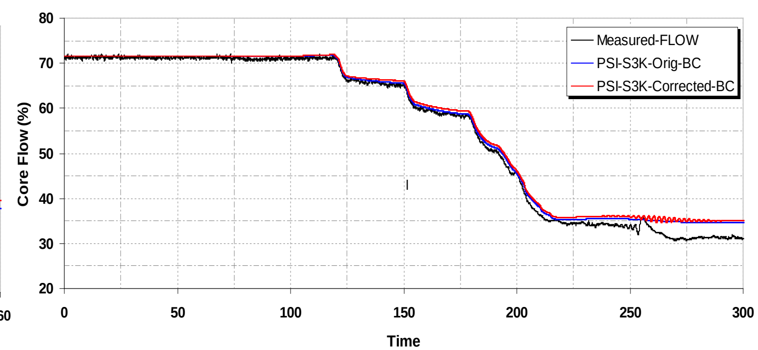
➔ Towards Resolution of Validation Difficulties for most Cumbersome “Unstable” KKL Test (Cycle 10, rec. 10)



Further Assessment through OECD/NEA Oskarshamn Benchmark

Development and Validation of S3K Model for Phase 1 (Event Analysis: Feedwater Transient ➔ Unstable Core)





	Measured	PSI-S3K
DR (-)	1.31	1.35
RF (Hz)	0.48	0.45

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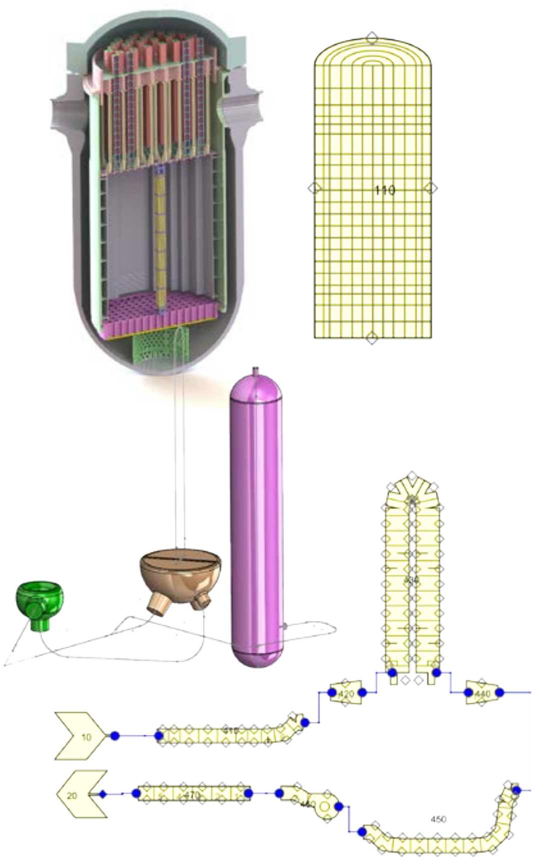
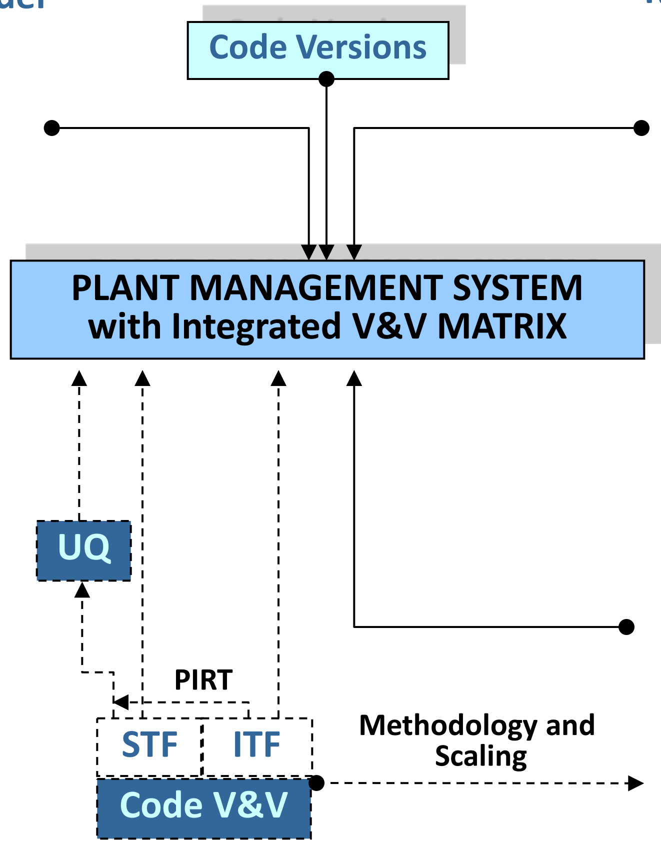
Plant Behaviour — TRACE Modelling for the Swiss Plants

Consolidated Approach for Plant Model Development and Maintenance (PMSYS)

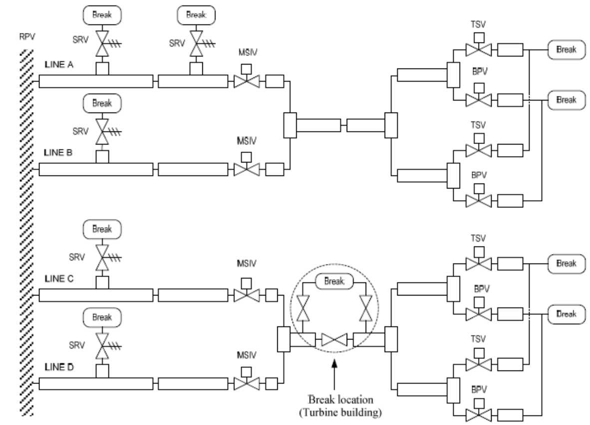
Update of KKG TRACE Vessel (3-D)/Primary System based on Solid Model

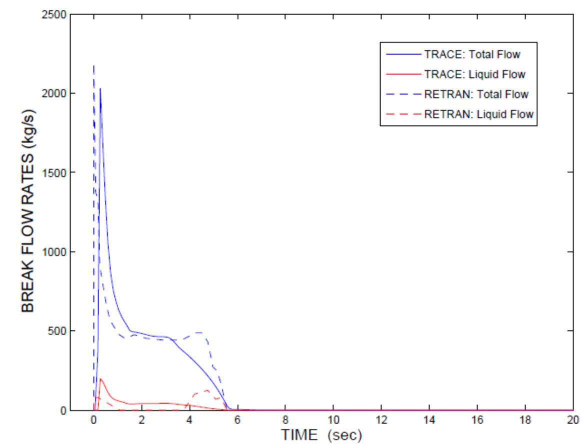




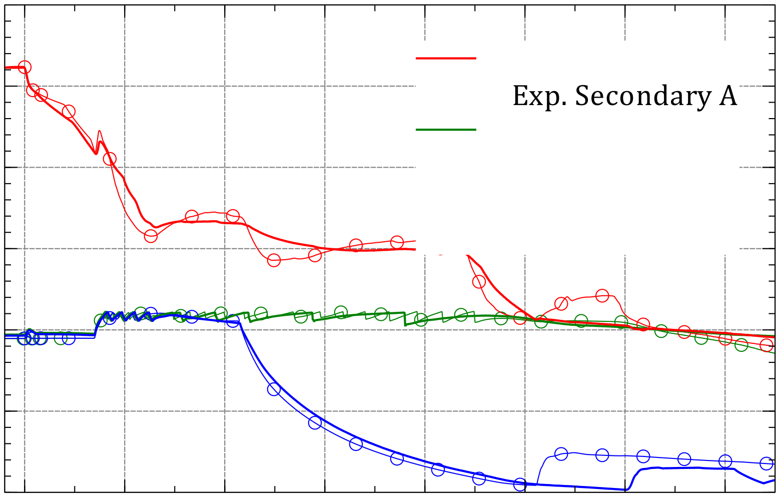
Continously "New" Situation Targets for Assessment and V&V

KKM Analysis of SLB in Turbine Building and Comparison with previous RETRAN-3D Solution (HSK On-Call)

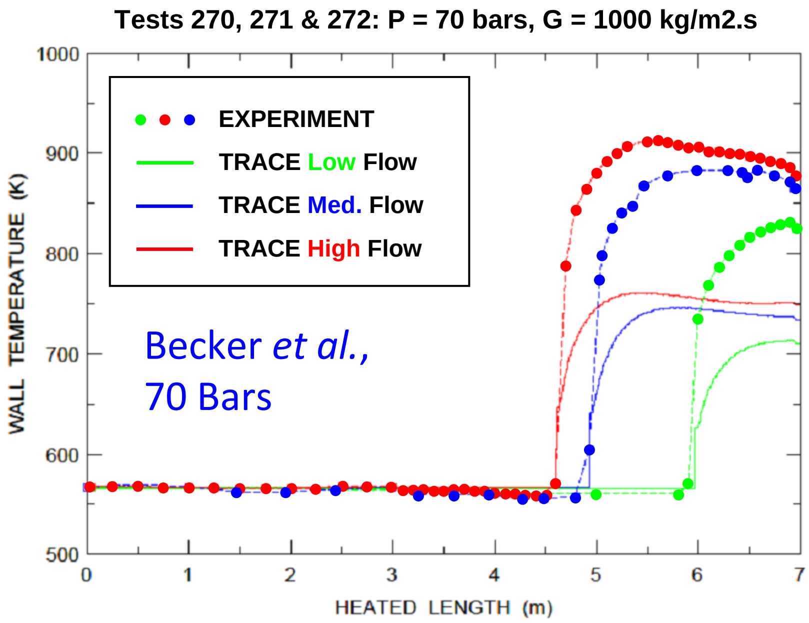




ITF
Steam-Generator-Tube-Rupture
ROSA-2 Test 4 Test Modelling and Analysis



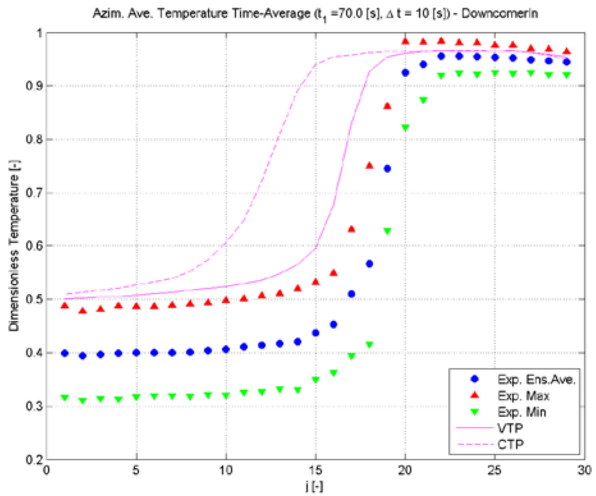
STF
CHF and Post-CHF
Single-Channel Heated Experiments



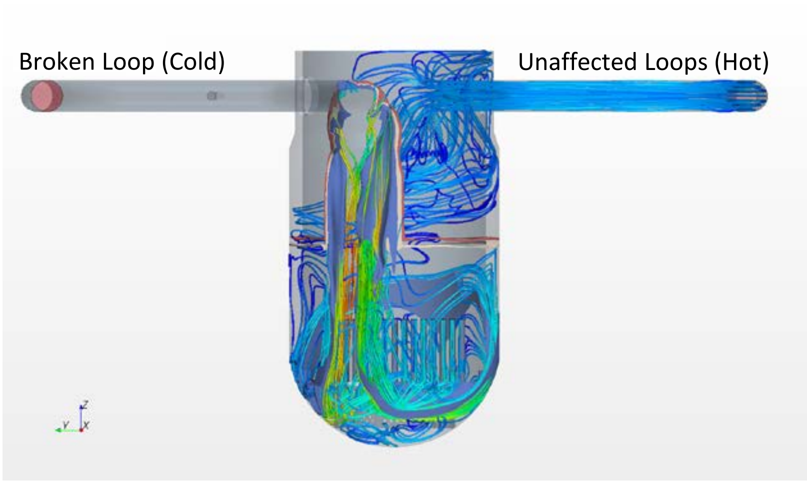
Validation of STAR-CCM+ () for Coolant Mixing and Boron Dilution

ROCOM MSLB Test 1.1 (PKL-2/PKL-3)

Mesh Optimization and Assessment of URANS Turbulent Heat Flux Models



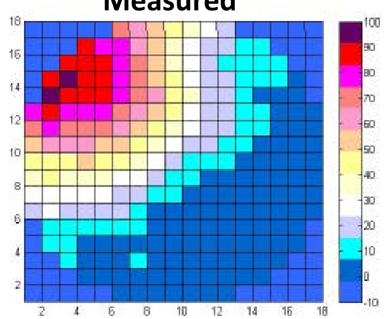
Study of Mixing and Stratification Patterns (Snapshot during Test)



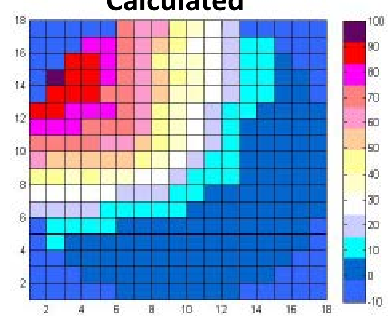
AREVA/Juliette (EPR) Experiments

Core Inlet Tracer Distribution

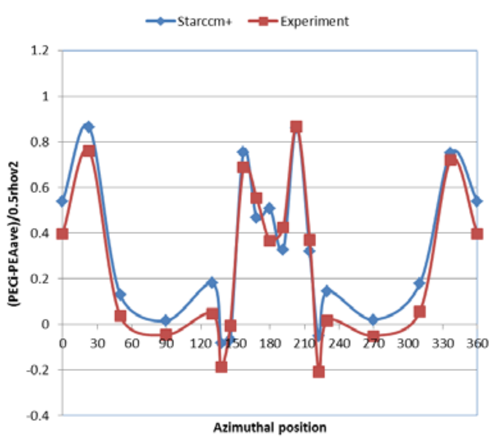
Measured



Calculated



Pressure Distribution in Downcomer



Areva/Juliette

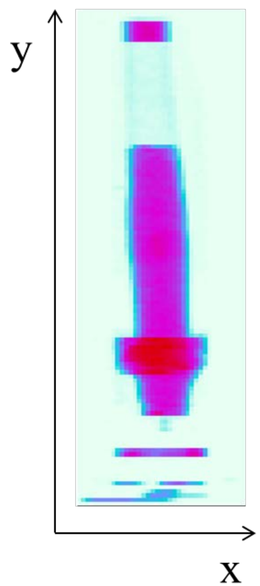
Azimuthal Pressure Distribution in DC

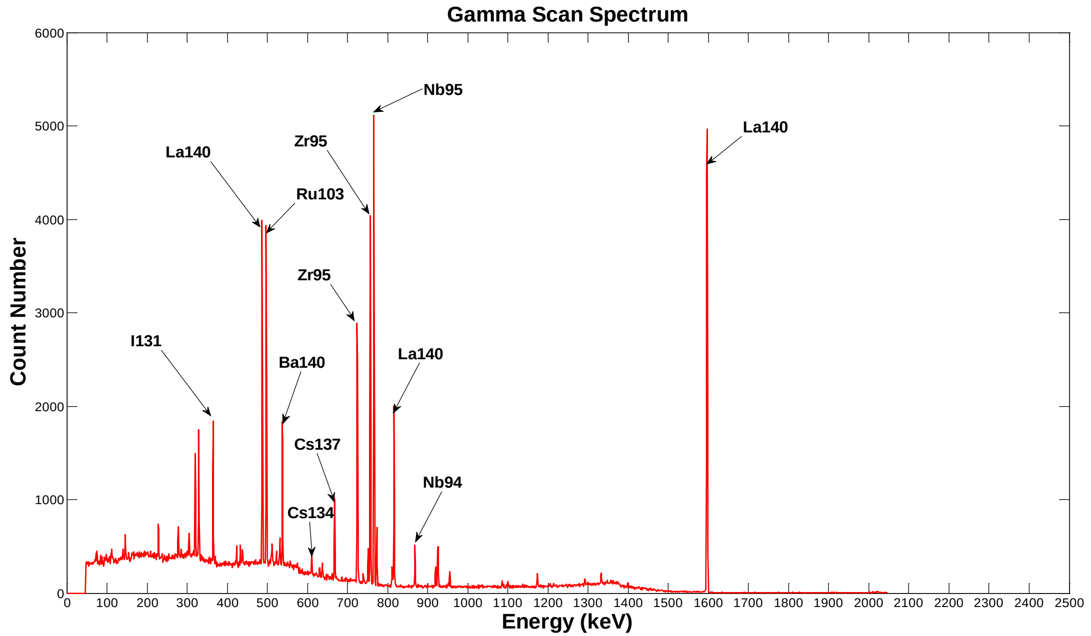
Modelling and Design with FALCON MOD001/GRSW-A of Halden HBU LOCA Tests

- Validation (Post-Analysis) for KKL IFA-650.13 Test 3 (Balloon and Rupture/burst)
- Design of KKL IFA 650.14 Test (Balloon but no Rupture) – *Conducted end of 2013*

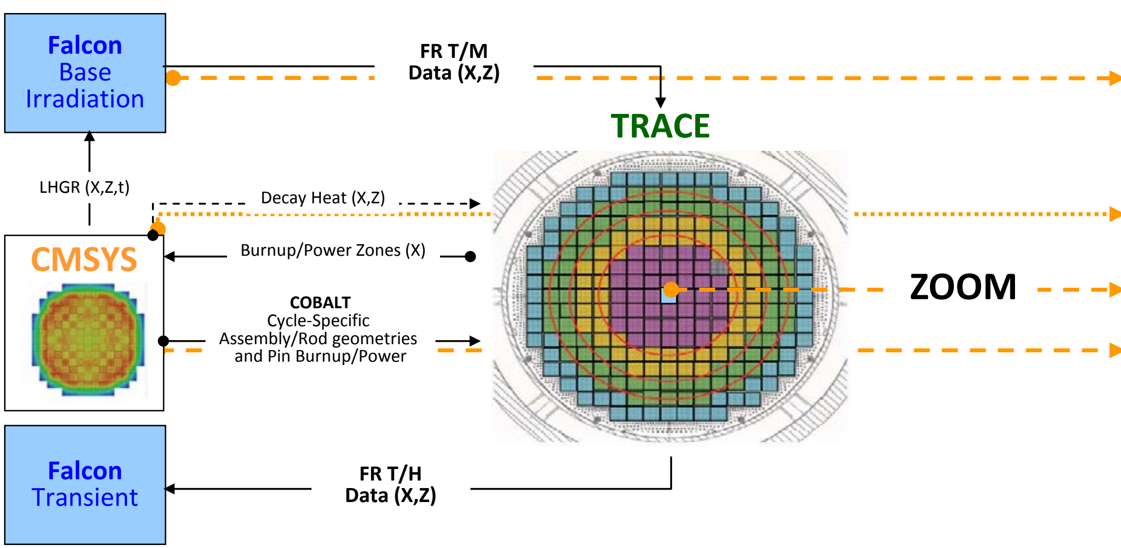
Related PhD Project started mid 2013

- **Objective:** Fuel Behavior Model Development for Fuel Fragmentation, Relocation and Dispersal (FRD)
- Participation to IFA-650.14 test realization and data acquisition
- No capability at Halden to measure ejected fuel quantity of burst tests
  ➔ Focus shifted towards development of fuel relocation model based on inference from gamma scan measurements

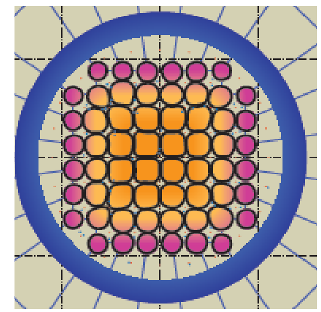




Full- Core LOCA Analysis
Development of “Off-Line“ Multi-Physics Scheme

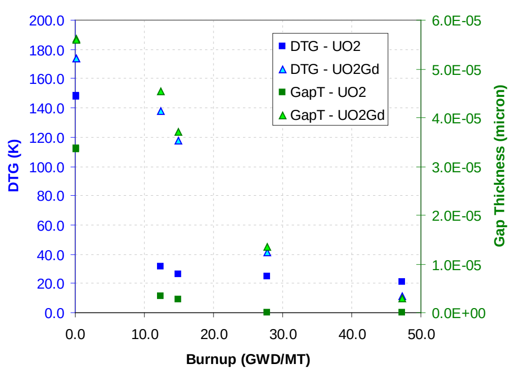


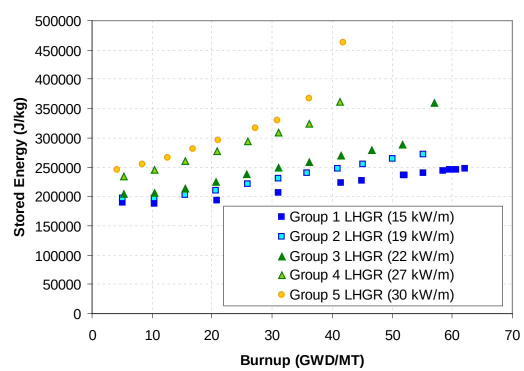
Development of Dynamical TRACE/FALCON Coupling for Single/Multiple Rod Clusters



- Fuel T-M Analysis with Account of Local 2-Phase 3-D Flow Effects
- Local T-H Analysis with account of Flow Obstruction and Changes in Heat Flux and Sources

Preliminary Testing for EPR 12-Month EQC





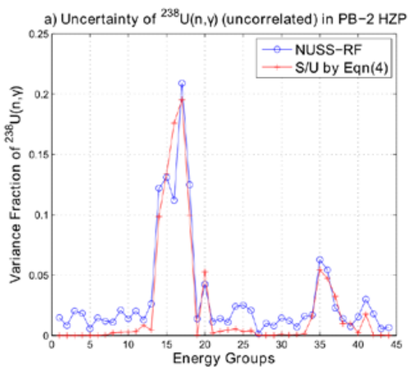
Uncertainty Analysis MCNPX Modelling

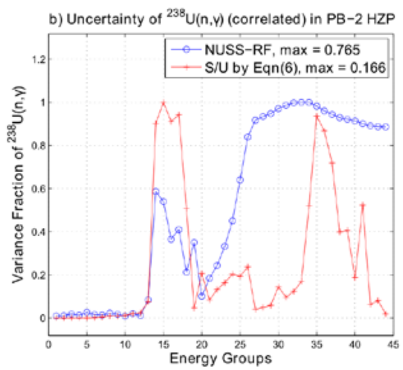
Nuclear Data Uncertainty (PhD)

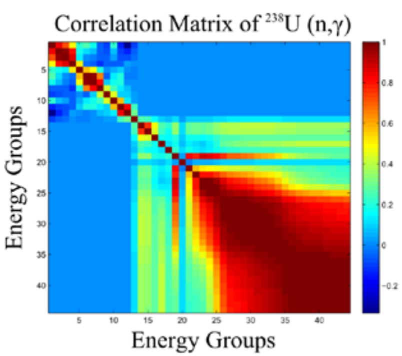
Development of Global Sensitivity Analysis

NUSS-RF (RDF + FAST Method)

First Assessment for OECD/NEA UAM-Phase 1







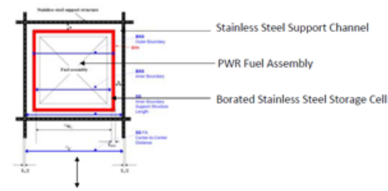
Manufacturing and Technological Parameters

Development of MTUQ Methodology

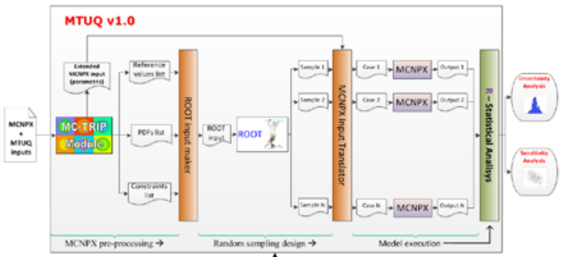
Arbitrary Perturbations of SFMS Models based on Repeated-Structure Concept

First Assessment for OECD/NEA UACSA-2

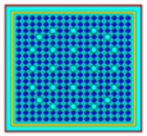
OECD/NEA UACSA-II Benchmark



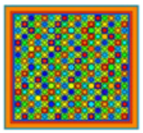
PSI MTUQ Methodology for MCNPX Model Perturbations and Uncertainty Quantification



Global Modelling (Uniform Perturbations)



Individual Modelling (Individual Pertuirbatsion with Constraints)



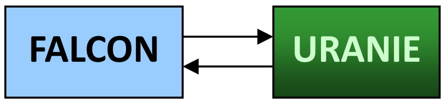
Statistical Analysis

Case	UQ Methodology			Keff Sample mean	S.t.d. (VOV) [pcm]	UTL (c. l. [%])
A	MTUQ	Individual	400	1.00120	720 (20)	1.01396 (96.4)
B1	MTUQ	Global	100	1.00107	629 (98)	1.01560 (96.2)
B2	MTUQ	Global	700	1.00102	684 (42)	1.01215 (95.5)
C	SUSA	Global	100	1.00023	754 (55)	1.01384 (96.3)

Development of Uncertainty/Sensitivity Analysis Methodology for FALCON Modelling and Analyses

Assessment for OECD/NEA UAM-2 Benchmark

Methodology – Coupling Falcon/URANIE

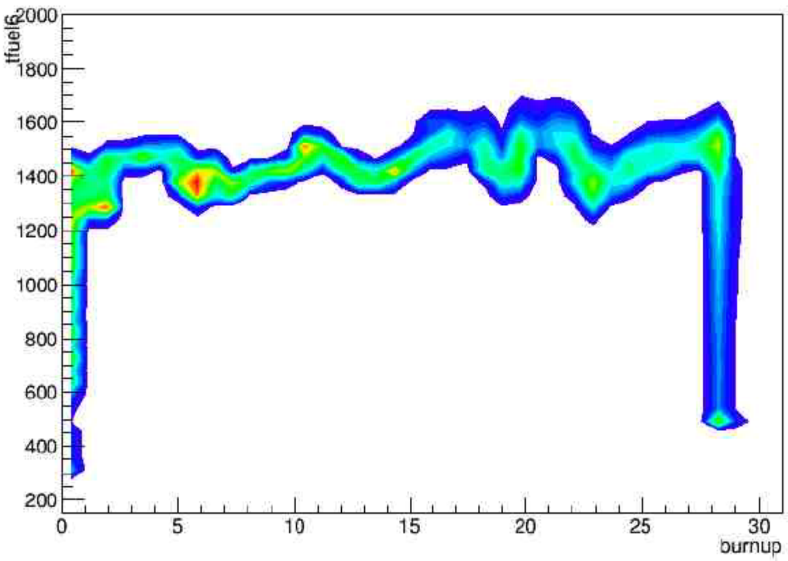


BWR Case Specifications

	BWR	
Test type	Numerical	Experimental
Reactor	PB-2	Ifa-432
Manufacturing Uncertainty parameters	-Cladding ID -Cladding Thickness -Cladding Roughness -Fuel Pellet OD -Fuel Density -Fuel Pellet Roughness -Rod Fill Pressure	
Power history	Constant	LHGR and history provided

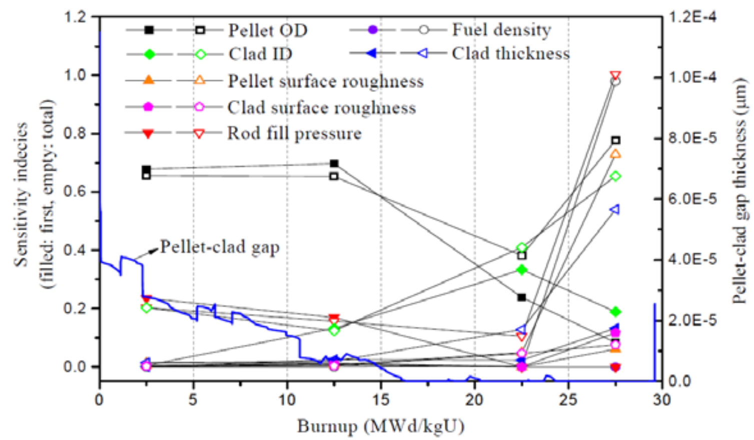
Statistical Sampling

Uncertainty in Fuel Centerline Temperature (Steady-State BWR Experimental Case)



Global Sensitivity Analysis

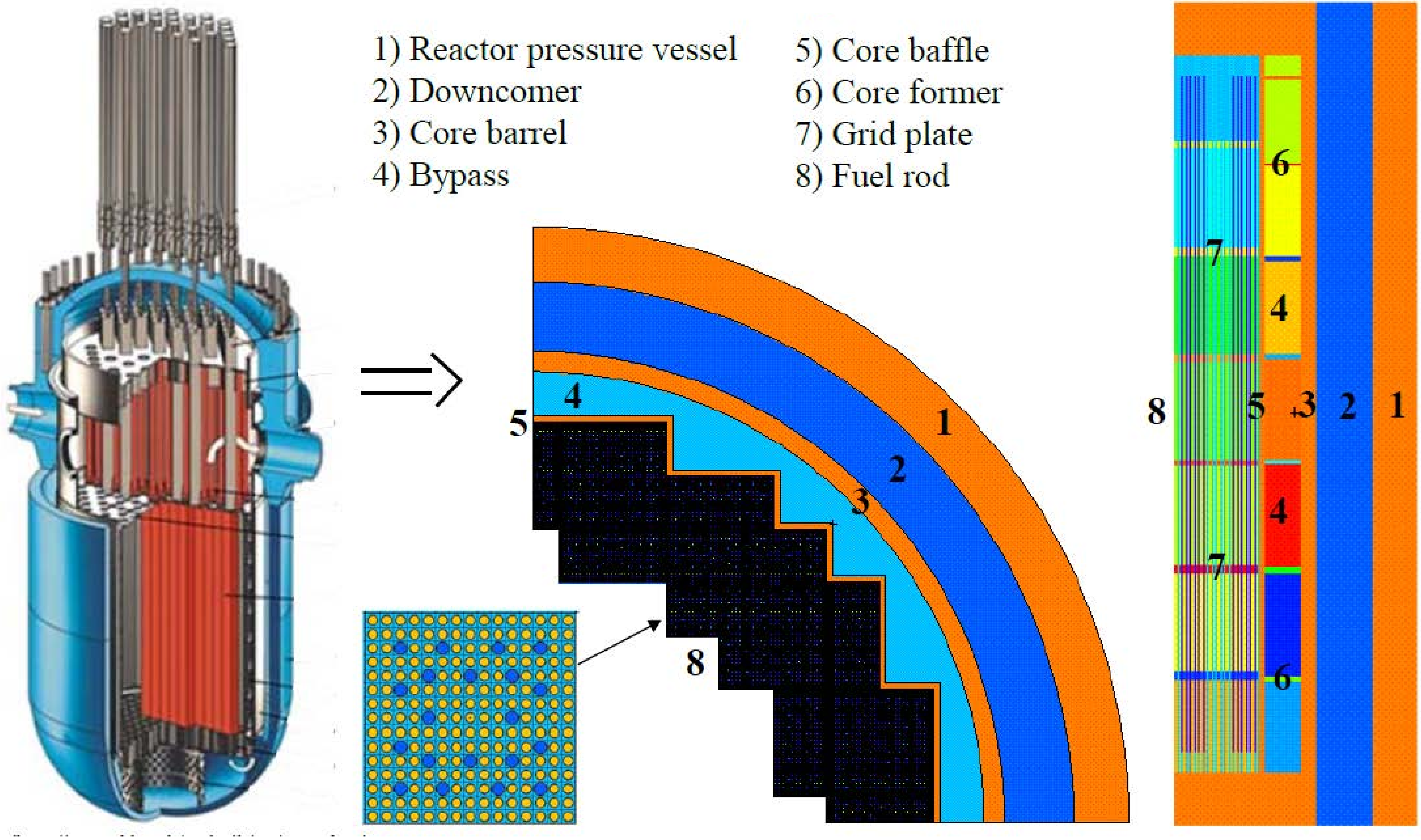
Methodology based on Sobol Sensitivity Indexes



UAM-II **CSNI/RIA UQ**

PSI Methodology SOURCE4MC Modelling Approach

- Fully Consistent CMSYS/MCNPX "In-Core" Models
- Detailed MCNPX "Out-of-Core" SCC Models



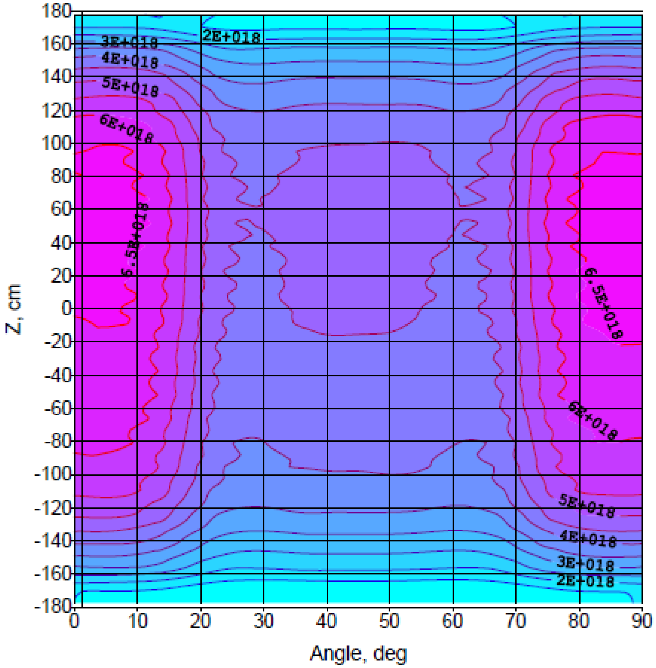
PSI Methodology SOURCE4MC Scope – Swiss FNF Assessments

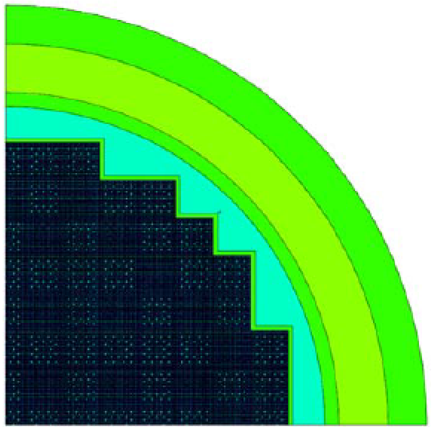
Verification / Validation basis:

Benchmarks (e.g. H.B. Robinson-2)

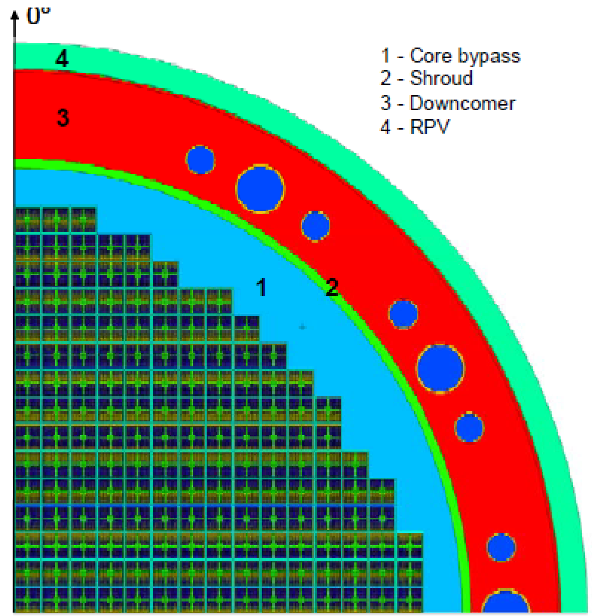
Dosimeter monitors / probes (short/long –term irradiation)

Scraping tests

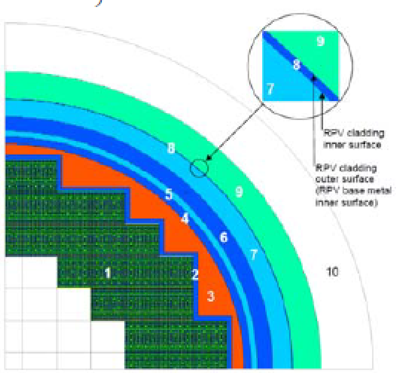




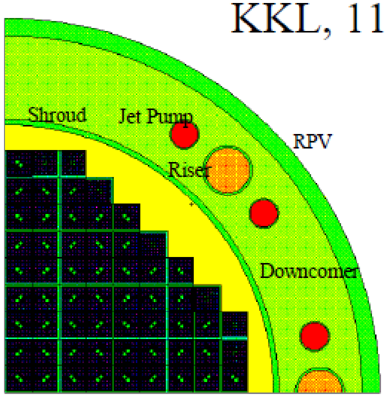
KKG, 985 MWe



KKL, 1165 MWe

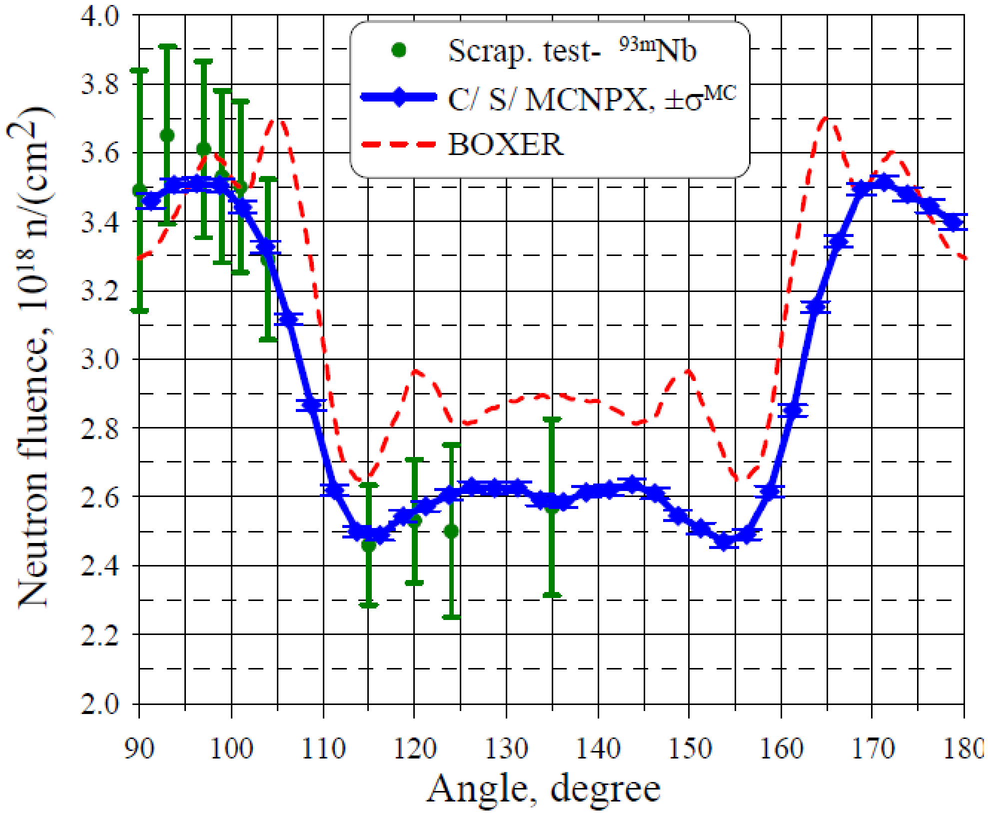


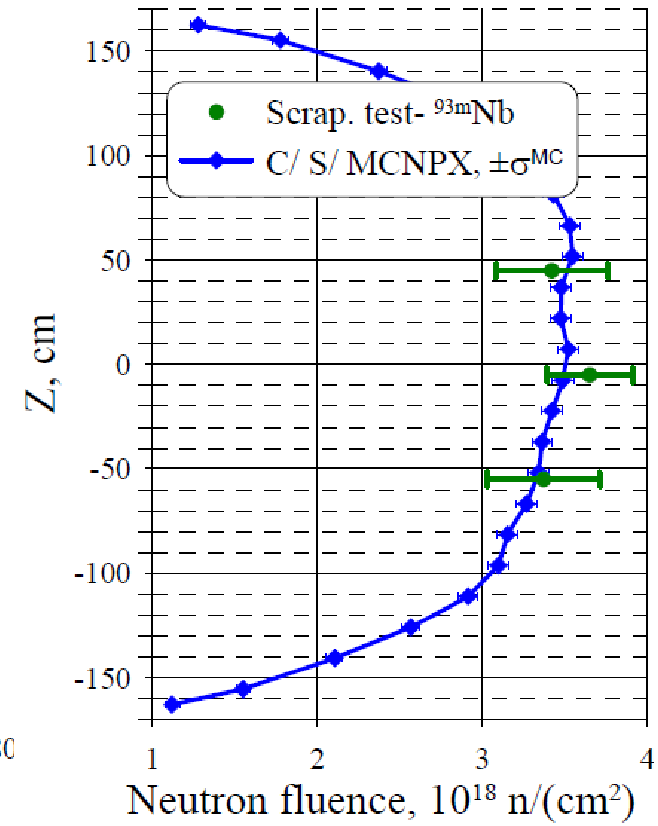
KKB, 365 MWe



KKM, 372 MWe

Modelling and Validation against KKG Cycle 10 Scrapping Tests

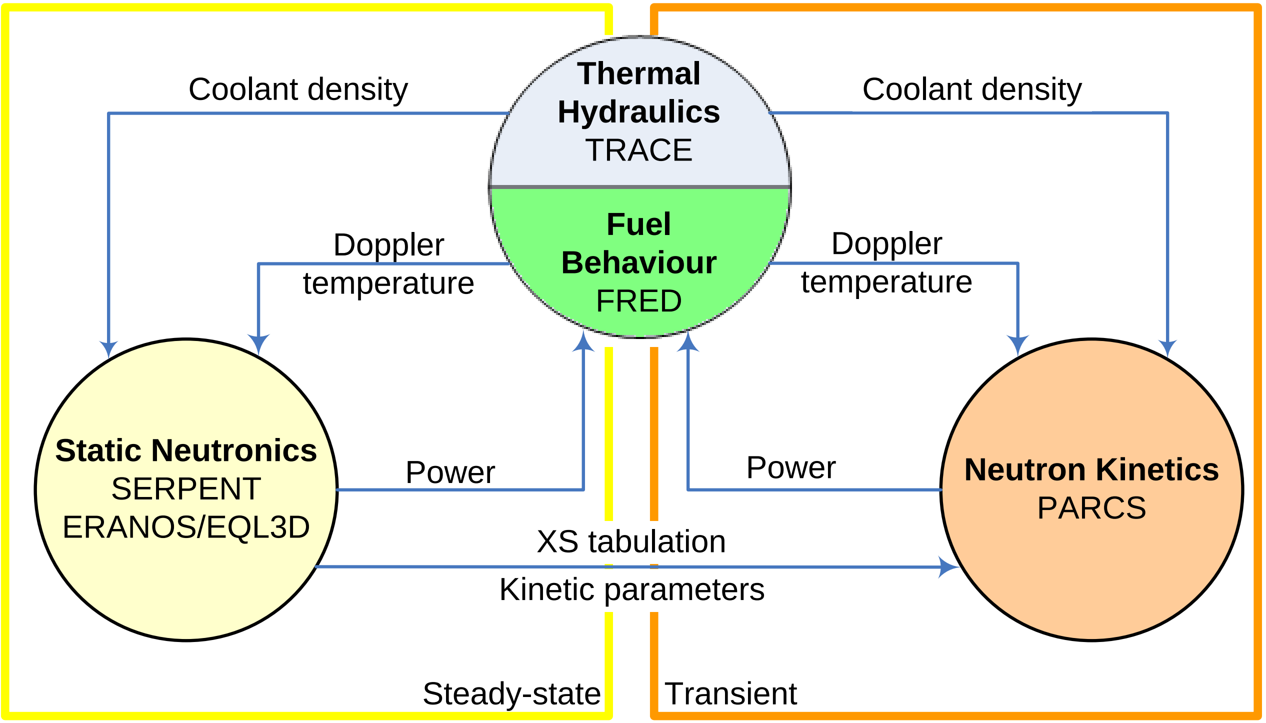




Validation against Axial Probes (Cycles 22-27) on-going

LRS Highlights: FAST

FAST code system

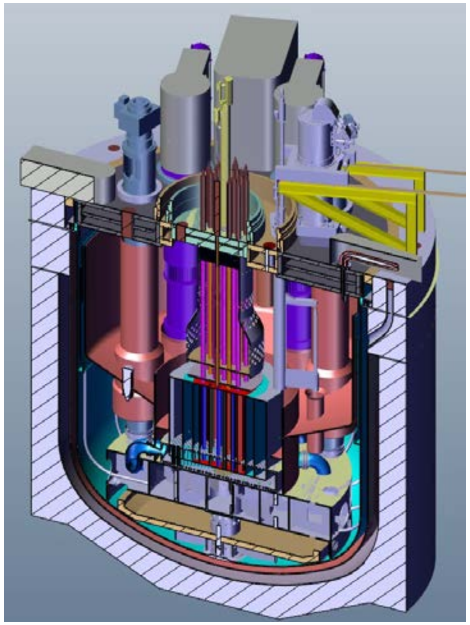


OpenFOAM
Multiphysics Solver

FALCON / GRSW-A
Fuel Behaviour

- In 2011 and 2012 we integrated **Serpent** into the code system.
- In 2013 we started to use **OpenFOAM** by developing a new solver for coupled NK/TH/TM simulation of the reactor core.
- We will adopt **FALCON/GRSW-A** for FR applications.

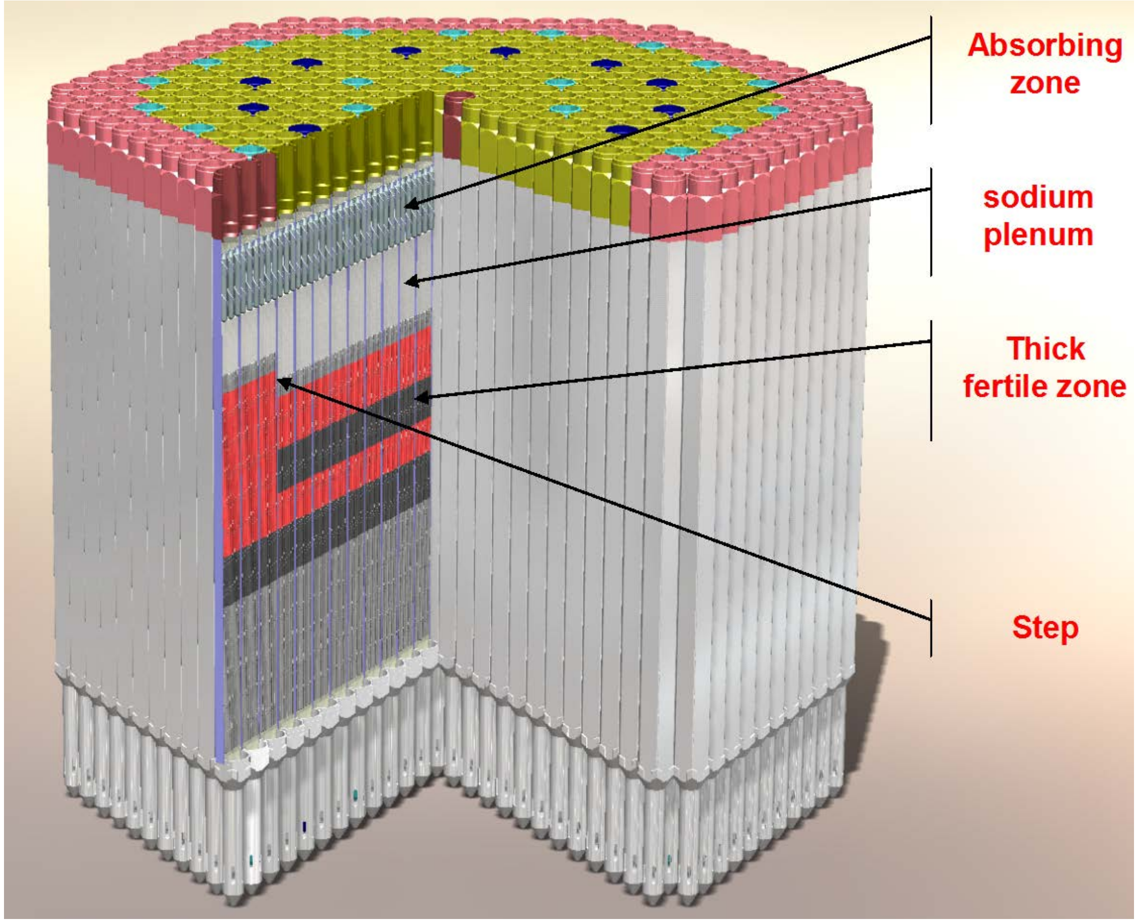
ARDECo: Astrid R&D European Cooperation



- ASTRID has several innovations and should meet more demanding safety requirements. R&D needs are significant.
- Objective of the new conceptual design phase (2013-2015) is to develop *bilateral* R&D cooperation (in addition to the EU projects).
- PSI (FAST) is the first partner invited to ARDECo.
- 50/50 cost sharing. Duration: 4 years.
- Exchanges between different R&D partners and dedicated communication channel with the ASTRID team.
- We have proposed 1 PhD (2014) and 1 postDoc (2015) in the area of analysis of the ASTRID core behaviour in Unprotected Loss of Flow

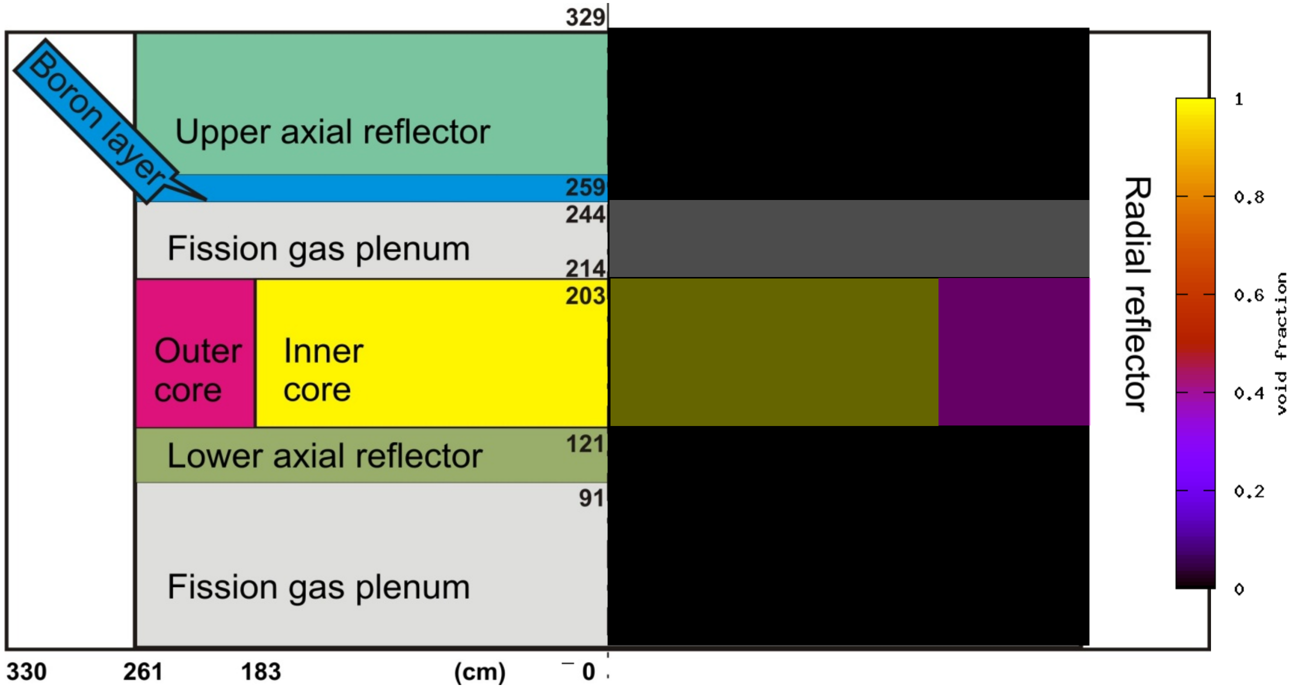
ASTRID low void effect core

- Very innovative core (internal fissile blanket, fuel zones with different heights, large sodium plenum)



Our experience in ESFR ULOF analysis

- In frame of FP7 CP-ESFR project and of 2 PhD studies, we developed and validated a capability to simulate the coupled neutron kinetics/thermal-hydraulic behaviour of an SFR core in unprotected loss of flow event.
- We have ideas how to mitigate the consequences of this accident.
- We will apply our knowledge to ASTRID.



Why MSR? Motivation & appealing features

- **Neutronics advantages: MSR has excellent neutron economy.**
  (especially in U-Th cycle the capture of ^{233}U is low, but also the parasitic absorptions of carrier salt and graphite are small)

- **Fuel in liquid state does not need fabrication.**
  (it enables TRU recycling, on-line refueling, on-line reprocessing, on-line removal of gaseous and volatile fission products)

- **MSR can be operated with flexible fuel cycle.**
  (as thermal, epithermal, or fast breeder and/or burner thanks to the Th-U cycle properties and liquid fuel)

- **MSR can be designed as an inherently safe reactor with reduced risk.**
  (low inventory of gaseous and volatile fission products, negative temperature feedbacks, passive fuel drainage)

Some MSR challenges

- **Structural materials corrosion and irradiation embrittlement.**
(high Ni content alloys to be applied and redox potential to be controlled to prevent corrosion, the alloys suffer also from irradiation embrittlement)

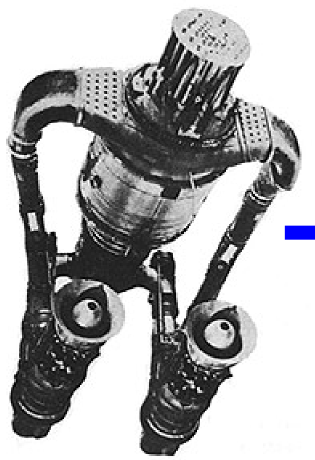
- **Thermal-hydraulics, dynamics, and limited graphite lifespan.**
(molten salt is volumetrically heated medium, delayed neutrons are drifted out of core, if applied, graphite mechanical stability suffers from irradiation)

- **Complicated molten salt reprocessing techniques.**
(fluoride volatilization techniques, electro-separation processes, molten salt / liquid metal reductive extraction)

- **Fuel salt selection, chemical treatment and proliferation risk.**
(redox potential control, on-line refueling, He bubbling to remove gaseous and volatile FPs, proliferation risk of ^{233}Pa or ^{233}U separation)

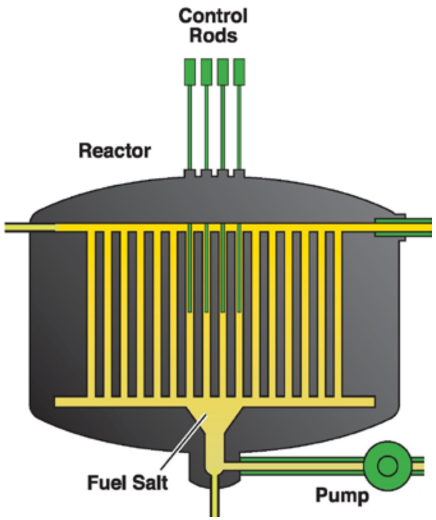
MSR: A Platform for Education

- 1 PhD and 2 MSs on-going at FAST.
- We are learning the past (in particular EIR) MSR-related experience.
- We are establishing inter-laboratory cooperation.
- We joined EURATOM FP7 EVOL project as observers.
- We have established links to international partners in USA, China, …

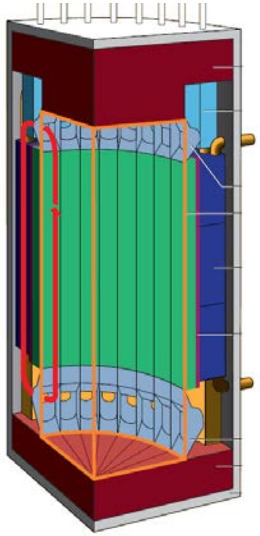


Aircraft propulsion

MSRE



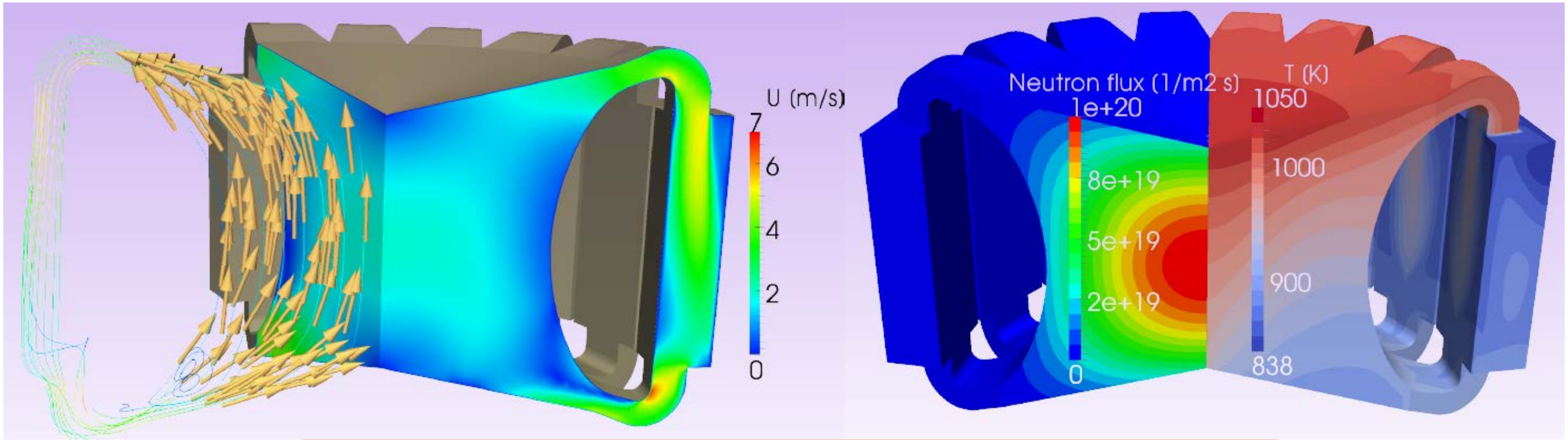
MSBR



MSFR

Coupled solvers

- Example: MSR transient behavior

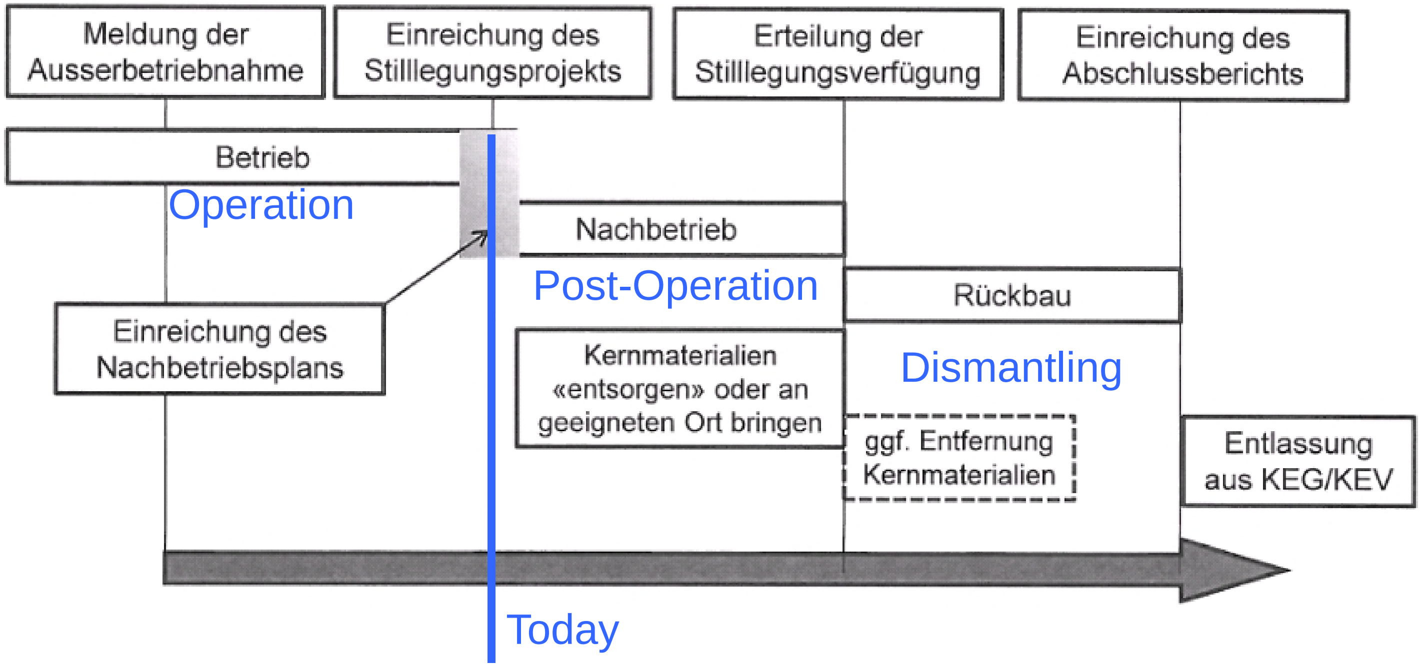



```
solve
(
    fvm::div(phi, prec1)
  - fvm::laplacian(turbulence->nut()/Sct, prec1)
  + fvm::Sp(lam1, prec1)
  - ((xs->nu_tot() & xs->sigma_f()) & flu) * beta1 * (1/k_eff)
);

solve
(
    fvm::div(-phi, prec1_adj)
  - fvm::laplacian(turbulence->nut()/Sct, prec1_adj)
  + fvm::Sp(lam1, prec1_adj)
  - (xs->chi_d() & flu_adj) * lam1
);
```

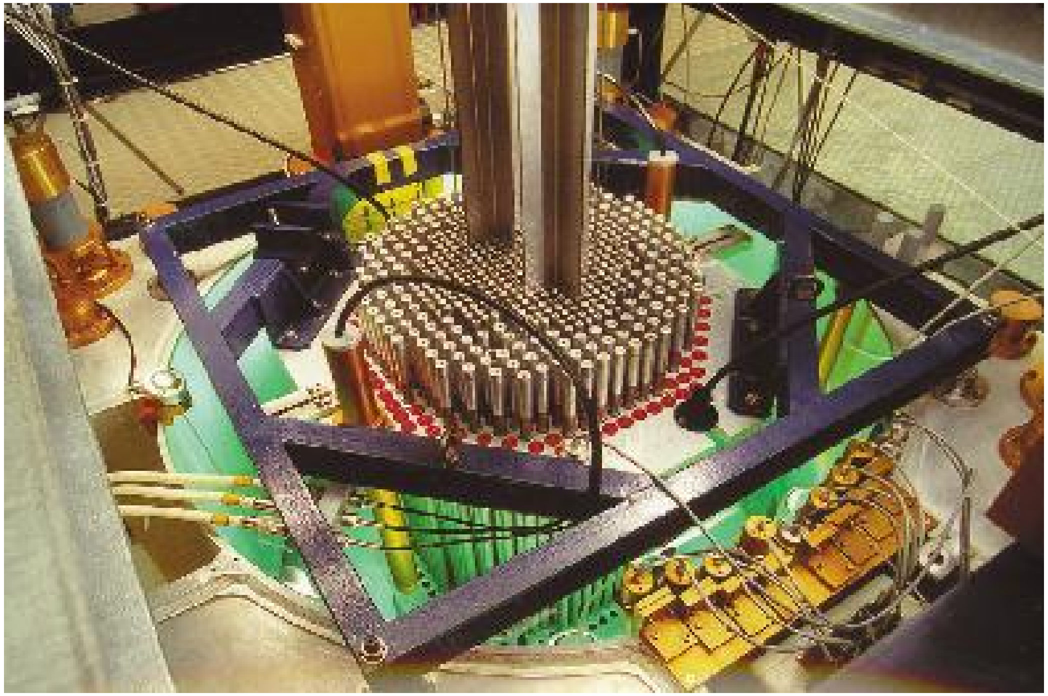
Aufiero, M., 2014. "Development of Advanced Simulation Tools for Circulating-Fuel Nuclear Reactors". PhD Thesis.

Safe Decommissioning of PROTEUS



- Today: Reactor unloaded, fuel in the OPRA building
- Post-Operation Activities:
  - Inventory radioactive material,
  - Disposal of D_2O, Glovebox, experimental components,
  - **Fuel Characterization and disposal,**
  - Reactor instrumentation shutdown

CROCUS – the nuclear reactor for the master program



Training Reactor CROCUS / EPFL

- EPF Lausanne committed to maintain CROCUS
- Staff: currently two scientists + one full-time technician
- Research: feasibility of flexible core configurations and power upgrade being studied

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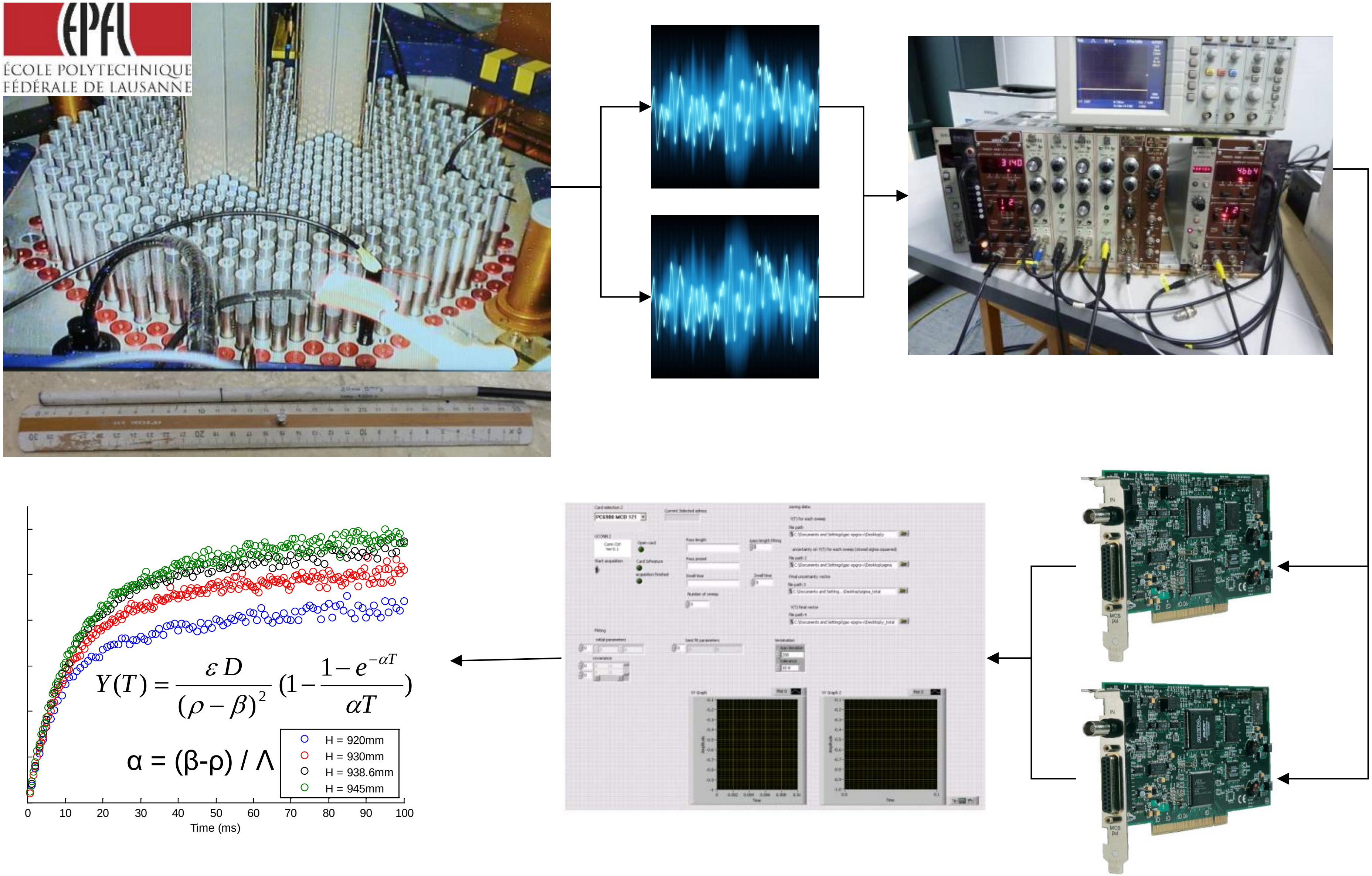
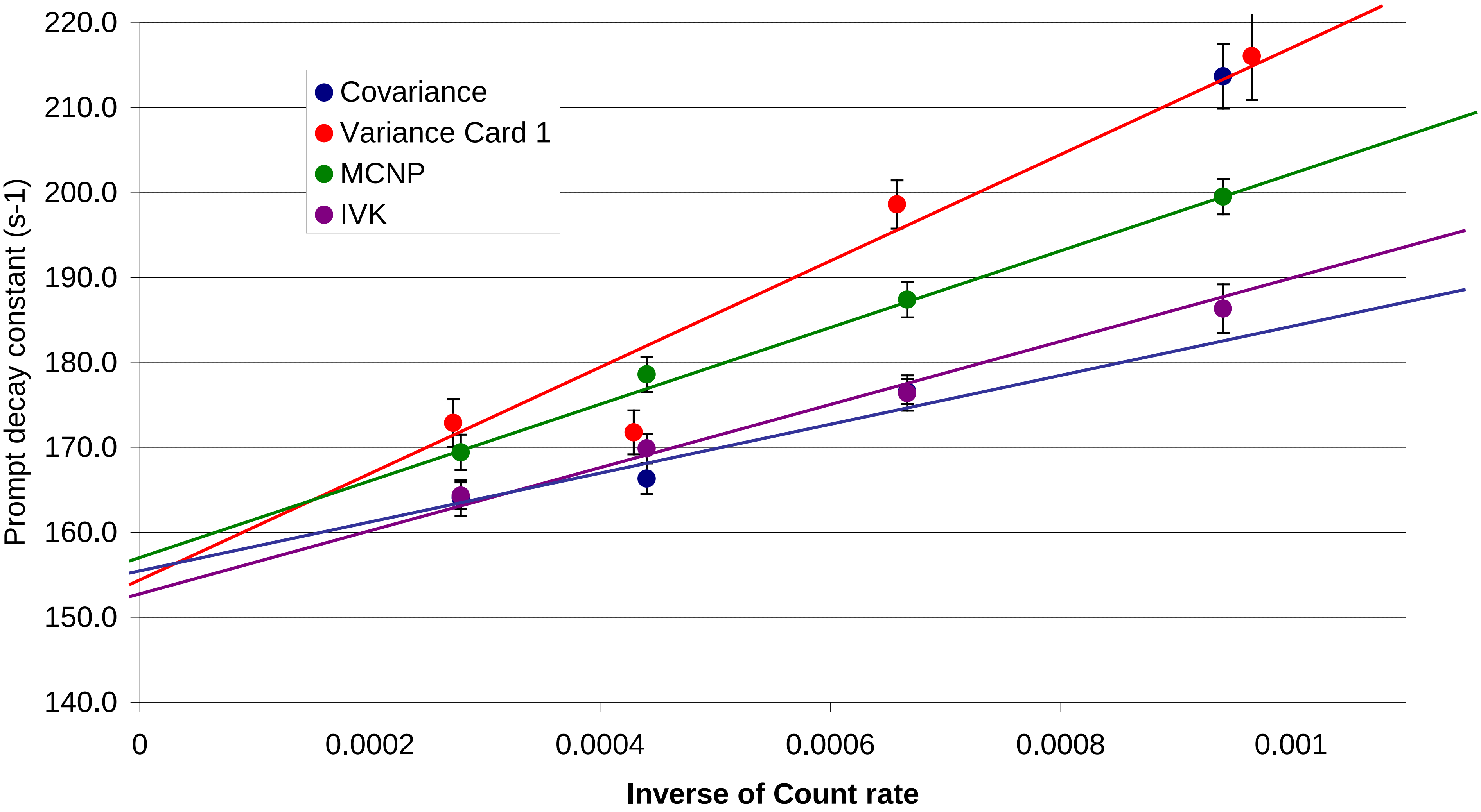
Neutron noise measurements



Extrapolation at delayed critical

$$\alpha = \alpha_0 (1-\rho_\$) \approx \alpha_0 - K / C$$



Research activities 2014-15

- Finalize Neutron noise (swissnuclear) project
- Spent fuel neutron source measurements at AHL
- Data assimilation of the past experimental programme results
  - LWR-PROTEUS in collaboration with swissnuclear
  - GCFR, HTR for SNF proposal and HTR and MSR systems

- Venus-Eole-Proteus collaboration
  - Finish generation time project
  - Perform measurements for delayed neutron and gamma-ray at BR1
  - Representativity analysis of PROTEUS fuel
  - Inter-comparison of neutron noise measurement techniques
- Modelling and V&V activities towards a High-Fidelity CROCUS model

EPFL/PSI as Co-Organizers of ThEC13

PSI as Host and Co-Organizer of SMR Workshop

A Workshop on Small Modular Reactors (SMRs):
Implications of SMRs on low carbon energy and nuclear security

Hosted by
Carnegie Mellon University, Pittsburgh PA, U.S.A.
The Paul Scherrer Institute, Villigen, Switzerland
The International Risk Governance Council, Lausanne, Switzerland
November 18 and 19, 2013

Support for this event has been provided by The John D. and Catherine T. MacArthur Foundation, the U.S. National Science Foundation, The International Risk Governance Council, The Paul Scherrer Institute, and Carnegie Mellon University.

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THANK YOU for your Attention !