Paul Scherrer Institut
Andreas Pautz
NES “Kompetenzen und Highlights”: Laboratorium für Reaktorphysik und Systemverhalten (LRS)
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)

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Pavel Frątka
Adolfo Rais
L. Braun / D. Godat / C. Pletscher

LRS / OG 4100
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H. Ferroukhi (Deputy)

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Exp. Neutronics
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Core Behaviour
OG 4102
H. Ferroukhi (1)

Fuel Modelling
OG 4103
A. Pautz I.P.

System Behaviour
OG 4104
O. Zerkal a.i.

Fast Reactors
OG 4105
K. Mil'kityuk

STARS

Decommissioning
PROTEUS Operation
OG 4106
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FAST

Lab Head Deputy
Post Doc
PhD Student
Master Student
Intern
Guest Scientist
Proteus Facility Manager
Deputy
LRS Mission and Strategy
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
Essence of STARS
Maintain and Further Develop the “Swiss Simulation Platform”

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

New during 2013
Core Physics

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
Scientific Support

Regulatory Support for Licensing of new BWR Fuel Design

Fuel Assembly Design 11x11

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

Core Statics - Changes in Physics Characteristics - EQC vs Cycle 27

Stabilising Trend

S3K Stability Calculations - EQC vs. Cycle 19/27
Core Physics

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

SS 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)

3-D CMFD Calculation with Axial SP3 Kernel
to Resolve Global Balance and Generate 3-D Power Distribution

Planar MOC Calculations
to Generate Planewise Pin-cell Homogenized Xsса

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

Thermal-Hydraulics
- Sub-Channel 3-D Flow

3D CMFD Solver incorporating with Axial SP3 Nodal Method

Planar MOC Solver

Cell Homogenised XS
Radial Cell Coupling Coefficients

Cell Average Flux
Axial Leakage

Intramodel Axial Flux Shape
by SP3 Nodal Solution
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 $^{210}\text{Pb}/^{210}\text{Po}$ 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

Primary $^{210}\text{Po}$ Production Path
Secondary $^{210}\text{Po}$ Production Path
Negligible Naturally Occurring Isotopes

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.

NES Kompetenzen & Highlights, 27.03.2014
Core Physics

High-Fidelity Fuel Depletion

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

- Actinides (Act.)
  - (Average Relative Difference)
  - 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).

- Fission Products (FP)
  - (Average Relative Difference)

Parallelization and Scaling Performance (2.5 M Histories)

- U1 Pin-Cell
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Serpent adopted as main MC Depletion Solver

- Development of Hybrid Neutronic CASMO/Serpent Assembly/Multi-Assembly Depletion Scheme
- Verification and Validation (PROTEUS-II Sample)
- Parallelization and Scaling Performance (2.5 M Histories)
- Development of Coupled Neutronic/Thermo-Mechanics Fuel Rod Depletion

On-Going MSc Project

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Core Physics

Reactor Dynamics and Stability

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)
Plant Behaviour

Consolidated Approach for Plant Model Development and Maintenance (PMSYS)

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

TRACE Modelling for the Swiss Plants

Continuously “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)

PLANT MANAGEMENT SYSTEM with Integrated V&V MATRIX

Code Versions

UQ

PIRT

STF

ITF

Methodology and Scaling

Code V&V

stars.web.psi.ch
Plant Behaviour

Assessment and Validation of TRACE

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

**STF**
CHF and Post-CHF
Single-Channel Heated Experiments

Tests 270, 271 & 272: $P = 70$ bars, $G = 1000 \text{ kg/m}^2$.s

- EXPERIMENT
- TRACE Low Flow
- TRACE Med. Flow
- TRACE High Flow

Becker et al.,
70 Bars
Plant Behaviour

CFD for Safety Applications and Multi-Scale

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)

Broken Loop (Cold)
Unaffected Loops (Hot)

AREVA/Juliette (EPR) Experiments
Core Inlet Tracer Distribution

Measured
Calculated

Pressure Distribution in Downcomer

Areva/Juliette
Azimuthal Pressure Distribution in DC
Fuel Behaviour

-q 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*

-q 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

![Gamma Scan Spectrum](image-url)

*Note: The gamma scan spectrum image shows the distribution of various isotopes such as La140, Zr95, Cs137, Cs134, Ru103, Zr95, Nb95, I131.*
Multi-Physics

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

Falcon Base Irradiation

CMSYS

Falcon Transient

FR T/M Data (X,Z)
Decay Heat (X,Z)
Burnup/Power Zones (X)

COBALT
Cycle-Specific Assembly/Rod geometries and Pin Burnup/Power

LHGR (X,Z,t)

TRACE

FR T/H Data (X,Z)

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

Preliminary Testing for EPR 12-Month EQC

- 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
Uncertainty Analysis

Nuclear Data Uncertainty (PhD)
Development of Global Sensitivity Analysis
NUSS-RF (RDF + FAST Method)

First Assessment for OECD/NEA UAM-Phase 1

MCNPX Modelling

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

Uncertainty Analysis

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
Uncertainty Analysis

Development of Uncertainty/Sensitivity Analysis Methodology for FALCON Modelling and Analyses Assessment for OECD/NEA UAM-2 Benchmark

Methodology – Coupling Falcon/URANIE

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

BWR Case Specifications

<table>
<thead>
<tr>
<th>Test type</th>
<th>Numerical</th>
<th>Experimental</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor</td>
<td>PB-2</td>
<td>Ipa-432</td>
</tr>
</tbody>
</table>

- Cladding ID
- Cladding Thickness
- Cladding Roughness
- Fuel Pellet OD
- Fuel Density
- Fuel Pellet Roughness
- Rod Fill Pressure

Power history
- Constant
- LHGR and history provided

Global Sensitivity Analysis
Methodology based on Sobol Sensitivity Indexes

UAM-II
CSNI/RIA UQ

stars.web.psi.ch
PSI Methodology

• 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

1 - Core bypass
2 - Shroud
3 - Downcomer
4 - RPV
Modelling and Validation against KKG Cycle 10 Scrapping Tests

Validation against Axial Probes (Cycles 22-27) on-going
LRS Highlights: FAST
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.
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, ...
Coupled solvers

- Example: MSR transient behavior

- **Today:** Reactor unloaded, fuel in the OPRA building
- **Post-Operation Activities:**
  - Inventory radioactive material,
  - Disposal of D$_2$O, Glovebox, experimental components,
  - **Fuel Characterization and disposal,**
  - Reactor instrumentation shutdown
CROCUS – the nuclear reactor for the master program

- 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
Neutron noise measurements

\[ Y(T) = \frac{\varepsilon D}{(\rho - \beta)^2} \left( 1 - \frac{1 - e^{-\alpha T}}{\alpha T} \right) \]

\[ \alpha = (\beta - \rho) / \Lambda \]

\[ H = 920\text{mm} \]
\[ H = 930\text{mm} \]
\[ H = 938.6\text{mm} \]
\[ H = 945\text{mm} \]
Extrapolation at delayed critical

\[ \alpha = \alpha_0 (1 - \rho_s) \approx \alpha_0 - \frac{K}{C} \]
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

Thorium Energy Conference ThEC13
October 27 - 31, 2013, Globe of Science and Innovation, CERN, Geneva, Switzerland

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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

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THANK YOU for your Attention!