Outline

- Laboratory of Reactor physics and Systems behavior
  - Education in the field of Nuclear Engineering
  - Overview of research activities

- CORTEX, a Horizon 2020 project

- The VOID project, a swiss collaboration

- Summary
Mandate of LRS

- The primary mandate of the LRS is the education of the next generation of nuclear engineers and scientists through the joint Master program with ETHZ and PSI.
- The secondary mandate of the LRS is the safe and efficient operation of the only research reactor in Switzerland, **CROCUS**.
- The third mandate of the LRS is the undertaking of cutting edge research and development in the nuclear engineering field.

Team

- Under the supervision of Professor Andreas Pautz, a team of 4 scientists, 2 technicians, a secretary, 2 postdocs and 4 PhD students.
ETHZ-EPFL MSc in Nuclear Engineering

- Swiss joint MSc program between ETHZ and EPFL
  - Established in 2008, more than 110 graduates
  - Two-year program, 120 ECTS credits

- Scientific support and research projects through cooperation with the Paul Scherrer Institute
  - Has always been a small program (~10-15 students/y)
  - Makes extensive use of the CROCUS reactor

- 1st semester at EPFL, 2nd at ETHZ, 3rd-4th at PSI
**ETHZ-EPFL MSc in Nuclear Engineering**

**Focus**
- Neutronics
- Thermohydraulics
- Nuclear Material Science
- Nuclear Safety
- Waste Management
- Radiation Protection
- ...and more

**Unique world-class facilities**
- CROCUS research reactor (EPFL)
- Swiss Light Source synchrotron
- Hot Lab facility (PSI)
- Numerous TH experimental facilities (ETHZ, PSI)
- Proton therapy center (PSI)

**Included**
- Three-month industrial internship
- Research project
- Master thesis
ETHZ-EPFL MSc in Nuclear Engineering

- Students enrolled
- Students admitted
- Applications received


Dr Mathieu Hursin
A survey was organized in 2016
For more information visit master-nuclear.ch
The CROcus reactor

Last research reactor in CH

Reactor type
- LWR with partially submerged core
- Room T (controlled) and atmospheric P

Operation
- 100 W (zero-power reactor)
- i.e. maximum neutron flux ~ $2.5 \times 10^9$ cm$^{-2}$.s$^{-1}$
- Control: B$_4$C rods and spillway

Reactivity (pcm) vs Rod position (mm)
Precision: ±0.5 mm ⇔ ±0.2 pcm

Reactivity (pcm) vs Water level (cm)
Precision: ±0.1 mm ⇔ ±0.4 pcm
The CROCUS reactor

Last research reactor in CH

Reactor type
- LWR with partially submerged core
- Room T (controlled) and atmospheric P

Operation
- 100 W (zero-power reactor)
- i.e. maximum neutron flux ~ $2.5 \times 10^9$ cm$^{-2}$.s$^{-1}$
- Control: B$_4$C rods and spillway

Core
- $\varnothing 60$ cm/100 cm, 2-zone
  - Inner: 336 UO$_2$ ~2 wt% 1.837 cm
  - Outer: 176 U$_{\text{met}}$ ~1 wt% 2.917 cm
Use of CROCUS for education

- **At EPFL**
  - Experimental courses at various levels
  - ~ 2 days / week during semesters
  - ~ 170 students per year

- **Outside of EPFL**
  - PSI Reaktorschule
    - Training of shift personal for the Swiss power plants
  - Ecole D'Ingénieurs de Genève
    - 3 days, focus on basic reactor experiments
  - Institut National Polytechnique de Grenoble
    - ~ 20 students over two days focusing on basic reactor experiments
LRS Research in a Nutshell

- Safety Margins in Large Scale Facilities
  - Safety
  - Economics (power uprate, better fuel utilization, etc...)

![Diagram of a nuclear reactor with safety margins and fuel temperature graph]

- Safety limit (Ex: Melting point of UO₂)
- Regulatory limit
- Conservative prediction
- Higher fidelity prediction

Loss of coolant accident
Example of Goesgen Kernkraftwerk:

- Core
  - 3.4m diameter x 4m height
  - 107.7 tons of UO₂
- 51’000 fuel rods and over 16M fuel pellets in the core of the reactor

- Complex probability of interaction

- Approximations used for modeling lead to “conservative methods”
Improvement to Simulation Tools

- Improvement without local quantities
- How reliable are those results?

Swiss National Supercomputing Centre

Gen-FOAM

OFFBEAT
LRS Research in a Nutshell

Modeling
- GeN-Foam: a multiphysics solver
- OFFBEAT: OpenFOAM for fuel behaviour

Predictions of Safety Margins
- Safety limit (Ex: Melting point of UO2)
- Regulatory limit
- Improved margin
- Predicted safety margin
- Conservative prediction
- Higher fidelity prediction
- Unc. range
- Meas. value (hypothetical)

Experimental Measurements
- Reactor noise experiments (VOID, COLIBRI)
- Instrumentation development for high-resolution meas. (min. scintillators, diamond det.)
- Nuclear data meas. (PETALE)

Verification & Validation
- Uncertainty Quantification
- Data assimilation
IAEA
International Atomic Energy Agency

École Polytechnique Fédérale de Lausanne (EPFL)

IAEA Collaborating Centre

For

Advanced Reactor Experiments and High-Fidelity Multiphysics Nuclear Simulation Techniques for Open-Source Code Development and Validation

2019 - 2023
Experimental Data

- Use of CROCUS to generate experimental data for code validation

  “If you want to sleep well at night, do not compare simulations with measurements”
  Professor M. Adams, Texas A&M University

- CROCUS strengths
  - Easy access /space available
  - Neutron and gamma spectra are well characterized

- Two on-going projects
  - CORTEX, a European project making use of COLIBRI device
  - VOID, a swiss collaboration
  - Both rely on «reactor noise» theory
Fluctuations arise from physical phenomena happening inside the reactor
  - turbulent flow
  - coolant boiling
  - vibrations of reactor internals

Signal fluctuations carry valuable information about the system behavior
Reactor Noise

- Neutron noise simulators aim at computing $G$
- $G^{-1}$ determination is difficult; use of Machine Learning
Some examples of core monitoring using reactor noise analysis

- Location of excessively vibrating control rods
- BWR stability monitoring
- Core barrel monitoring in PWRs
- Location of excessively vibrating fuel assemblies

➢ In more general terms: detection of anomalies
Reactor Noise

- In CROCUS, we produce known “anomaly” and record the associated signals
  - CORTEX/COLIBRI: fuel rod controlled oscillations
  - VOID: injection of air bubbles in the core

\[ G(r, r_p, w) \]

\[ [G(r, r_p, w)]^{-1} \]

Validation of the tools computing \( \delta P \)
• COREx monitoring Techniques, EXperimental validation and demonstration
  • Monitor the instantaneous state of the reactor during operation
  • Detect possible anomalies early on
  • Pinpoint the reasons of the anomalies

• Need for core monitoring techniques recently demonstrated by the increase in the neutron noise levels in some Spanish, German, and Swiss Pre-Konvoi PWRs

• Project led and coordinated by Chalmers University of Technology
  • Budget ~ 5M€ over 4 years (EPFL ~ 0.9M€)
  • 18 European, 2 non-European organizations involved
  • 7 additional organizations involved in the Advisory End-User Group
In-core and ex-core detectors’ signals

Signal processing

Anomaly characterisation and localisation

Machine learning trained with validated simulation tools

Follow the project on LinkedIn and at http://cortex-h2020.eu/
COLIBRI: fuel rods displacement experiments

- Current experimental program in CROCUS for measuring noise induced by fuel oscillation
- Device designed for selection of up to 18 $U_{\text{met}}$ rods, ±2.5 mm radial, 2 Hz$^1$
- Two experimental campaigns in 2018 and 2019

Investigation of power fluctuations induced by fuel vibration

▪ Current experimental program in CROCUS for measuring noise induced by fuel oscillation

▪ Device designed for selection of up to 18 U metal rods, ±2.5 mm radial, 2 Hz

▪ First oscillation experimental campaign in September 2018 • within the framework of the CORTEX H2020 project • Up to 18 rods, ±0.5 to 2 mm, 0.1 to 2 Hz • 11 and 15 detectors in pulse and current modes, and instrumentations from three partners (TUD, ISTec and EPFL)

▪ Second oscillation campaign on-going: 15 detectors

▪ Static campaign by the end of the year

Visit of Prof. Starflinger (Uni. Stuttgart) / Presentation of LRS

Prof. Andreas Pautz
Data for neutron noise simulator validation

**Goal:** Compare simulated and experimental CPSD amplitudes and phases for these selected experiments.

- **Time series** (for each detector)
- **Cross/Auto Power Spectral Density**
- **Relative peak power**
- **Phase at fundamental frequency**

- **Amplitude**
COLIBRI experiment 13 – Amplitude

- Fuel rod displacement = +/- 2 mm
- Frequency = 1 Hz

- First-of-a-kind exercise
- Participants:
  - Chalmers University
  - UP Valencia
  - CEA
  - Kyoto University
**Void content measurements**

- Void profile in operating BWRs is only computed.
- Steam velocity can be determined using signal fluctuations.
- With simple correspondence between velocity and void fraction, the void fraction is determined experimentally.

\[
\alpha(z) \approx 1 - \frac{v_0}{v(z)}
\]

- For now, a theoretical model\(^1\)

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PSI, EPFL and *swissnuclear* funding

Validation in the clean conditions in CROCUS

Separate void profile characterization using gamma attenuation techniques, out of core
Velocity measurements using signal fluctuations

Detector 1 ($z_1$) time series

Detector 2 ($z_2$) time series

Time domain analysis

$CCF(\tau) = \int_{-\infty}^{+\infty} X_1(t)X_2(t - \tau)dt$

Frequency domain analysis

$CPSD(z_1, z_2, \omega) = APSD(z_1, \omega). e^{-i\omega \tau_{12}}$

Correlations outside of time zero represent $\tau_{12}$

Slope of CPSD phase gives $\tau_{12}$

Knowledge of $\tau_{12}$ allows determining the average gas velocity between $z_1$ and $z_2$
VOID: Comparison of measurements and simulations

- Successful measurements of air velocity through noise measurements in CROCUS
- Qualitative estimation of void fraction
- Agreement between simulations and measurements should be improved
- Application to BWR monitoring
  - Could be done with Kernkraftwerk Leibstadt signals
  - Change of pattern during a cycle; from cycle to cycle
- LRS and CROCUS play a large role in Nuclear Engineering education in Switzerland and outside.

- LRS R&D activities are dedicated to code development for safety analysis of Nuclear Power Plants; and to their validation.

- Since 2012, LRS has “resurrected” an experimental program built around CROCUS:
  - CORTEX and VOID are examples of activities producing data for code validation.
  - Those programs were designed for industry applications.
  - Demonstrated the strengths/usefulness of CROCUS for research purposes.
Merci!