Neutron noise experiments in the AKR-2 and CROCUS reactors for the CORTEX European project

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The CORTEX project

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• The AKR-2 reactor
• Perturbation systems
• Detection instrumentation
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• Fuel rods oscillator
• Detection instrumentation
• Measurements performed
The Horizon 2020 CORTEX project\textsuperscript{1}

CORRe monitoring Techniques and EXperimental validation & demonstration

\begin{itemize}
  \item develop a core monitoring technique for the early detection, characterization, and localization of anomalies using neutron noise
\end{itemize}

\textit{In-core and ex-core detectors’ signals} $ightarrow$ Signal processing

\textit{Anomaly characterisation and localisation} \rightarrow Machine learning trained with validated simulation tools

\textsuperscript{1} Demazière C., Vinai P., Hursin M., Kollias S., and Herb J., Overview of the CORTEX project, Proc. Int. Conf. Physics of Reactors – Reactor Physics paving the way towards more efficient systems (PHYSOR2018), Cancun, Mexico, April 22-26, 2018 (2018)
The Horizon 2020 CORTEX project

20 partners for 5 work packages

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<th>WP1</th>
<th>Development of modelling capabilities for reactor noise analysis:</th>
</tr>
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<td>• Task 1.1</td>
<td>Modelling of fluid-structure interactions</td>
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<td>• Task 1.2</td>
<td>Modelling of the effect of fuel assembly vibrations</td>
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<td>• Task 1.3</td>
<td>Generic modelling of reactor transfer function</td>
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<td>• Task 1.4</td>
<td>Methodology for uncertainty and sensitivity analysis applied to reactor noise simulations</td>
</tr>
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<table>
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<tr>
<th>WP2</th>
<th>Validation of the modelling tools against experiments in research reactors</th>
</tr>
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<tr>
<td>• Task 2.1</td>
<td>Generation of high quality experimental data for code validation</td>
</tr>
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<td>• Task 2.2</td>
<td>Validation of the computational tools</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>WP3</th>
<th>Development of advanced signal processing and machine learning methodologies for analysis of plant data</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Task 3.1</td>
<td>Generation of basic scenarios and simulated data</td>
</tr>
<tr>
<td>• Task 3.2</td>
<td>Advanced data processing in the time- and frequency-domains</td>
</tr>
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<td>• Task 3.3</td>
<td>Data analysis using machine learning techniques and deep neural networks</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>WP4</th>
<th>Application and demonstration of the developed modelling tools and signal processing techniques against plant data</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Task 4.1</td>
<td>Preparation of available measurements and core data; performance of additional measurements; packaging and distribution of tools to project partners</td>
</tr>
<tr>
<td>• Task 4.2</td>
<td>Demonstration of the computational tools and methodologies developed in WP1 and WP3</td>
</tr>
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<td>• Task 4.3</td>
<td>Recommendations on in-core and out-of-core instrumentations</td>
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</tbody>
</table>

<table>
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<tr>
<th>WP5</th>
<th>Knowledge dissemination and education</th>
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</thead>
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<td>• Task 5.1</td>
<td>Education in reactor dynamics, neutron noise and diagnostics</td>
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<tr>
<td>• Task 5.2</td>
<td>Knowledge dissemination</td>
</tr>
<tr>
<td>• Task 5.3</td>
<td>Communication</td>
</tr>
</tbody>
</table>
Experimental campaigns for CORTEX

20 partners for 5 work packages

- WP1 – Development of modelling capabilities for reactor noise analysis:
  - Task 1.1 – Modelling of fluid-structure interactions
  - Task 1.2 – Modelling of the effect of fuel assembly vibrations
  - Task 1.3 – Generic modelling of reactor transfer function
  - Task 1.4 – Methodology for uncertainty and sensitivity analysis applied to reactor noise simulations

- WP2 – Validation of the modelling tools against experiments in research reactors
  - Task 2.1 – Generation of high quality experimental data for code validation
  - Task 2.2 – Validation of the computational tools

- WP3 – Development of advanced signal processing and machine learning methodologies for analysis of plant data
  - Task 3.1 – Generation of basic scenarios and simulated data
  - Task 3.2 – Advanced data processing in the time- and frequency-domains
  - Task 3.3 – Data analysis using machine learning techniques and deep neural networks

- WP4 – Application and demonstration of the developed modelling tools and signal processing techniques against plant data
  - Task 4.1 – Preparation of available measurements and core data; performance of additional measurements; packaging and distribution of tools to project partners
  - Task 4.2 – Demonstration of the computational tools and methodologies developed in WP1 and WP3
  - Task 4.3 – Recommendations on in-core and out-of-core instrumentations

- WP5 – Knowledge dissemination and education
  - Task 5.1 – Education in reactor dynamics, neutron noise and diagnostics
  - Task 5.2 – Knowledge dissemination
  - Task 5.3 – Communication

First AKR-2 campaign in March 2018
- rotating neutron absorber
- vibrating absorber

First CROCUS campaign in Sep. 2018
- fuel rods oscillator
Data acquisition systems (DAQ)

**TUD**  Pulse-mode DAQ (1 channel): ORTEC Easy-MCS multichannel scaler and MAESTRO software

**EPFL**  Pulse- (4 ch.) and current-mode (4 ch.) DAQ:
- ORTEC PCI-based multichannel scalers and LabVIEW routines
- Lecroy Wavesurfer 10 oscilloscope

**ISTec** SIGMA industry-grade current-mode system (16 ch.), used with Robotron 20046 frequency to voltage converters for pulse-mode.

---

First AKR-2 campaign
6-15 March 2018
AKR-2 Characteristics

- Thermal, zero-power reactor
- Homogeneous uranium-oxide, polyethylene core
- U-235 enrichment of 19.8 % (ca. 790 g)
- Graphite reflector
- $\Phi_{\text{max}} = 2.7 \cdot 10^7 \text{ cm}^{-2}.\text{s}^{-1}$
- $P_{\text{therm,max}} = 1.4 \text{ W (2W)}$
AKR-2 Components

- Fuel
- Reflector
- Control- and Safety rods
- Experimental Channels
- Shielding
# AKR-2 Kinetic Parameters & ZPTF

**MCNP 6.0**
**ENDF/B-VIII.0**

<table>
<thead>
<tr>
<th>Estimate</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Generation time</td>
<td>$\Lambda$</td>
</tr>
<tr>
<td>Beta effective</td>
<td>$\beta_{\text{eff}}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Precursor</th>
<th>$\beta_{\text{eff}}$</th>
<th>$\lambda_i$ (s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.00027</td>
<td>0.01334</td>
</tr>
<tr>
<td>2</td>
<td>0.00137</td>
<td>0.03273</td>
</tr>
<tr>
<td>3</td>
<td>0.00133</td>
<td>0.12079</td>
</tr>
<tr>
<td>4</td>
<td>0.00296</td>
<td>0.30293</td>
</tr>
<tr>
<td>5</td>
<td>0.00123</td>
<td>0.85011</td>
</tr>
<tr>
<td>6</td>
<td>0.00050</td>
<td>2.85508</td>
</tr>
</tbody>
</table>

**Transfer function (1/Hz)**

![Graph showing transfer function vs. frequency (f in Hz)]
AKR-2 Locality of Perturbations

Linear moving absorber (pile oscillator)

Rotating absorber
AKR-2 Perturbation systems
Linear moving absorber

• Drive: pneumatic
• Distance: fixed, 20 cm
• Frequency: 0.08 to 0.71 Hz
• Motion profile: fixed, trapeze (jump)
• Total reactivity: $\rho'_t = 0.0126$ $\$
AKR-2 Perturbation systems
Rotating absorber

MCNP simulation of the flux in the tangential channel 3-4
AKR-2 Perturbation systems
Rotating absorber

MCNP simulation of the flux in the tangential channel 3-4

Total reactivity: $\rho'_{t}=0.0109$

Measured reactivity of the rotating absorber
AKR-2 Position of detectors

1 to 3  He-3 proportional counter
AKR-2 Position of detectors

1 to 3: He-3 proportional counter
4: Fission chamber
5 & 6: Fission chamber, wide range
7: γ- compensated ion chamber, power range
AKR-2 Position of detectors

He-3 proportional counter
Fission chamber
Fission chamber, wide range
γ- compensated ion chamber, power range
AKR-2 Measurement Campaign

Linear Moving Absorber (Pile Oscillator)

<table>
<thead>
<tr>
<th>IsTec</th>
<th>EPFL</th>
<th>TUD</th>
<th>Comparable</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>17</td>
<td>16</td>
<td>15 (17)</td>
</tr>
</tbody>
</table>

Reactor Power: 0.8 to 2.0 W; Perturbation frequency: 0.08 to 0.71 Hz

Rotating Absorber

<table>
<thead>
<tr>
<th>IsTec</th>
<th>EPFL</th>
<th>TUD</th>
<th>Comparable</th>
</tr>
</thead>
<tbody>
<tr>
<td>23</td>
<td>10</td>
<td>4</td>
<td>4 (10)</td>
</tr>
</tbody>
</table>

Reactor Power: 0.2 to 2.0 W; Perturbation frequency: 0.2 to 2.0 Hz

Static measurements of ISTec (and TUD) at different power levels
First CROCUS campaign
17-21 September 2018
The CROCUS reactor

• Reactor type
  LWR with partially submerged core
  Room T (controlled) and atmospheric P
  Forced water flow (160 l.min⁻¹)

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

- **Reactor type**
  - LWR with partially submerged core
  - Room T (controlled) and atmospheric P
  - Forced water flow (160 l.min⁻¹)

- **Operation**
  - 100 W (zero-power reactor)
  - i.e. maximum $2.5 \times 10^9$ cm².s⁻¹
  - Control: $\text{B}_4\text{C}$ rods and spillway

### Reactivity vs Rod Position

- Precision: $\pm 0.5$ mm $\Leftrightarrow \pm 0.2$ pcm

### Reactivity vs Water Level

- Precision: $\pm 0.1$ mm $\Leftrightarrow \pm 0.4$ pcm
The CROCUS reactor

- **Reactor type**
  LWR with partially submerged core
  Room T (controlled) and atmospheric P
  Forced water flow (160 l.min⁻¹)

- **Operation**
  100 W (zero-power reactor)
  i.e. maximum $2.5 \times 10^9$ cm².s⁻¹
  Control: B₄C rods and spillway

- **Core dimensions**
  $\varnothing 60$ cm/100 cm

- **Fuel lattices**
  2-zone: 336/176 rods actually
  Inner: UO₂ 1.806 wt% 1.837 cm
  Outer: U₄met 0.947 wt% 2.917 cm
CROCUS Kinetic Parameters & ZPTF

MCNPv5-1.6
JEFF 3.1.1

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<td>Generation time</td>
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<td>Beta effective</td>
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Estimated APSD from an efficient detector \((10^{-5})\)
Fuel rods oscillator

Design for investigating power fluctuations induced by fuel oscillations

- COLIBRI experimental program in CROCUS
- Up to 18 $U_m$ rods, ±2.5 mm (i.e. 8 pcm), 2 Hz
- Authorization in July 2018 for step-by-step loading and testing procedure, from in-air out of the vessel to critical operation\(^1\)

\(^1\) V. Lamirand et al., “The COLIBRI experimental programme in the CROCUS reactor: development and licensing of a fuel rods oscillator,” RRFM/IGORR 2019, Swemieh (Jordan), 24-28 March 2019
Fuel rods oscillator

Design for investigating power fluctuations induced by fuel oscillations

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Presentation on Thursday at 14:40 (Europa)

Fuel rods oscillator

Specifications

- No elements in the active zone
- Rigid transmission top to bottom, with Al beam
- Fuel rods lifted for oscillation: 10 mm

Oscillator with core structures, and few pins inserted in the device.
Fuel rods oscillator

Specifications

- No elements in the active zone
- Rigid transmission top to bottom, with Al beam
- Fuel rods lifted for oscillation: 10 mm
- Signal outputs
  - Motor’s position from control
  - Motor’s rotation via inductive captor
  - Position at device bottom via cable sensor

All signals collected by the operation software, + extraction of the inductive captor’s output.
Configuration

Experimental locations and associated detectors

NORTH

Water level: 1000 mm

Control rod operation
Detection instrumentation

Experimental locations and associated detectors

Safety Monitor
Photonis CFUM2I $^{235}$U FC
$\varnothing 25.4 \times 120 \text{ mm}$
$10^{-2} n_{th}^{-1}$
Detection instrumentation

Monitor
Merlin Gerin CC54 $^{10}$B CIC
$\varnothing 50 \times 355$ mm
$3 \times 10^{-14}$ A.n$_{th}^{-1}$

Monitor CFUM21 $^{235}$U FC (W)

Experimental locations and associated detectors
Detection instrumentation

Monitor CC54 $^{10}$B CIC (N)

Monitor CFUM21 $^{235}$U FC (W)

Photonis CFUL01 $^{235}$U FC
$\varnothing 48 \times 211$ mm
$1 \text{n}_{th}^{-1}$

Experimental locations and associated detectors
Detection instrumentation

Monitor CC54 $^{10}$B CIC (N)

CFUL01 $^{235}$U FC (W) #654

Monitor CFUM21 $^{235}$U FC (W)

Transcommerce Int. MN-1 BF$_3$

$\varnothing 7.5 \times 100$ mm

$10^{-2}$ n$_{th}$ m$^{-1}$

Experimental locations and associated detectors
Detection instrumentation

Monitor CC54 $^{10}$B CIC (N)

CFUL01 $^{235}$U FC (W) #654

Monitor CFUM21 $^{235}$U FC (W)

MN-1 BF$_3$ (SW) #G45270

BF$_3$

$\varnothing 7.5 \times 100$ mm

$10^{-2} n_{th}^{-1}$

NORTH

Experimental locations and associated detectors
Detection instrumentation

Monitor $^{10}$B CIC (N)
BF$_3$ (NW) #G20056
CFUL01 $^{235}$U FC (W) #654
Monitor CFUM21 $^{235}$U FC (W)
BF$_3$(COLIBRI) #G20055
MN-1 BF$_3$ (SW) #G45270

Photonis CFUF34 FC
$\varnothing 4.7 \times 27$ mm
$10^{-3}$ n$_{th}^{-1}$

Experimental locations and associated detectors
Experimental setup

In addition from COLIBRI:
- Inductive captor
- Cable coder via software
- Motor position output only

**Monitor CC54 $^{10}$B CIC (N)**
CHC 1

**BF$_3$ (NW) #G20056**
ch. 1

**CFUL01 $^{235}$U FC (W) #654**
ch. 597

**Monitor CFUM21 $^{235}$U FC (W)**
CHI 1

**BF$_3$(COLIBRI) #G20055**
ch. 2

**MN-1 BF$_3$ (SW) #G45270**
ch. 4

**Monitor CC54 $^{10}$B CIC (S)**
CHC 2

**MN-1 BF$_3$ (NE) #G47349**
ch. 3

**Monitor CFUM21 $^{235}$U FC (E)**
CHI 2

**CFUF34 $^{235}$U MFC (CC)**
TRAX

**CFUL01 $^{235}$U FC (E) #653, ch. 596**

**Control rod operation**

10 cm

Experimental locations and associated detectors
Acquisition

Experimental locations and associated detectors

In addition from COLIBRI:
- Inductive captor
- Cable coder via software
- Motor position output only

Monitor CC54 $^{10}\text{B} \, \text{CIC (N)}$

$^{35}\text{U} \, \text{FC (W)}$ #654

Monitor CFUM21 $^{35}\text{U} \, \text{FC (E)}$

CFUL01 $^{35}\text{U} \, \text{FC (E)}$ #654

BF$_3$(COLIBRI) #G20055

MN-1 BF$_3$ (NE) #G47349

CHC 1

CHI 1

BF$_3$ (NW) #G20056

ch. 1

ch. 3

ch. 597

ch. 596

ch. 596

TUD
In addition from COLIBRI:
- Inductive captor
- Cable coder via software
- Motor position output only

Experimental locations and associated detectors

Monitor CC54 $^{10}$B CIC (N)
CHC 1

BF$_3$ (NW) #G20056
ch. 1

CFUL01 $^{235}$U FC (W) #654
ch. 597

Monitor CFUM21 $^{235}$U FC (W)
CHI 1

BF$_3$(COLIBRI) #G20055
ch. 2

MN-1 BF$_3$ (SW) #G45270
ch. 4

CFUF34 $^{235}$U MFC (CC)
TRAX

CFUL01 $^{235}$U FC (E) #653,
ch. 596

Monitor CC54 $^{10}$B CIC (S)
CHC 2

MN-1 BF$_3$ (NE) #G47349
ch. 3

TUD EPFL
In addition from COLIBRI:
- Inductive captor
- Cable coder, via software
- Motor position output only

**Acquisition**

Experimental locations and associated detectors

Monitor CC54 \(^{10}\text{B} \text{CIC (N)}\)  
CHC 1

BF\(_3\) (NW) \#G20056  
ch. 1

CFUL01 \(^{235}\text{U FC (W)}\) \#654  
ch. 597

Monitor CFUM2I \(^{235}\text{U FC (W)}\)  
CHI 1

BF\(_3\) (COLIBRI) \#G20055  
ch. 2

MN-I BF\(_3\) (SW) \#G45270  
ch. 4

Monitor CFUM2I \(^{235}\text{U FC (E)}\)  
CHI 2

CFUF34 \(^{235}\text{U MFC (CC)}\)  
TRAX

CFUL01 \(^{235}\text{U FC (E)}\) \#653,  
ch. 596

Monitor CC54 \(^{10}\text{B CIC (S)}\)  
CHC 2

**TUD EPFL ISTec**
# Measurements

**Static measurements**
Reactor: 100 mW stable power, 20°C, 1000 mm water level, control rod operation

**COLIBRI measurements**
Reactor: same, but variable control rod insertion
Setup: 18 rods oscillation, 30 min to 2 h measurements

<table>
<thead>
<tr>
<th>Amplitude (mm)</th>
<th>0.1</th>
<th>0.5</th>
<th>1</th>
<th>1.5</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>±0.5</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>±1.0</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>±1.5</td>
<td>✓</td>
<td>✓</td>
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<td>✓</td>
<td>✓</td>
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<tr>
<td>±2.0</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Measurements

18 rods at ±1.5 mm and 1 Hz
Measurements

Preliminary results for COLIBRI with 18 rods at ±2 mm and 1 Hz modelled with CORE SIM (courtesy DREAM, Chalmers University)
Conclusions and outlook

CORTEX: an H2020 collaborative project for innovative core monitoring techniques

• The two first campaigns in AKR-2 and CROCUS were carried out successfully
• Data processed and distributed along a technical report to the Consortium
• Qualification study of TUD and EPFL acquisition systems with respect to ISTec
• On-going analysis of the experimental data, with uncertainty quantification
• Iteration with the modellers for the design and preparation of the next campaigns:
  • October 2019 for COLIBRI in CROCUS
  • Spring 2020 for AKR-2
• Upgrades of the perturbation devices and instrumentations
• Development of miniature fiber-coupled scintillators for core-mapping
Conclusions and outlook

CORTEX: an H2020 collaborative project for innovative core monitoring techniques

• The two first campaigns in AKR-2 and CROCU5 were carried out successfully
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• Upgrades of the perturbation devices and instrumentations
• Development of miniature fiber-coupled scintillators for core-mapping

Presentation on Thursday by F. Vitullo at 15:20 (#04-1456, Europa)
Measurements

18 rods at ±1.5 mm and 1 Hz
Thank you!