Experimental data for neutron transport & depletion code validation

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Belgian Nuclear Industry

50% of electricity is produced by nuclear energy.

68% of Belgians believe that nuclear power is hard to replace with other reliable sources of energy.

Nuclear energy is provided by 7 reactors on 2 sites.

Without nuclear energy, an extra 14 million tons of CO₂ would be emitted by electricity production.

20,000 jobs linked to the industry.

Stopping the nuclear energy production will lead to an increase of 22% of the average production cost.

MYRRHA project will create 2,000 new jobs.

36 years old is the average age of reactors.

European leader in radioisotopes production to cure cancer.

Courtesy of Thomas Thor

Source: Forum Nuclear
History
- 1952: Gathers nuclear research & technology development in Belgium
- > 60 years later: international player in nuclear R&D
  - 700 staff, >50% academic degree + 70 PhD students
  - 2017: ICERR certificate from AIEA

Missions
- 3 major scientific research areas
  - Nuclear materials sciences
  - Advanced nuclear systems
  - Environment, health and safety

Services towards industry, healthcare, government

Education and training
Unique infrastructure

- **Research reactors**
  - BR2: High Flux MTR – produces 25% of $^{99}$Mo/$^{99}$Tc worldwide!
  - BR1: Activation studies / training
  - Venus: low power facility
  - **Myrrha (in the future): ADS concept**
    - Start with high current proton accelerator

- **Nuclear laboratories**
  - Hot cells: nuclear material science
  - Radiochemistry: renown laboratory for composition analysis
  - Animalarium: biology studies
  - Hades: underground lab for waste & disposal
Experimental data for **neutron transport & depletion** code validation
Context:

Scarcity of (open!) depletion data

- Gd rods
  - Low burnup

- Well-characterized conventional fuels
  - Detailed databooks
  - Follow design evolution
Flavour of past international programmes

Actinide Research in Nuclear Element Radiochemical Analysis of MOX and UOX LWR Fuels Irradiated to High Burnup
<table>
<thead>
<tr>
<th>Reactor</th>
<th>Name</th>
<th>Fuel type</th>
<th>Enrichment (/ Pu content)</th>
<th>Burnup, GWd/t&lt;sub&gt;HM&lt;/sub&gt;</th>
<th># of samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWR</td>
<td>Goesgen</td>
<td>UO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>3.4–4.1%</td>
<td>30 – 56</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Beznau</td>
<td>MOX</td>
<td>5.9% Pu</td>
<td>50 – 60</td>
<td>6</td>
</tr>
<tr>
<td>BWR</td>
<td>Dodewaard</td>
<td>UO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>4.9%</td>
<td>50</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MOX</td>
<td>6.4% Pu</td>
<td>50 – 60</td>
<td>4</td>
</tr>
</tbody>
</table>
**Laboratories**

- **ITU**
  - ICP-MS, TIMS

- **PSI**
  - ICP-MS
  - \(^\gamma\)-spectrometry
  - SIMS

- **SCK•CEN**
  - TIMS, ICP-MS
  - \(\alpha\)-, \(\beta\)-, \(\gamma\)-spectrometry

**Base actinides**
- \(^{232}\text{U}\), \(^{234}\text{U}\), \(^{235}\text{U}\), \(^{236}\text{U}\), \(^{238}\text{U}\)
- \(^{238}\text{Pu},^{239}\text{Pu},^{240}\text{Pu},^{241}\text{Pu},^{242}\text{Pu}\)

**Minor actinides**
- \(^{237}\text{Np}\)
- \(^{241}\text{Am},^{242m}\text{Am},^{243}\text{Am}\)
- \(^{242}\text{Cm},^{243}\text{Cm},^{244}\text{Cm},^{245}\text{Cm}\)

**Fission Products**

- **Volatile:**
  - \(^{129}\text{I}\), \(^{133}\text{Cs},^{134}\text{Cs}\)
  - \(^{135}\text{Cs},^{137}\text{Cs}\)

- **Metallic:**
  - \(^{99}\text{Tc},^{90}\text{Sr},^{95}\text{Mo},^{101}\text{Ru},^{106}\text{Ru},^{103}\text{Rh},^{109}\text{Ag},^{125}\text{Sb}\)

- **Lanthanides:**
  - \(^{144}\text{Ce}\)
  - \(^{142}\text{Nd},^{143}\text{Nd},^{144}\text{Nd}\)
  - \(^{145}\text{Nd},^{146}\text{Nd},^{148}\text{Nd},^{150}\text{Nd}\)
  - \(^{147}\text{Sm},^{149}\text{Sm},^{150}\text{Sm}\)
  - \(^{153}\text{Eu},^{154}\text{Eu},^{155}\text{Eu}\)
  - \(^{147}\text{Pm},^{155}\text{Gd}\)
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</tr>
</thead>
<tbody>
<tr>
<td>PWR</td>
<td>Goesgen</td>
<td>UO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>X%</td>
<td>45 - 70</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Ringhals</td>
<td>MOX</td>
<td>X%</td>
<td>69</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Gundremmingen</td>
<td>UO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>3.7%</td>
<td>62 – 68</td>
<td>2</td>
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<tr>
<td></td>
<td>Leibstadt</td>
<td>MOX</td>
<td>X%</td>
<td>50 – 81</td>
<td>3</td>
</tr>
<tr>
<td>BWR</td>
<td></td>
<td>UO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>3.9%</td>
<td>56 – 63</td>
<td>3</td>
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Context

REGAL

SCALE

Perspectives

MALIBU Analyses

Laboratories

- **CEA**
  - XX

- **PSI**
  - HPLC-MC-ICP-MS, ICP-MS
  - γ- spectrometry

- **SCK•CEN**
  - TIMS, ICP-MS
  - α-, γ- spectrometry

- **Studsvik**
  - DRC-ICP-MS, HPLC-MC-ICP-MS, ICP-MS
  - α-, γ- spectrometry

**Base actinides**

- $^{234}\text{U}$, $^{235}\text{U}$, $^{236}\text{U}$, $^{238}\text{U}$
- $^{238}\text{Pu}$, $^{239}\text{Pu}$, $^{240}\text{Pu}$, $^{241}\text{Pu}$, $^{242}\text{Pu}$

**Minor actinides**

- $^{237}\text{Np}$
- $^{241}\text{Am}$, $^{242}\text{mAm}$, $^{243}\text{Am}$
- $^{242}\text{Cm}$, $^{243}\text{Cm}$, $^{244}\text{Cm}$, $^{245}\text{Cm}$

**Fission Products**

- Volatile:
  - $^{129}\text{I}$, $^{133}\text{Cs}$, $^{134}\text{Cs}$, $^{135}\text{Cs}$, $^{137}\text{Cs}$
  - $^{90}\text{Sr}$, $^{95}\text{Mo}$, $^{99}\text{Tc}$, $^{101}\text{Ru}$, $^{106}\text{Ru}$
  - $^{103}\text{Rh}$, $^{109}\text{Ag}$, $^{125}\text{Sb}$

- Metallic:
  - $^{144}\text{Ce}$, $^{147}\text{Pm}$, $^{155}\text{Gd}$
  - $^{142}\text{Nd}$, $^{143}\text{Nd}$, $^{144}\text{Nd}$
  - $^{145}\text{Nd}$, $^{146}\text{Nd}$, $^{148}\text{Nd}$
  - $^{150}\text{Nd}$
  - $^{147}\text{Sm}$, $^{148}\text{Sm}$, $^{149}\text{Sm}$
  - $^{150}\text{Sm}$, $^{151}\text{Sm}$, $^{152}\text{Sm}$, $^{154}\text{Sm}$
  - $^{151}\text{Eu}$, $^{153}\text{Eu}$, $^{154}\text{Eu}$, $^{155}\text{Eu}$
Next step

Context

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Ariane  Malibu
Purposes

Analytical work (RCA)
+ Techniques cross-check
+ Laboratory cross-check
+ Reduction of uncertainties
+ Interpretation

= High quality data
Material available

‘Databooks’

High duty UO$_2$ rods

Gado rod

Fabrication data

Irradiation data

Macro-cell data

Thermo-mechanical evaluation

Internal “exercise” to check for coherence!

Essential for interpretation of the results!
Context

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Gross-γ scanning, Rod FT1X57-D05

- Calculated burnup
- FGR, %
- Gap, μm

γ-scanning results:
- First-Nuclides samples
- Wetfuel / AGAF segments (2003 Campaign)
- R5 segment
- R4 segment
- R3 segment
- R2 segment

Estimated extremity influence zones

Estimated grid influence zones

UO₂ fuel rods
(U,Gd)\textsubscript{2}O\textsubscript{2} fuel rod

Gross $\gamma$-scanning, Rod FT1A52-E14

- Calculated burnup
- $\gamma$-scanning results:
  - REGAL samples
  - CT1 (2006 analysis)
  - R1 segment
  - R2 segment
  - R3 segment
  - R4 segment

- Estimated extremity influence zones
- Estimated grid influence zones
Comprehensive assessment

- Already performed:
  - FGR
  - RCA
  - OM
  - EPMA
  - Leaching
  - Gas axial communication

- Currently ongoing:
  - RCA (additional samples)
  - Leaching (additional samples)

- Foreseen in the near future:
  - Neutron emission (early 2018)
  - Calorimetry (2019)
Context

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SCALE analysis

Perspectives
### SCALE Model

#### Triton depletion sequence
- **Transport:** Keno Va module
- **Origen-S for depletion**

#### Cross-sections
- **ENDF/B-VII.0**
- **Problem-dependant 238g MC**

#### Discretization
- **Each rod depleted separately**
- **Gd rod in 16 - 20 radial nodes**

#### Materials / composition
- **Fuel:** nominal values
- **Water:** density & boron

#### Operator power history
- **Blind calculations**

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**Context**

**REGAL**

**SCALE**

**Perspectives**

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**FUEL ASSEMBLY 15X15; 16 GD RODS**
Radial profile
D05 rod (High duty UO₂)

Context

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Initial HM

FGR

↑

↓
Radial profile
E14 rod (Gado rod)

Context
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Radial profile
E14 rod (Gado rod)
Performance of SCALE versions

- **SCALE 6.1.x**
  - 28 ‘regular’ UO$_2$ rods
  - Meshed rods: 16 rings
    - 2 UO$_2$ rods
    - 3 Gd rods
  - 4 $10^8$ neutrons (npg x gen)
  - 9 – 10 h / timestep (25% Σ, 75% transport)

- **SCALE 6.2(.1)**
  - Memory(?) crash after few timesteps
  - Need to down-size the problem (e.g. 6-2-1 rods)

- **SCALE 6.2.2**
  - Works fine!
  - ~7h / timestep (5% Σ, 95% transport)
Context

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SCALE analysis

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Code benchmark exercise

- Gd depletion: challenge for neutron transport / depletion codes
  - Huge resonant capture cross-section
  - Important self-shielding effects

- First code-to-code comparison
  - Some codes fail to reproduce experimental values
  - Vesta: revised procedure to properly address the issue
  - Further assessment after bias reduction

- Open to non-REGAL partners
  - No access to experimental values
  - NDA for other aspects
Experimental data for neutron transport & depletion code validation

Highlights

• High quality characterization of UO$_2$ and Gado fuel rods
  • Improved RCA procedures for Gd & burnup

• Rods also used in other projects, with possibly publications
  • Comprehensive characterization of a UO$_2$ fuel pin

• SCALE analysis
  • Encouraging results, good C/E

• Code benchmark exercise for UO$_2$ and Gado pin was set up
  • Open for external partners