Experimental validation of reactivity monitoring techniques for power ads systems to incinerate radioactive wastes

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3. PNS techniques
   • Methodology to correct the prompt decay constant technique
   • Methodology to correct the area-ratio technique
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ADS (Subcritical Accelerator Driven Systems) are the main candidates for dedicated intensive transmutation of actinides.

Reactivity monitoring is one of the critical topics for ADS feasibility.

Industrial ADS will probably not be allowed to reach criticality at any time by design and regulation.

A reactivity monitoring system has to be designed without use to the critical reference.

A solution has been proposed in a series of EURATOM projects including MUSE, PDS-XADS and EUROTRANS by combination of a chain of several techniques, most of them based on kinetic behavior of subcritical systems.
Introduction

Chain of several techniques for the determination of reactivity

- During normal power operation
  - **Current-to-power.** Is based on the proportionality between reactivity and the ratio charged particle beam current to power.
  - **Beam trips technique.** Is based on the dependency of the neutron flux evolution with reactivity after the fast interruption of the charged particle beam (external neutron source).
  - **Noise techniques.** Are based on the statistical properties of the fission chains.
- During loading and start-up
  - **Pulsed Neutron Source (PNS) technique.** Is based on the kinetic response of the neutron flux in a series of periodical neutron pulses.
  - **Noise techniques.** With different sources.
### Introduction

<table>
<thead>
<tr>
<th>Current-to-flux</th>
<th>Beam trips (S.Jerk/Shape) + Noise techniques</th>
<th>PNS (Area/Decay shape) Noise techniques</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Used at full power continuously</td>
<td>• Used at full power</td>
<td>• Used at zero or v. low power</td>
</tr>
<tr>
<td>• High sensitivity in relative changes</td>
<td>• Induced beam trips</td>
<td>• When possible</td>
</tr>
<tr>
<td>• Sensitive to systematics</td>
<td>• Provide the absolute value of reactivity</td>
<td>• Special pulsed proton/neutron source</td>
</tr>
<tr>
<td>• Not for the absolute value of reactivity</td>
<td>• Used to calibrate Current-to-flux</td>
<td>• Provide the absolute value of reactivity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Higher control of systematics</td>
</tr>
</tbody>
</table>
- After corrections PNS can be used as a reference for the reactivity monitoring techniques based on Beam trips and Current-to-flux.

- The interpretation method for beam trips and current-to-flux is equivalent to the interpretation of PNS. The required corrections for local effects are better tested in PNS.

- In the frame of IP-EUROTRANS, a series of experiments have been performed in YALINA-Booster to investigate Beam trips and Current-to-flux reactivity monitoring techniques.

- The YALINA-Booster facility at JIPNR (Belarus) with a 14 MeV D-T source, both in pulsed or continuous mode, with a zero power coupled fast-thermal reactor, has provided unique conditions to test the full chain of reactivity monitoring systems.
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YALINA is a subcritical assembly located in JIPNR-SOSNY institute in Belarus used for this validation in the EURATOM IP-EUROTRANS project.
Subcritical assembly

Fast zone:
- 36% enriched UO₂ in Pb

Thermal zone:
- 10% enriched UO₂ in a polyethylene matrix

Valve zone:
- 108 pins of natural U
- 116 pins of B₄C

Reflector zone:
- Graphite

NG-12-1 neutron generator:
- Deuteron maximum current 1.5 mA.
- Neutron maximum intensity of $\sim 10^{11}$ neutrons/s ($4\pi$).
- Can be operated in pulsed or continuous mode.
- The continuous wave can be interrupted for ~30-40 ms.
- The repetition rate of the beam trips was 1 Hz.
YALINA-Booster DAQ

Pulsed mode detection electronic chain

Analog detection electronic chain
Experimental Configurations

\[
\begin{align*}
SC3a & : k_{\text{eff}} \approx 0.95 \\
& \text{Inner booster: 132} \\
& \text{Outer booster: 563} \\
& \text{Thermal zone: 1077}
\end{align*}
\]

\[
\begin{align*}
SC3b & : k_{\text{eff}} \approx 0.95 \\
& \text{Inner booster: 0} \\
& \text{Outer booster: 563} \\
& \text{Thermal zone: 1090}
\end{align*}
\]

\[
\begin{align*}
SC0 & : k_{\text{eff}} \approx 0.98 \\
+ & \\
SC6 & : k_{\text{eff}} \approx 0.85
\end{align*}
\]

Small reactivity variations were introduced by movements of the control rods ($\Delta \rho \approx 350$ pcm) for SC3a and SC3b.
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Experimental results

Evolution of the counting rate in different detector positions after an external source neutron pulse: SC3a

![Graph showing the evolution of the counting rate over time for different detectors.]
Reactivity determination with the prompt decay constant technique

\[ n_p(t) \propto e^{-\alpha t} \Rightarrow \]
\[ \Rightarrow \alpha = \frac{\rho - \beta_{\text{eff}}}{\Lambda} \Rightarrow \]
\[ \Rightarrow \rho = \alpha \Lambda + \beta_{\text{eff}} \]
\[ \Rightarrow \frac{\rho}{\beta_{\text{eff}}} = \frac{\alpha}{\beta_{\text{eff}}} / \Lambda + 1 \]

Simmons, B. E. and King, J.S., Nucl. Sci. Eng. 3 (1958) 595-608
The local response of the neutron flux measured in a detector can behave far from point kinetics:

- different prompt decay constant and area ratios for different detectors.

Spectral and space dependent effects at each detector position must be taken into account in the evaluation of the experimental results.

Detailed simulations of the subcritical system, with MCNPX, provide the calibration constants and can be used in methods largely tolerant to inaccuracies of the model or nuclear data.
Interpretation and corrections to the prompt decay constant

1) In the first approach we can use point kinetic with $\beta_{\text{eff}}$ and $\Lambda$ experimental or evaluated by detailed simulation.

$\Lambda$ has been calculated with the methodology proposed in [Verboomen et al., Ann. Nucl. En. 33 (2006) 911-916]: $\Lambda$ ($\mu$s) = 60.2 ± 1.0

2) To take into account the local spectral and geometrical effects one effective values of $\Lambda^*$ is computed by MC for each detector.

But, how sensible is the interpretation of the experimental data (the values of $\Lambda^*$) from the details of MC simulation? What if the description of the system in the simulation was not exact?

3) 

$$\frac{1}{k_{\text{eff}}} = 1 - \alpha_{\text{eff}} \Lambda^* - \beta_{\text{eff}}$$

$$\Delta \rho = \Delta \left( \frac{1}{k_{\text{eff}}} \right) = \Delta \alpha \Lambda^*$$

So the question is equivalent to whether: there is a universal relation between $\Delta \rho$ and $\Delta \alpha$, for a given detector position in a given system. If so use it to correct the experimental data.
Validation of the relation of $\rho$ and $\alpha$ with space and energy effects in the kinetics (by MCNPX)

$\Delta\rho = \Delta \left(\frac{1}{k_{\text{eff}}}\right) = \Delta \alpha \Lambda^*$

implies a systematic uncertainty in $k_{\text{eff,exp}}$ of $\sim 80$ pcm

Corrected Point Kinetic $\Lambda^*$

One high statistics full MCNPX simulation per point

$\Lambda^* = \frac{\Delta \rho}{\Delta \alpha}$

$\varepsilon(\Lambda^*) = 8 - 13\%$

(depending on the detector location)

Varying polyethylene density
Varying uranium enrichment
Varying height to width

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The area ratio technique

Reactivity determination with the area-ratio technique

\[ \frac{\rho}{\beta_{\text{eff}}} = - \frac{A_P}{A_d} \]

Sjöstrand, N. G., Ark. Fys. 11 (1956) 233-246
Interpretation and corrections to the area-ratio technique

In point kinetics we have that:

\[ \frac{\rho}{\beta_{\text{eff}}} = - \frac{A_p}{A_d} \]

To take into account spatial kinetics, we introduce correction factors with MCNPX (for each detector position - \( i \)):

\[ - \frac{A_p,\text{MC}^i}{A_d,\text{MC}^i} = C_{\text{MC}}^i \rho_{\text{MC}} = C_{\text{MC}}^i \frac{k_{\text{effMC}} - 1}{k_{\text{effMC}}} \Rightarrow C_{\text{MC}}^i = \frac{A_p,\text{MC}^i}{A_d,\text{MC}^i} \left( \frac{k_{\text{effMC}}}{1 - k_{\text{effMC}}} \right) \]

And we use these factors to correct the experimental data:

\[ \rho_{\text{exp}}^i = - \frac{A_p,\text{exp}^i}{A_d,\text{exp}^i} \Rightarrow k_{\text{eff}} = \left( 1 + \frac{A_p,\text{exp}^i}{A_d,\text{exp}^i} \right)^{-1} \]
In a similar way to the prompt decay methodology we have to determine how sensible is the interpretation of the experimental data (the values of $C_{i,MC}$) from the details of MC simulation.

What if the description of the system in the simulation was not exact?

$$\rho = -\frac{A_p^i / A_d^i}{C_i} \rightarrow \Delta \rho = \xi^i \Delta (A_p^i / A_d^i)$$

Again, the question is equivalent to: How universal is the relation between $\Delta \rho$ and $\Delta (A_p / A_d)$, for a given detector position in a given system.

A large number of MCNPX simulations with perturbations on the geometry/materials of the system and using different libraries were performed to investigate this universality.
Validation of the relation of $\rho$ and $A_p/A_d$ with space and energy effects in the kinetics (by MCNPX)

$$\Delta \rho = \Delta \left( \frac{1}{k_{eff}} \right) = \xi \Delta \left( \frac{A_p}{A_d} \right)$$

Interpretation and corrections to the area ratio technique

One high statistics full MCNPX simulation per point

- Varying polyethylene density
- Varying uranium enrichment
- Varying height to width
- Experimental
Validation of the relation of $\rho$ and $A_p/A_d$ with space and energy effects in the kinetics (by MCNPX)

$$\Delta \rho = \Delta \left( \frac{1}{k_{eff}} \right) = \xi \Delta \left( \frac{A_p}{A_d} \right)$$

Interpretation and corrections to the area ratio technique

One high statistics full MCNPX simulation per point
Raw and Corrected estimations of $\rho$ ($k_{eff}$) for SC3b configuration

Area method

Prompt decay constant

CR out $\Delta k = 1000$pcm

CR out

CR in $\Delta k = 1200$pcm

CR in

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Continuous beam: Current-to-Flux & Beam trips

Explanation of the Beam Trip experiments

Current-to-flux

\[ \rho = cte \cdot \varphi \cdot \frac{I}{P} \]

Reactivity monitoring techniques using Beam Trip experiments

Source-jerk

\[ - \frac{\rho}{\beta_{\text{eff}}} = \frac{L_p}{L_d} \]

Prompt-decay constant

\[ - \frac{\rho}{\beta_{\text{eff}}} = \frac{\alpha}{\beta_{\text{eff}}} \cdot \frac{1}{\Lambda} \]

Equivalent to Area ratio and Prompt decay constant in PNS

One reactivity measurement every Beam Trip

Same corrections than in PNS experiments to get \( k_{\text{eff}} \)
The YALINA-Booster case

- Beam with a 50 Hz oscillation.
- Actual neutron source not proportional to the Beam current.
- (Very) large dead time corrections in pulsed mode detection.
- Detectors in analog mode presented large electronic noise.

In order to analyze we had to:
- averaged over the 50 Hz oscillation,
- correct for Dead time,
- filter the Electronic noise,
- Use the Online Neutron Source Monitoring (14 MeV neutron detector).
YALINA-B Beam trip results: stationary case

- Online reactivity monitoring of a subcritical reactor driven by an external neutron source feasible.
- Source-jerk and PNS area method compatible within uncertainties.
- Pulsed mode detection and analog mode detection.
- Source-jerk lower statistical uncertainties but needs 50s to stabilize after long beam interruption
- Prompt decay constant immediate response but with larger statistical uncertainties.

\[ \rho_{\text{PNS}} = 7.23 \pm 0.01 \]

Analog mode recording of 1000 beam trips (1Hz) (uncorrected source jerk)

\[ \rho = 7.26 \pm 0.15 \]

Counter mode recording

- Source-jerk
- Prompt decay constant
YALINA-B Beam trip results: control rod movement

Reactivity monitoring during a control rod movement using source-jerk method

- The source-jerk technique can detect reactivity variations as small as 350 pcm.
- Source-jerk estimation of reactivity requires to wait for the delayed neutron stabilization before providing the actual reactivity.
Current-to-flux results: stationary case

Proportionality between neutron source and neutron flux is maintained: from 0.03 mA to 0.8 mA beam intensity. Less proportionality for larger intensities.

20 counts/ms in Neut. Source
≈1 mA D beam
Current-to-flux results: control rod movement

Current-to-flux reactivity monitoring during a control rod insertion

- The current-to-flux technique can detect reactivity variations as small as 330 pcm.
- Variations in the source importance + detector efficiency have to be taken into account to obtain the correct $\Delta \rho$.
- The correction is similar to the MSM correction factor

Booster zone

$\Delta k \sim 210 \text{ pcm}$
$\Delta k_{\text{PNS}} \sim 330 \text{ pcm}$

$\varphi^*_{\text{correction}} \sim 140 \text{ pcm} \Rightarrow \Delta k_{\text{corrected}} \sim 350 \text{ pcm}$

Thermal zone

$\Delta k \sim 150 \text{ pcm}$
$\Delta k_{\text{PNS}} \sim 330 \text{ pcm}$

$\varphi^*_{\text{correction}} \sim 170 \text{ pcm} \Rightarrow \Delta k_{\text{corrected}} \sim 320 \text{ pcm}$
### Noise experiments

#### Experimental results: Rossi-α

![Graph showing auto-correlation and fitting results for Rossi-α](image)

\[ R(t) = C + \sum_{k=0}^{N-1} \sum_{l=0}^{N-1} C_{k,l} e^{\alpha_t(t)} - (\alpha_k + \alpha_l) \]

### Experimental results: Feynman-α

![Graph showing Y(T) vs T for Feynman-α](image)

\[ Y(\Delta T) = C_0 \sum_{k=0}^{N-1} \sum_{l=0}^{N-1} \frac{1}{\alpha_i \alpha_l} \left[ \frac{1}{1 + \frac{\alpha_i^2}{\alpha_k \alpha_l} \left( 1 - e^{\alpha_k \Delta T} \right) + \frac{\alpha_i^2}{\alpha_k \alpha_l} \left( 1 - e^{\alpha_l \Delta T} \right)} \right] \]

<table>
<thead>
<tr>
<th>Pos</th>
<th>Conf</th>
<th>CR</th>
<th>Rossi-alpha</th>
<th>Feynman-alpha</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>(\alpha_2 [s^{-1}])</td>
<td>(\alpha_1 [s^{-1}])</td>
</tr>
<tr>
<td>EC5T</td>
<td>SC0</td>
<td>Out</td>
<td>-11340 ± 426</td>
<td>-2442 ± 50</td>
</tr>
<tr>
<td></td>
<td>SC3a</td>
<td>Out</td>
<td>-1094 ± 77</td>
<td>-1114 ± 8</td>
</tr>
<tr>
<td></td>
<td>SC6</td>
<td>Out</td>
<td>-</td>
<td>-3094 ± 113</td>
</tr>
</tbody>
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Excellent coherence of $k_{\text{eff}}$ monitoring techniques after corrections (for set of complementary detectors the uncertainty < 200 pcm)
Up to 400 pcm systematics for beam trips with present analysis.
YALINA-Booster results have validated PNS techniques (Prompt decay constant and Area methods) in a complex system (very different systematics than MUSE).

It has been necessary to develop new methods implemented with MCNP to calculate the corrective factors to the raw data to obtain the reactivity.

After correction, the different kinetic reactivity monitoring methods are consistent. For a single detector with prompt decay constant method <150 pcm and with area-ratio method <1200 pcm. For a set of complementary detectors <170 pcm (for $K_{eff} \approx 0.95$).
Conclusions

• First validation test of:
  • Current to Power monitoring and analysis for an ADS.
  • Beam trips reactivity calibration techniques for an ADS.
  • First monitoring of a fast reactivity variation (control rod movements) by current-to-flux and beam trip reactivity measurement.
  • First estimation of the accuracy of the beam trip calibration techniques established.

The ADS scheme of the reactivity monitoring has been validated for YALINA (coupled fast-thermal reactor)

<table>
<thead>
<tr>
<th>Current-to-flux</th>
<th>Beam trips (analog/pulses)</th>
<th>PNS (Area/Slopes/MCNP corr.) Noise techniques</th>
</tr>
</thead>
</table>

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