Kinetic parameters estimation in the RA-0 research reactor

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1 Introduction

2 Reactor power calibration

3 Subcritical measurements

4 Subcritical reactimeter

5 Conclusions
Several kinetic parameters were estimated in the RA-0 reactor

This work tries to summarize two weeks of experiences. Only the main results are presented here.

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- Power calibration (requirement of the Regulatory Authority) and critical prompt decay constant $\alpha_c$

Second part of the experiences was done in subcritical configurations:
- Application of the $\alpha$-Feynman method with four neutron detectors
- Subcriticality level was modified in two ways: changing the level of the moderator and withdrawing a control rod
- Study of spatial effects present during the estimations

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Implementation of a reactimeter for subcritical states
Introduction

RA-0 Reactor location

Argentinian critical assembly located in the City of Córdoba
Introduction

RA-0 Reactor location

Belongs to the National University of Córdoba and CNEA
Introduction

RA-0 reactor

[Image of RA-0 reactor]
Introduction

RA-0 reactor
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Reactor power calibration

Description

- Based on the spectral analysis of the neutron fluctuations
- A reference measurement system is used for the neutron noise technique
- A linear power range channel of the reactor is calibrated (current to power factor)
- The linearity of the power range channel was checked
- Measurements were done in a steady state and critical reactor
- Five power levels from 0.1 W up to 10 W

Prompt critical decay constant

In each measurement the $\alpha_c$ was also estimated
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**Prompt critical decay constant**

In each measurement the $\alpha_c$ was also estimated
Normalized PSD (fitting parameters in red)

\[ NPSD(\omega) = \frac{PSD(\omega)}{\langle I \rangle^2} = \left[ \frac{2D(1 - \beta)L_1E_f}{\beta^2P} \right] \frac{1}{1 + \left( \frac{\omega}{\alpha_c} \right)^2} + W \]

- **D**: Diven factor
- **\(E_f\)**: Mean energy released per fission
- **\(L_1\)**: Correction factor due to reactor geometry
- **\(P\)**: Reactor power
- **\(\alpha_c\)**: Critical prompt neutron decay constant
- **\(W\)**: Non-correlated white noise
Reactor power calibration

RA-0 reactor core

Console

CR1
CR2
CR3
CR4

Fuel element
Graphite
Control rod
Irradiation channels
CI1 Reference CIC
N6 Reactor CIC

References
Reactor power calibration

Power spectral density

∆f = 40 Hz

\[ \alpha_c = (61 \pm 1) \text{s}^{-1} \]
\[ p = (0.125 \pm 0.006) \text{W} \]

∆f = 200 Hz

\[ \alpha_c = (60 \pm 2) \text{s}^{-1} \]
\[ p = (9.9 \pm 0.9) \text{W} \]

Example

PSD obtained in two different bandwidths. Reactor power was \( \approx 0.1 \text{ W} \) (left) and \( \approx 10 \text{ W} \) (right).
Reactor power calibration

Power spectral density

$\Delta f = 40 \text{ Hz}$

$\Delta f = 200 \text{ Hz}$

Estimated values:

$\alpha_c = (61 \pm 1) \text{s}^{-1}$

$p = (0.125 \pm 0.006) \text{W}$

$\alpha_c = (60 \pm 2) \text{s}^{-1}$

$p = (9.9 \pm 0.9) \text{W}$

Estimation of $\alpha_c$

$\langle \alpha_c \rangle = (65.2 \pm 0.4) \text{1/s}$
Reactor power calibration

Power spectral density

N6 system linearity

N6 system calibration

Calibration factor for N6 system

\[ f_{N6} = (1.37 \pm 0.02) \times 10^7 \text{W} / \text{A} \]
Subcritical measurements

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Subcritical measurements

$\alpha$-Feynman method

- Used for the estimation of the $\alpha$ in subcritical stationary states (with an external neutron source)
- Based on the count statistics of a neutron detector

If no multiplying media were present, the detected counts $N$ in $\tau$ would follow a Poisson process: $\langle N^2 \rangle - \langle N \rangle^2 = \langle N \rangle$

- The fission process produces an increment of the relative variance
- The increment depends on the time interval $\tau$
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Subcritical measurements

$\alpha$-Feynman method

$Y(\tau) = \frac{\langle N^2 \rangle - \langle N \rangle^2}{\langle N \rangle} - 1 = \frac{\epsilon D}{\alpha^2 \Lambda^2} \left( 1 - \frac{1 - e^{-\alpha \tau}}{\alpha \tau} \right) - 2Rd$

$\text{N}$: Counts during $\tau$  
$\alpha$: Prompt neutron decay constant  
$D$: Diven factor  
$\Lambda$: Neutron generation time  
$\epsilon$: Absolute efficiency  

- Other corrections are neglected (finite number of samples, delayed neutrons, etc.). They did not improve the results  
- Covariance method was also applied between two detectors
Subcritical measurements

$\alpha$-Feynman method

$\alpha$-Feynman method with dead time correction

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Covariance method was also applied between two detectors.
Subcritical measurements

Implementation of the method

- Time-stamping system acquiring simultaneously up to three detectors (TTL pulses)
- Any neutron noise method can be applied (\(\alpha\)-Rossi, \(\alpha\)-Feynman, spectral, covariance, etc.)
- The \(\alpha\)-Feynman method was used with the bunching technique, for reducing measurement time

Each measurement took \(\sim 10m\) and the time interval ranges from \(\tau = 50 \mu s\) up to \(\tau = 50 ms\). Two series were made at each level for collecting data from the four detectors.
Using the $\alpha$ values obtained in subcritical states, the value $\alpha_c$ can be estimated. Using its definition $\alpha_c = 1/\Lambda^*$, with the relations:

$$\alpha = \frac{1 - \$}{\Lambda^*} \quad \text{and} \quad R = -\frac{\Lambda^* \tilde{Q}}{\$}$$

The following expressions can be deduced:

**Linear relationship between $\alpha$ and $1/R$**

$$\alpha(R) = \frac{\tilde{Q}}{R} + \alpha_c$$

**Reactivity estimation**

$$\$ = 1 - \alpha \Lambda^* = 1 - \frac{\alpha}{\alpha_c}$$
Subcritical measurements

**Estimation of \( \alpha_c \)**

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Subcritical measurements

Location of detectors

Console

D1 - $^{3}$He 6 cps/nv
D2 - $^{3}$He 6 cps/nv
D3 - $^{3}$He 44 cps/nv
D4 - BF$_{3}$ 7.4 cps/nv

References

- Fuel element
- Graphite
- Control rod
- Irradiation channels

- D1 - $^{3}$He 6 cps/nv
- D2 - $^{3}$He 6 cps/nv
- D3 - $^{3}$He 44 cps/nv
- D4 - BF$_{3}$ 7.4 cps/nv
Subcritical measurements

Control rod extraction

- CR1 from 0 % to 100 % of extraction while the rest of the control rods remained completely withdrawn
- Moderator height at its maximum level $\sim 94 \text{ cm}$
The moderator height was increased from $H = 40\, \text{cm}$ (midplane of the core) up to $H = 70\, \text{cm}$ (∼ infinite)

All control rods remained completely withdrawn
Subcritical measurements

\( \alpha_c \) estimation

Determination of the critical prompt decay constant from the two previous experiences

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<tr>
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Subcritical measurements

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With a critical reactor, the value obtained was $\alpha_c = 65.2(4)$ 1/s (different detector and different core configurations).
It was observed that some of the $\alpha$ estimations depended on the location of the detector.

A new core configuration (Core 15) was arranged to study these effects. The central ring of fuel elements was removed.

Reactor with two separate zones (theory of coupled reactors)
Subcritical measurements

Spatial effects

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Spatial effects

- Detectors D1 (inner reflector) and D2 (outer reflector) were compared.
- The relative difference was obtained: \( \frac{\alpha(D1) - \alpha(D2)}{\alpha(D1)} \)
- Measurements were done at different heights of the moderator and compared to the previous ones.

As expected, the spatial effects were increased with the new configuration. Future work will analyze the results using the coupled reactor theory.
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4 Subcritical reactimeter

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A subcritical reactimeter was implemented in one of the start-up channels of the reactor (N2).

It uses the inverse kinetic equation:

$$\phi(t) = 1 + \frac{\Lambda^*}{R(t)} \left[ \frac{dR}{dt}(t) - \sum_{i=1}^{6} \lambda_i C_i(t) - \tilde{Q} \right]$$

The neutron source value \(\tilde{Q}\) must be estimated firstly (is detector dependant)

The source was obtained with the Least Squares Inverse Kinetic Method (LSIKM)

This experience was done in the Core 14A and detectors D1, D2 and D3 were removed (normal operation configuration)
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Validation of the subcritical reactimeter

With the value of $\tilde{Q}$ the digital reactimeter was implemented in the monitoring and acquisition system of the reactor (SEAD).

Validation was done using another method for the reactivity estimation: $\alpha$-Feynman.

It was done in a configuration different from the used in the LSIKM: changing the moderator level ($H$) with all control rods withdrawn.

<table>
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<th>$H$ [cm]</th>
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<th>SEAD</th>
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<tr>
<td></td>
<td>$\tilde{Q}$ [cps/s]</td>
<td>$\pi$</td>
</tr>
<tr>
<td>54,0</td>
<td>32000(4000)</td>
<td>$-7.1(4)$</td>
</tr>
<tr>
<td>59,6</td>
<td>28000(1600)</td>
<td>$-1.43(1)$</td>
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<tr>
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<th>$\alpha$-Feynman $\tilde{Q}$ [cps/s]</th>
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<tr>
<td>54,0</td>
<td>32000(4000) $-7,1(4)$</td>
<td>$-5,8$</td>
</tr>
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<td>59,6</td>
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<td>$\tilde{Q}$ [cps/s]</td>
<td>$\Delta$</td>
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Conclusions

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2 Reactor power calibration

3 Subcritical measurements

4 Subcritical reactimeter

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Acknowledgement

To all the RA-0 staff members who cooperated in this large and laborious experiments.
Thank you for your attention
Any questions?
Appendix

RA-0 characteristics

Characteristics

- **Tank type reactor with graphite reflector**
- Fuel rods made of LEU UO$_2$ (20%)
- Light water moderated and refrigerated (natural convection)
- Four cadmium control rods with stainless steel cladding
- Nominal power of 1 $W$ with transients of 10 $W$
- Thermal neutron flux $\sim 10^7$ $1/cm^2s$

Utilization

- Teaching and training
- Activation analysis
- Nuclear instrumentation test
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Kinetic parameters estimation in the RA-0 research reactor
RA-0 characteristics

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**Utilization**

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- Nuclear instrumentation test
Current from the detector is divided into its mean and fluctuating part. The last one is amplified and filtered. Two bandwidths are used: 40 Hz and 200 Hz.
**Bunching technique**

Time-stamped pulse train

Counts in $\tau = T_0$

<table>
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<th>2T₀</th>
<th>3T₀</th>
<th>4T₀</th>
<th>5T₀</th>
<th>6T₀</th>
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Counts in $\tau = 2T_0$

<table>
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Counts in $\tau = 3T_0$

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Counts in $\tau = 4T_0$

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<tbody>
<tr>
<td>Count</td>
<td>4</td>
<td></td>
<td>5</td>
<td></td>
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Moderator level

Midplane of the core at \( H = 37 \text{ cm} \)
Efficiency of the detectors

Change in the efficiency of the detectors for different moderator levels
Appendix

Least Squares Inverse Kinetic Method

This method is used for the determination of the neutron source value (for a given detector). Defining a new variable as

\[ D(t) = \frac{dR}{dt}(t) - \sum_{i=1}^{6} \lambda_i \tilde{C}_i(t) \]

the delayed evolution after the rod-drop takes the linear form:

\[ R(t) = \frac{\Lambda^*}{\$f - 1} D(t) - \frac{\Lambda^* \tilde{Q}}{\$f - 1} \]

where $\$f$ is the reactivity of the final state. From a linear fit of the $R(t)$ vs. $D(t)$ data, the parameters $\tilde{Q}$ and $\$f$ are obtained.
Appendix

Least Squares Inverse Kinetic Method

- Method used for estimation of the neutron source
- Linearization of the delayed evolution during a rod-drop between two subcritical states.

\[ \tilde{Q} = (26500 \pm 900) \text{ cps/s} \]