PROMPT NEUTRON DECAY CONSTANT MEASUREMENTS ON THE KRUSTY COLD CRITICAL CONFIGURATION

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George McKenzie

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Overview

• What is KRUSTY?
  o Reactor purpose
  o Phases of experimentation

• What is Rossi-α?
  o Method
  o Why measured?

• Specifics for experiment
  o Detector Placement
  o Execution
  o Results

• Comparison to simulation

• Conclusions
What is KRUSTY? – Reactor Purpose

- Kilopower sized reactor intended for manned deep space missions.
- Concept uses heat pipes to generate electricity.
- Nuclear component is BeO reflected HEU.
- Full scale testing of nuclear component completed early 2018.
What is KRUSTY? – Phases of experimentation

- **Phase 0**
  - Fe surrogate of the core used for systems checks and build practice.
  - DU surrogate core used for systems checks with chemically identical surrogate.
  - Electrically heated system test.
- **Phase 1**
  - Component Criticals.
  - HEU core, reflectors, and absorbers only.
  - Worth of reflector and absorber components measured.
  - Rossi-α measurements performed.

Assembly of the DU Surrogate
What is KRUSTY? – Phases of experimentation

• **Phase 2**
  o Cold Critical
  o Add in heat pipes, electrical generation equipment, and vacuum chamber.
  o Worth measurements of removable components measured.

• **Phase 3**
  o Incremental increase in heat generation through three different “Free Run” scenarios.

• **Phase 4**
  o Full power test. (~800°C)
  o 28 hour continuous test.
  o Examined transient scenarios.

Transition to Cold Critical Configuration
What is Rossi-α? - Method

- The prompt neutron decay constant α is the rate at which the prompt neutron population changes as a function of time.
  \[ \alpha = \frac{k_p - 1}{l} \]
- Measureable quantity is α, used to infer parameter of interest neutron lifetime, l.
- At delayed critical, this constant is the α-eigenvalue of the system.
  \[ \alpha_{DC} = \frac{-\beta}{l} \]
- At prompt critical α = 0.

Example Rossi-α Distribution
What is Rossi-α? - Method

- The prompt neutron decay constant is calculated by measuring the correlations between neutrons emitted by a fissioning system.
- Rossi-α is an autocorrelation of neutron detection events.
  - Combination of the probability of detecting a neutron from a fission chain and also detecting a second neutron from that same chain.

- \[ p(t) = A + Be^{\alpha t} \]
  - A is related to the population of accidental neutrons.
    - Typically related to the source and multiplication of the system.
  - B is related to the population of correlated neutrons.
    - By definition correlated neutrons must be prompt.
    - The probability of detecting correlated neutrons drops exponentially with time (if the system is below prompt critical), so the exponential term is included with the correlated term.
What is Rossi-α? - Method

- The $\alpha$-eigenvalue can be determined two ways.
  - Direct measurement at delayed critical.
  - Inference using two or more subcritical data points.
    - Plot $\alpha$ versus the inverse count rate.
    - The y-intercept is the $\alpha$-eigenvalue.
    - Example for the polyethylene class foils experiment shown on the right.

Example for the polyethylene class foils experiment.
What is Rossi-α? – Why measured?

- Rate at which the prompt neutron population decays as a function of time.
- At DC comprises the fundamental α-eigenvalue.
- Useful for neutron spectrum hardness comparisons in critical experiments.
- Useful for determining neutron lifetime of a system.
- Used to measure subcritical reactivity in a system.

<table>
<thead>
<tr>
<th>Assembly</th>
<th>$\alpha_{DC}$ (1/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lady Godiva</td>
<td>-$1.1 \times 10^6$</td>
</tr>
<tr>
<td>Godiva IV</td>
<td>-$8.4 \times 10^5$</td>
</tr>
<tr>
<td>Topsy (Oy(94) w/ NU reflector)</td>
<td>-$3.7 \times 10^5$</td>
</tr>
<tr>
<td>Zeus</td>
<td>-$8.9 \times 10^4$</td>
</tr>
<tr>
<td>Zeus LEU Lead</td>
<td>-$5.6 \times 10^4$</td>
</tr>
<tr>
<td>Zeus HEU Lead</td>
<td>-$3.8 \times 10^4$</td>
</tr>
<tr>
<td>Sheba</td>
<td>-$200$</td>
</tr>
<tr>
<td>Poly Class Foils</td>
<td>-$199.4$</td>
</tr>
</tbody>
</table>
Specifics for experiment – Detector placement

- Consists of largely commercial off the shelf equipment.
- List-mode module is custom LANL designed and built module.
  - Time tags detection events.
- **Detector is Reuter-Stokes 40 atm 0.25” diameter, 4” long $^3$He detector.**
  - Other detectors could be used.
  - Chosen because of its fast recovery and size.
Specifics for experiment – Detector placement

- For this system, the detectors were placed into the heat pipe channels of the core.
- Closest location feasible to the core.
- Approximately centered active region on the core.
- Radially spread out.
Specifics for experiment – Execution

- **Reactivity on this system adjusted in two ways.**
  - By adjusting the total height of BeO on the machine.
  - By manipulating the critical assembly machine to adjusted the “effective” height of BeO around the core.
- **Three configurations measured.**
  - Two with 10.375” BeO on Platen.
    - 25 mils below critical position.
    - 35 mils below critical position.
  - One with 10.25” BeO on Platen
    - subcritical

BeO reflector loaded onto the Platen.
Specifics for experiment – Results

- $\alpha_{DC} = -1109.4 \pm 14.5 \text{ s}^{-1}$
- Value determined through extrapolation of measured data.
- High count rate near critical (and thermal system) saturated detectors, so measurement was not made at DC.

<table>
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<tr>
<th>1/CR</th>
<th>$\alpha$ (s$^{-1}$)</th>
<th>$p$ ($)</th>
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<tbody>
<tr>
<td>-25 mils</td>
<td>2.42E-05</td>
<td>-1218.9</td>
</tr>
<tr>
<td>-35 mils</td>
<td>3.38E-05</td>
<td>-1268.4</td>
</tr>
<tr>
<td>10.25” BeO</td>
<td>3.98E-05</td>
<td>-1289.5</td>
</tr>
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</table>

y = -5E+06x - 1109.4
$R^2 = 0.991$
Comparison to simulation

- **Measured value**
  - $\alpha_{DC} = -1109.4 \pm 14.5$ s$^{-1}$

- **Calculated value**
  - $\alpha_{DC} = -1317.7 \pm 7.6$ s$^{-1}$

- **About 18% difference**
  - Typically see discrepancy near 10%.
    - Simulation typically calculates high.
  - Likely caused by the value being rather small already and the exclusion of the detectors from the model.
  - Also caused by model not being exactly 1.
  - Overall adequate agreement.
Conclusions

- **Measured value**
  - $\alpha_{DC} = -1109.4 \pm 14.5$ s$^{-1}$
  - Compares well to solution systems.
    - Because of thick thermalizing BeO reflection.

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KRUSTY
This work was supported by the DOE Nuclear Criticality Safety Program, funded and managed by the National Nuclear Security Administration for the Department of Energy.
Questions?
Theory – Prompt Neutron Decay Constant (cont.)

Correlated Neutrons
• Neutrons that have a common fission ancestor.
• Must all be prompt neutrons.

Accidental Neutrons
• Neutrons that do not have a common fission ancestor.
• Include delayed neutrons, source neutrons, and prompt neutrons from different fission chains.

Every branching signifies a fission.