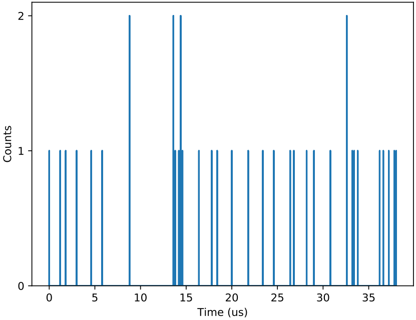
A review of neutron list-mode data processing methods for safeguards applications

Paul Mendoza Alexis Trahan

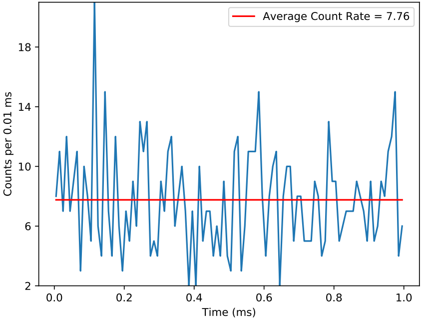
Wednesday, May 2, 2018, 1:25 pm

Introduction

What is list-mode data?



What is Reactor Noise?



- What do people do with this data?
- How do people collect and process this data?

Introduction

Different Processing Methods:

- Rossi-Alpha
- Pulsed Source
- Feynman-Y
- Multiplicity
- Time Interval
- et cetera

Is it possible to use multiple methods?
Are there other ways of processing this data?
Earthquake predictions[1]

Typical Assumptions

- Point Reactor

$$\frac{dn(t)}{dt} = \frac{\rho - \beta_{\text{eff}}}{\Lambda_{\text{eff}}} n(t) + \sum_{i=1}^{I} \bar{\lambda}_i \bar{C}_i$$

n	–	Neutron density
ρ	–	System reactivity
β_{eff}	–	Delayed neutron fraction
Λ_{eff}	–	Neutron generation time
λ	–	Precursor decay constant
C	–	Precursor concentration

- Single Energy Group

$$\sigma = \frac{\int \phi(E)\sigma(E)dE}{\int \phi(E)dE}$$

σ	–	Single-group cross section
ϕ	–	Neutron scalar flux

- Markov Processes
  - State Transitions → Time Diff. Eq. → State probability dist.

Grouping of Processing Techniques

Nicola Pacilio[2–5]

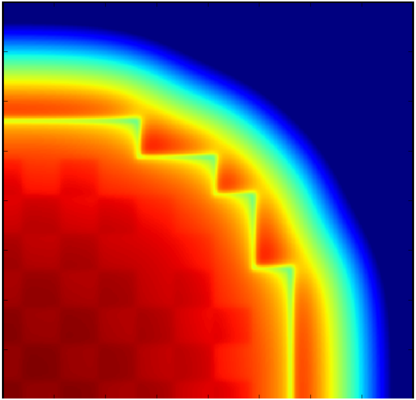
1. Probability profiles of neutron counts
2. Moments of neutron count distribution
3. Correlation among neutron counts in the time domain
4. Correlation among neutron counting level polarities in the time domain
5. Power level correlations in the frequency domain

Imre Pázsit[6–8]

1. Zero Power
2. At Power

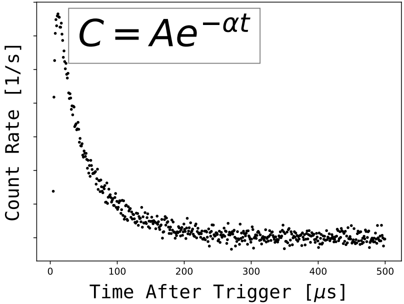
Recent Work

- Estimation of β_{eff} and Λ_{eff} for bare critical systems using the Transient Fission Matrix – TFM (2015)[9]
- Noise source reconstruction (2013)[10]
- Moderator temperature coefficient monitoring using thermocouples and neutron noise signals (2010)[11]
- Calculating β_{eff} in molten salt reactor (2014)[12], Calculating β_{eff} using different noise techniques (2012)[13]



Zero Power

- Rossi-Alpha Distributions (RAD)
  - Binned times between pulses and a triggers
  - $\alpha = \frac{\beta_{\text{eff}} - \rho}{\Lambda_{\text{eff}}}$
  - β_{eff} calculated with Nelson-Number method[14]
- Pulsed neutron source
  - Die-away distribution after a neutron generator pulse
  - The die away is similar to that of the RAD, except the use of a pulsed source more rapidly fills in the distribution



Zero Power

- Feynman-Y

$$Y(t) = A\left(1 - \frac{1 - e^{-\alpha t}}{\alpha t}\right) = \frac{\overline{c^2}(t) - \overline{c}(t)^2}{\overline{c}(t)} - 1$$

Where c is the average neutron count rate for a given gate of width t and A is a fitting parameter

- Pulse-to-Pulse time interval method
  - Distribution of time between pulses
  - Estimate α, along with average time between pulses
- Random Origin time interval method
  - Three-parameter least squares fit to probability distribution derived by Babala[5, 15]

Traditional Safeguards Processing Schemes[16]

- Multiplicity counting can occur in passive, active, cadmium lined, or in systems with varying levels of moderation and number of detectors
- Mostly used for special nuclear material
- Singles (S), Doubles (D), Triples (T), calculated with a gate width and doubles gate utilization factor (f_d)
- Solve for fission rate (F), multiplication (M), and (α, n) fraction

$$a + bM + cM^2 + M^3 = 0$$

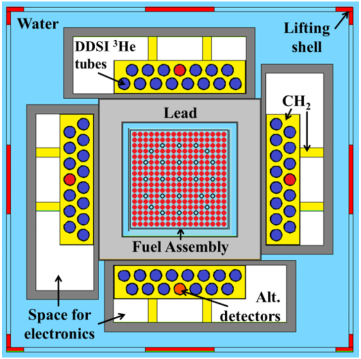
a,b,c are functions of S,D,T, multiplicity moments (ν) and detector efficiency (ϵ)

$$F = \frac{\left[\frac{2D}{\epsilon f_d} - \frac{M(M-1)\nu_{i,2} S}{\nu_{i,1}-1}\right]}{\epsilon M^2 \nu_{s,2}}$$

$$\alpha = \frac{S}{F \epsilon \nu_{s,1} M} - 1$$

Differential Die-Away Self Interrogation Instrument

- DDSI is a nondestructive assay instrument for fuel assembly characterization
- Neutrons thermalize in water and interrogate fuel pins
- Neutron coincidence counting: detect two neutrons that are temporally correlated
  - Same fission event, same fission chain
- Record times of neutron detections
  - list-mode data



Applications

- Neutron list-mode data can be processed in all of the previously mentioned schemes
- DDSI Instrument specific caveats
  - Triples not feasible for fuel assembly measurement[17]
  - “Prompt” and “Delayed” portions of RAD from DDSI measurements are from geometry
  - Pseudo pulsed methods[5] needed with DDSI
  - Potentially redundant information
- Regression Analysis
- Train Neural network system
  - On predictor variables
  - On Raw data like [1]

Partial List of Predictor Variables

- $S \pm \sigma_s$ (BGW)
- $D \pm \sigma_d$ (BGW)
- α_o^* (2G)
- α_o^* (RAD)
- α_f, α_s^* (RAD)
- f_d (2G)
- f_d (2E)
- f_t (2G)
- f_t (2E)
- D_f
- D_s
- Y (BGW)
- $Y \times S/D$ (BGW)
- $\frac{\beta-\rho}{\Lambda}$ (FEY)
- β_{est}
- Λ_{est}
- ρ_{est}
- γ, α, A (RO)

Partial Key:

BGW	–	At "Best" Gate Width
S,D	–	Singles Doubles
2G	–	Two gate method (assumes single exponential)
2E	–	Numeric solution for double exponential assumption
o	–	Overall
f	–	Gate Utilization Factor
RO	–	Random Origin fitting paramters
*	–	Coupled with sum percent error of the assumed exponential type

Conclusions and Acknowledgments

Conclusions

- Neutron list-mode data has been processed for reactor parameters as well as for fissile mass
- Different neutron list-mode data processing methods are expansive
- Synergistic use of calculated parameters and raw data will be attempted with current list-mode data and modern machine learning algorithms

Acknowledgments

The work presented in this paper was supported by the National Nuclear Security Administration of the Department of Energy, Office of International Safeguards, Human Capital Development and Concepts and Approaches.

References I

[1] Bertrand Rouet-Leduc, Claudia Hulbert, Nicholas Lubbers, Kipton Barros, Colin J Humphreys, and Paul A Johnson. Machine learning predicts laboratory earthquakes. *Geophysical Research Letters*, 44(18):9276–9282, 2017.

[2] N Pacilio, A Colombino, R Mosiello, F Norelli, and VM Jorio. The analysis of reactor noise: Measuring statistical fluctuations in nuclear systems. In *Advances in Nuclear Science and Technology*, pages 67–134. Springer, 1979.

[3] Nicola Pacilio, Vincenzo M Jorio, Francesco Norelli, Raffaele Mosiello, Andrea Colombino, and Emilio Zingoni. Toward a unified theory of reactor neutron noise analysis techniques. *Annals of Nuclear Energy*, 3(5-6):239–251, 1976.

[4] N Pacilio. Reactor neutron noise analysis: State of the art. Technical report, Comitato Nazionale per l'Energia Nucleare, Rome (Italy), 1972.

[5] Nicola Pacilio. *Reactor-noise analysis in the time domain*. US Atomic Energy Commission, Division of Technical Information;[available from Clearinghouse for Federal Scientific and Technical Information, Springfield, Va., 1969.

[6] I Pázsit and Y Yamane. The backward theory of feynman-and rossi-alpha methods with multiple emission sources. *Nuclear Science and Engineering*, 133(3):269–281, 1999.

References II

[7] Imre Pázsit and Lénard Pál. *Neutron fluctuations: A treatise on the physics of branching processes*. Elsevier, 2007.

[8] Imre Pázsit and Christophe Demazière. Noise techniques in nuclear systems. In *Handbook of Nuclear Engineering*, pages 1629–1737. Springer, 2010.

[9] A Laureau, M Aufiero, PR Rubiolo, E Merle-Lucotte, and D Heuer. Transient fission matrix: Kinetic calculation and kinetic parameters βeff and λeff calculation. *Annals of Nuclear Energy*, 85:1035–1044, 2015.

[10] Seyed Abolfazl Hosseini and Naser Vosoughi. Noise source reconstruction using ann and hybrid methods in vver-1000 reactor core. *Progress in Nuclear Energy*, 71:232–247, 2014.

[11] Sándor Kiss, Sándor Lipcsei, and János Végh. Monitoring mtc using cold leg thermocouple and background neutron detector noise signals in a vver-440 reactor during a whole fuel cycle. *Annals of Nuclear Energy*, 37(6):827–834, 2010.

[12] Manuele Aufiero, Mariya Brovchenko, Antonio Cammi, Ivor Clifford, Olivier Geoffroy, Daniel Heuer, Axel Laureau, Mario Losa, Lelio Luzzi, Elsa Merle-Lucotte, et al. Calculating the effective delayed neutron fraction in the molten salt fast reactor: analytical, deterministic and monte carlo approaches. *Annals of Nuclear Energy*, 65:78–90, 2014.

References III

[13] S Okajima, T Sakurai, JF Lebrat, V Zammit Averlant, and M Martini. Summary on international benchmark experiments for effective delayed neutron fraction (βeff). *Progress in Nuclear Energy*, 41(1-4):285–301, 2002.

[14] Gregory D Spriggs. Two rossi-α techniques for measuring the effective delayed neutron fraction. *Nuclear Science and Engineering*, 113(2):161–172, 1993.

[15] Dšsan Babala. Interval distributions in neutron counting statistics. *Nuclear Science and Engineering*, 28(2):243–246, 1967.

[16] DG Langner, JE Stewart, MM Pickrell, MS Krick, N Ensslin, and WC Harker. Application guide to neutron multiplicity counting. Technical report, Los Alamos National Laboratory, Los Alamos, NM, 1998.

[17] Stephen Croft, Louise G Evans, Schear A Melissa, Martyn T Swinhoe, and Stephen J Tobin. Feasibility of classic multiplicity analysis applied to spent nuclear fuel assemblies. Technical report, Los Alamos National Laboratory (LANL), 2011.

[18] BE Simmons and JS King. A pulsed neutron technique for reactivity determination. *Nuclear science and engineering*, 3(5):595–608, 1958.

[19] Tsuyoshi Misawa, Seiji Shiroya, and Keiji Kanda. Measurement of prompt neutron decay constant and large subcriticality by the feynman-α method. *Nuclear Science and Engineering*, 104(1):53–65, 1990.