A Semi-empirical Approach to Validating Results from a Fast-neutron Coincidence Collar

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Agenda

- FNCL instrument
- Problem statement
- New approach
- Validation
The Fast Neutron Coincidence Collar (FNCL)
Fast Neutron Coincidence Collar (FNCL)

The FNCL is a neutron coincidence collar designed to verify unirradiation fuel assemblies using fast coincident neutrons from induced fission.

The FNCL is in the late development stage and has been trialed at the following locations:
- JRC Karlsruhe
- INB fuel fabrication plant Brazil
- KNF fuel fabrication plant in the Republic of Korea

Around 60 measurements of PWR fuel have been obtained demonstrating:
- Fast measurement times (20-25 minutes total) per assembly
- High precision (~1% random uncertainty on doubles)
- Low influence from Gd (~3% with maximum Gd loading)

→ Performance is better than He-3 systems.
Fast Neutron Coincidence Collar (FNCL)

- The FNCL will be applied to unirradiated LEU fuel assemblies (PWR and WWER-1000)
- Measurement of fast neutrons in coincidence counting with fast digitizing electronics almost eliminates accidentals (false positives on coincidence events)

High accidentals

V. low accidentals

He-3 based system

Liquid scintillator based system

- Fast neutrons also have lower cross-section with burnable neutrons poisons (e.g. Gd) present in the fuel matrix
- Neutrons < 0.5 MeV are more likely to interact with burnable poisons but are invisible to the detectors
Fast Neutron Coincidence Collar (FNCL)

- Twelve 0.5L liquid scintillation detectors (EJ-309) arranged in three detector panels
- One source slab with typically two AmLi neutron sources (~40 GBq each)
- Cs-137 source (~1MBq) for energy calibration
- Data acquisition unit (DAQ)
  - 500 MHz 14-bit digitizers
  - HV supplies
  - PC and interface
Digitize up to 1M events per second with:

- Detector number (1-12)
- Time stamp (±1 ns)
- Digital sampling of its waveform at 500 MHz 14 bit depth in a time window of 256 ns
- Record pulse train for data re-evaluation
FNCL Data Analysis

Cut non-correlated events and cross-talk

Neutron doubles rate

Cut pile-up events

Energy thresh cut

PSD
Neutrons
Cut gamma rays
Problem statement
### Problem statement: experimental

#### Current approach
- Calibration sources used to test functionality of FNCL system and analysis algorithms
- Cs-137 used to generate gamma-ray data
- Cf-252 used to generate neutron data
- Data recorded and stored in FNCL format

#### Issues
- Gamma-ray data includes some pile-up events, background gamma rays and background neutrons
- Neutron data includes the above plus fission gamma rays and other gamma rays from the source
- Neutron data cannot be isolated from gamma rays, pile-up etc.
- Effects cannot be studied independently
Problem statement: initial simulation

Current approach

- FNCL detectors modelled in MCNPX
- MCNPX-Polimi used to generate time-dependent energy deposition in scintillators
- SimPlis post-processor used to generate pulse heights
- FNCL analysis filters are modelled within SimPlis environment

Identified issues

- The data stream model does not include pulse shapes
- Filters are approximated e.g. PSD or pile-up rejection can only be accurately assessed with complete data including waveforms
- No possibility to generate pulse trains independent from MCNP
- Polimi data inc. passive gamma would be 200 GB+
Synthetic data generation
Empirical inputs

- Data collected from Cf-252, Cs-137 and background
- Data binned into pulse-height spectra
- Background subtracted (where applicable) to find base spectra

- Data filtered to find pulses with good statistics on pulse shape and minimal interference (e.g. pile-up)
- 1000’s of pulses normalized and waveforms averaged
- Base waveforms produced for n, γ
Detector mathematical model

Light output determined previously in previous work [1]

Photons produce linear light output from energy deposition via electrons

\[ \theta_e(E_e) = QE \cdot a \cdot E_e \]  

\( a = 2.6 \) photons/keV(e⁻)

Neutron light output is non-linear via protons

\[ \theta_p(E_p) = QE \cdot a \cdot (b_0 \cdot E_p + \frac{b_1 \cdot E_p}{1 + b_2 \cdot E_p}) \]

where \( b_0 = 0.082 \)  
\( b_1 = 1.36 \times 10^{-4} \)  
\( b_2 = 1.8 \times 10^{-4} \)

Photocathode efficiency \( QE \) assumed to be 30%

Polimi-seeded approach

Time intervals corrected with spacing $\Delta t = -\ln(\zeta)S^{-1}$

S is source emission rate

$\zeta$ is random number

MCNPX-Polimi used to generate energy deposition

Light pulse sequence generated (keVee)

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Light pulse sequence is combined with other data if required e.g. spectrum seeded data

Pulses then generated
Spectrum-seeded approach

Pulse-height spectrum and rates $R$ at each detector are recorded.

Spectrum is sampled at time intervals according to $\Delta t = -\ln(\zeta)R^{-1}$

$\zeta$ is random number

Light pulses are representative of initial spectrum

Light pulse sequence is generated (KeVee)
FNCL data synthesis

Light pulses above a threshold trigger recording of a 256 ns pulse followed by a 22 ns dead-time. Identical to the FNCL digitizers.

1. Neutron and gamma-ray light pulses are generated from base waveforms

2. Statistical noise is applied to the waveforms and integer binning of electrons is applied

3. Baseline noise is also applied
Validation
Validation of gamma-ray synthesis

Cs-137 data was generated for both the spectrum-seeded method and Polimi-seeded method.

Data was analyzed and compared with real data from Cs-137 for both output energy spectrum and PSD distribution.

Good agreement seen.
Validation of gamma-ray and neutron synthesis

Cf-252 neutrons difficult to isolate experimentally therefore both the neutron and gamma-ray spectra were validated together

Cf-252 data generated:

- Fission neutrons and gamma rays - Polimi-seeded method
- Fission products – Spectrum-seeded method using sampled Cf-252 gamma spectrum

The data were combined and analyzed and compared with real data from Cf-252
Validation of gamma-ray and neutron synthesis

Real data

Synthetic data
Validation of gamma-ray and neutron synthesis

PSD analysis shows good agreement between real and synthesized data.

The synthesized spectra can be isolated into constituent parts as shown – these are useful for testing the FNCL under given conditions.
Validation of time dependency

The synthetic data for Cf-252 was analyzed on board the FNCL to determine the doubles rates with the collective inclusion of the gamma-ray components.

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<th>Source</th>
<th>Doubles (cps)</th>
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<tr>
<td>S1. Cf-252 (synthetic) Fissions neutrons only</td>
<td>292.0 ± 2.3</td>
<td>14% higher rate than R1</td>
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<td>S2. Cf-252 (synthetic) Fission neutrons and γ</td>
<td>263.5 ± 2.2</td>
<td>n-γ pile-up events (rejected by filter)</td>
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<td>S3. Cf-252 (synthetic) All fission and fission products</td>
<td>257.4 ± 2.1</td>
<td>Good match with R1</td>
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<tr>
<td>R1. Cf-252 (real) All fission and fission products</td>
<td>256.3 ± 2.4</td>
<td>Good match with S3</td>
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Conclusions and further work

✓ This approach can be used to accurately synthesize neutron and gamma-ray data including waveforms for liquid scintillator detectors

✓ Neutron (or other) data can be isolated from gamma-ray fields to allow controlled examination

✓ Time-dependent information is maintained and can be applied to coincidence or multiplicity simulations

✓ The spectrum-seeded method allows the accurate simulation of passive gamma-ray fields without the need for lengthy Monte Carlo calculations and processing, and additional large data files

+ Study effects of pile-up and neutron misclassification in more detail

+ Further optimize analysis filters