Sara A. Pozzi
Department of Nuclear Engineering and Radiological Sciences, University of Michigan, Ann Arbor, MI 48109

Los Alamos National Laboratory
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Outline

- Motivation
- MCNP-PoliMi Code System
- Scintillation Detectors
- Scalable-Platform Electronics
- Analysis Algorithms for SNM Identification
- Conclusions
- Upcoming Events
“It should not be assumed,” write physicists Richard Garwin and Georges Charpak, “that terrorists or other groups wishing to make nuclear weapons cannot read.” Consequently, the main obstacle to a terrorist planning a nuclear nightmare would be acquiring fissile material — plutonium or highly enriched uranium capable of rapid nuclear fission. Nearly 2 million kilograms of each have already been produced and exist in the world today. It takes less than ten kilograms of plutonium, or a few tens of kilograms of highly enriched uranium, to build a bomb.
Resurgence of Nuclear Power

Challenge # 2 – Safeguarding Nuclear Fuel

- The resurgence of nuclear power requires advanced materials control and accounting techniques for nuclear fuel reprocessing in order to prevent diversions, ensure safety, and reassure the international community.
- Near real-time accountability measurements are needed for material at all stages of the fuel cycle.
- Quantification of Pu-239 and other fissile isotopes.
Detection Technology

Challenge # 3 – Replacement Technology for He-3 Neutron Detection

- $^3$He counters are widely deployed in radiation portal monitors
  - They are a common choice for detecting neutrons
    - Energy information is lost
    - $^3$He is currently in short supply

- Candidates for $^3$He replacement should have:
  1. High efficiency
  2. Reliable neutron/gamma-ray discrimination
  3. Neutron spectroscopic capabilities
Description of Simulation Tools

**MCNP-PoliMi Monte Carlo Code**

- MCNP-PoliMi was developed to simulate correlation measurements with neutrons and gamma rays

- Unique features:
  1. Physics of particle transport (MCNP-PoliMi code)
     - Prompt neutrons and gamma rays associated with each event are modeled explicitly; neutron and photon-induced fission multiplicity distributions have been implemented
     - Improved simulation of correlation and multiplicity distributions
  2. Physics of detection (Detector Response Module)
     - Each collision in the detector is treated individually
     - Improved simulation of detector response
MCNP-PoliMi Code System

Detector Response Simulation Capabilities

- MCNP-PoliMi was developed to simulate correlated particle interactions on an event-by-event basis.
- The code allows for high-fidelity detector response simulation:
  1. Nonlinearity in the light output from neutron collisions
  2. Varying light output from carbon and hydrogen collisions
  3. Pulse generation time within the scintillator
  4. Detector dead time
  5. Detector resolution is being implemented

$^{252}$Cf time-of-flight with a liquid scintillator
The resolution functions are based on measured plastic-scintillator data.

\[ R(E) = A \cdot E + B \sqrt{E} + C \]
Passive Measurements in Ispra, Italy

Cross-Correlations of Plutonium Oxide

- Measurements of PuO$_2$ standards were performed in August, 2008 at the JRC in Ispra, Italy
- Passive cross-correlation data was acquired using six cylindrical EJ-309 liquid scintillation detectors
  - Offline pulse shape discrimination (PSD) was used to separate the neutron and gamma contributions
Passive Measurements in Ispra, Italy

Measurement Summary

- We collected approximately 10k correlations for each of five different samples:
  1. Low burnup, 100 g
  2. Low burnup, 300 g
  3. Low burnup, 500 g
  4. High burnup, 50 g
  5. High burnup, 100 g

<table>
<thead>
<tr>
<th>Sample Isotopics (mass percent)</th>
<th>Isotope</th>
<th>Low Burnup</th>
<th>High Burnup</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pu-238</td>
<td>0.20%</td>
<td>1.72%</td>
<td></td>
</tr>
<tr>
<td>Pu-239</td>
<td>70.96%</td>
<td>58.10%</td>
<td></td>
</tr>
<tr>
<td>Pu-240</td>
<td>24.58%</td>
<td>24.77%</td>
<td></td>
</tr>
<tr>
<td>Pu-241</td>
<td>3.29%</td>
<td>9.77%</td>
<td></td>
</tr>
<tr>
<td>Pu-242</td>
<td>0.98%</td>
<td>5.65%</td>
<td></td>
</tr>
</tbody>
</table>
Passive Measurements in Ispra, Italy

PuO$_2$ Powder Sample
Measured Data

Low-Burnup PuO$_2$, 500 g
Passive Detection Results

Simulated and Measured

PuO₂ samples and containers: varying fill heights

Pb shielding

Pu-238(SF)  Pu-238(a,n)  Pu-239(SF)  Pu-239(a,n)  Pu-240(SF)  Pu-240(a,n)  Pu-241(a,n)  Pu-242(SF)  Pu-242(a,n)  Pu-239(a,n)
Passive Measurements of MOX
Experimental Geometry

- Idaho National Laboratory
- Zero-Power Physics Reactor Facility (ZPPR)
- Measurement of Mixed-Oxide Fuel pins (MOX)
## Passive Measurements of MOX Material Composition

<table>
<thead>
<tr>
<th></th>
<th>Pin #1</th>
<th>Pin #2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MOX weight [g]</strong></td>
<td>89.55</td>
<td>89.78</td>
</tr>
<tr>
<td><strong>Total Pu weight [g]</strong></td>
<td>11.74</td>
<td>14.01</td>
</tr>
<tr>
<td>Pu-238</td>
<td>0.01</td>
<td>0.01</td>
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<tr>
<td>Pu-239</td>
<td>10.19</td>
<td>9.81</td>
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<tr>
<td>Pu-240</td>
<td>1.36</td>
<td>3.66</td>
</tr>
<tr>
<td>Pu-241</td>
<td>0.04</td>
<td>0.15</td>
</tr>
<tr>
<td>Pu-242</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Am-241</td>
<td>0.16</td>
<td>0.51</td>
</tr>
<tr>
<td><strong>Total U weight [g]</strong></td>
<td>66.90</td>
<td>64.58</td>
</tr>
<tr>
<td>U-235</td>
<td>0.15</td>
<td>0.14</td>
</tr>
<tr>
<td>U-238</td>
<td>66.75</td>
<td>64.45</td>
</tr>
<tr>
<td>O-16</td>
<td>10.57</td>
<td>10.59</td>
</tr>
</tbody>
</table>
Monte Carlo Simulation
MCNP-PoliMi Model

This work was supported by the U.S. Department of Energy Office of Nuclear Energy and the Advanced Fuel Cycle Initiative Safeguards Campaign. Idaho National Laboratory is operated for the U.S. Department of Energy by Battelle Energy Alliance under DOE contract DE-AC07-05-ID14517.
Monte Carlo Simulation
MCNP-PoliMi Model

Aluminum Can
MOX fuel material
Fuel pin cladding
### Neutron Creation Data

<table>
<thead>
<tr>
<th>Data Type</th>
<th>Pin #1</th>
<th>Pin #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrons/sec from Spontaneous Fission</td>
<td>1426.1</td>
<td>3767.9</td>
</tr>
<tr>
<td>Neutrons/sec from (alpha,n) Reactions</td>
<td>854.3</td>
<td>1414.7</td>
</tr>
<tr>
<td>Neutrons/sec from Induced Fission</td>
<td>278.6</td>
<td>665.7</td>
</tr>
<tr>
<td>Average Energy of Neutrons from Spontaneous Fissions</td>
<td>1.98</td>
<td>1.98</td>
</tr>
<tr>
<td>Average Energy of Neutrons from (alpha,n) Reactions [MeV]</td>
<td>2.30</td>
<td>2.31</td>
</tr>
<tr>
<td>Average Energy of Neutrons from Induced Fission [MeV]</td>
<td>1.69</td>
<td>1.69</td>
</tr>
</tbody>
</table>

### Photon Creation Data

<table>
<thead>
<tr>
<th>Data Type</th>
<th>Pin #1</th>
<th>Pin #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photons/sec from Spontaneous Fission</td>
<td>4261.1</td>
<td>11258.4</td>
</tr>
<tr>
<td>Photons/sec from (alpha,n) Reactions</td>
<td>645.7</td>
<td>1132.1</td>
</tr>
<tr>
<td>Average Energy of Photons from Spontaneous Fissions</td>
<td>0.94</td>
<td>0.94</td>
</tr>
<tr>
<td>Average Energy of Photons from (alpha,n) Reactions [MeV]</td>
<td>0.76</td>
<td>0.74</td>
</tr>
</tbody>
</table>
Simulation Results and Comparison
Neutron Energy Spectra and Average Energy

- The quantity of MOX fuel material effects the emitted neutron energy distribution
- As the number of fuel pins increases the average neutron energy decreases
Simulation Results and Comparison
Neutron Energy Spectra

- The combination of six MCNP-PoliMi sources provide the anticipated neutron energy distributions for the 90 fuel pin can
- Neutron energy tally on the exterior of the fuel pin can

**Diagram**: Neutron Energy Spectra

- Blue line: Pin#1-2009, <E>=1.86 MeV
- Red line: Pin#2-2009, <E>=1.85 MeV
- Green line: Oxygen Elastic Cross-Section

**Axes**:
- Neutron Energy (MeV)
- Normalized Probability
- Elastic Scattering Cross-Section (barns)

**Legend**: ENDF/B-VII.0 (USA, 2006)
Measurement Results
Cross-Correlation Functions

- PSD allows for study of individual components of the cross-correlation curve
- neutron-neutron correlations provide information on fission events

12 minute acquisition, 90 pins of #2, 40 cm detector distance, 70 keVee threshold, 2 in lead shielding
Measurement Results
Cross-Correlation Functions

- Comparison of (n,n) to (n,p) and (p,n) correlations:
  - Pin #1—0.74
  - Pin #2—2.34

Pin #1

Pin #2

3.45 (n,n) cps

5.18 (n,n) cps
Measurement vs. Simulation
Cross-Correlation Functions

- Good agreement in neutron-neutron correlations
- High gamma-ray background from radioactive decay of fuel elements hinders good photon related correlations
Capture-Gated Detectors

Working Concept

Capture-gated detectors* provide enhanced neutron spectroscopic information

- Initial neutron scattering pulses is followed by capture pulse
- Size of the scattering pulse is directly related to the initial neutron energy

Capture-gated neutron spectroscopy can be performed by adding material(s) with high $\sigma_a$ for thermal neutrons ($^{10}\text{B}$, $^6\text{Li}$, $\text{natGd}$, Cd, etc.)

![Graph showing scattering and capture pulses](image)

Passive Measurements, $^6$Li Detector

**Heterogeneous, $^6$Li Glass/Plastic Scintillator**

- The detector consists of 7 slabs (4 BC-408 and 3 GS20 slabs)
- 1 Ci $^{239}$Pu-Be source shielded by 2 in. of lead
- The source was placed 30 cm from the detector
- Ratio of neutron captures from all neutron collisions: 2.5%
Scintillation Detectors: $^{10}$B-Liquid Measurement Results

- Saint-Gobain BC-523A homogeneous detector based on liquid scintillator BC-501A
- The detector is loaded with 4.41% wt. of $^{10}$B
- Large thermal-neutron capture cross section (3858 barns) is utilized to produce capture pulses

$$\frac{10}{3}B + \frac{1}{6}n \rightarrow ^{11_{\frac{5}{3}}}B \rightarrow \frac{4}{2}\alpha + \frac{7}{3}Li + \gamma$$

$E_\alpha = 1.47$ MeV
$E_{Li} = 0.84$ MeV
$E_\gamma = 0.48$ MeV (94%)
Scintillation Detectors: Cd-Plastic

**Measurement Results**

- **CAEN V1720 waveform digitizer**
  - 12-bit vertical resolution
  - 250-MHz sampling rate (4-ns step)
  - DNNG data-acquisition software

- **Cadmium detector at 15 cm from a $^{252}$Cf source**
  - $U = 1350$ V
  - ~62000 neutrons/s from the source
  - ~3300 neutrons/s at the face of the detector

- **Binary data files obtained**
  - Measurement time 300 s, 8 files
  - ~740,000 pulses/file
  - 100 points/pulse

- **Thresholds**
  - Measurement threshold = 75 keVee
  - Coincidence (capture-gated) window = 40 µs

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April 22, 2010
Scintillation Detectors: Cd-Plastic

**MCNP-PoliMi Simulation Results**

- The MCNP-PoliMi code produces a specialized output file detailing all collisions within a detector.
- DNNG-developed algorithms analyze the information in this file to predict detector response.
- Result Examples:
  - Positions of a specific collision type in detector.
  - Track histories with description of collision types.

3-D Plot of Neutron Capture vs. Position

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Detection for Nuclear Nonproliferation Group

Los Alamos National Laboratory

April 22, 2010
Scalable-Platform Electronics

Digitizer Development

- CAEN V1720 waveform digitizer
  - 12-bit vertical resolution
  - 250-MHz sampling rate (4-ns step)
  - 8 channels
  - 2-V dynamic range
  - One motherboard FPGA
  - 8-channel FPGAs
  - DNNG custom-made data-acquisition software
  - Optimized for offline mode

- FPGA waveform digitizer
  - 14-bit vertical resolution
  - 250-MHz sampling rate
  - 4 channels
  - 2-V dynamic range
  - One FPGA
  - DNNG custom-made data-acquisition software
  - Optimized for online mode
The electronics developed in this project will allow extraction of very low-energy pulses.
Such pulses are generated from neutrons depositing very little energy within the scintillators.
Accurately measured low-energy portion of the fission spectrum will lead to more accurate neutron spectroscopy.

Fast, robust identification and characterization.
Scalable-Platform Electronics

*Platform Analysis Algorithms*

- Normalized Cross Correlation
- Widely used in template matching for image processing, wireless communication etc
- 2x improvements in probability of detection
- Real-time detection
- Simulations show lowest detectable energy to be 3 keVee
- Eventually real-time PSD on FPGA

![Probability of Detection vs. Pulse Energy Graph]

Correlation threshold can be varied to tolerate different error rates
Analysis Algorithms

Digital Pulse Shape Discrimination (PSD)

- Detector pulses are digitized at 250 MHz
- Each pulse is integrated offline and classified by comparison to a discrimination line

![Diagram showing pulse shapes and integration areas]

\[ R = \frac{\text{Tail Integral}}{\text{Total Integral}} = \frac{A_2}{A_1} \]

This technique breaks down at low detection thresholds (200-keV neutron energy deposited)

Misclassified particles!
Analysis Algorithms

Reference-Pulses PSD

- To improve low-energy PSD, neutron and gamma-ray reference pulses have been created.
- This allows for higher-fidelity measurements of fission spectra.

Accuracy of measured neutron data limited by PSD performance.

For classification, each measured pulse is compared point-by-point to each reference pulse.
Analysis Algorithms

Neutron Spectrum Unfolding

- Neutron pulse height distributions are related to the neutron energy spectra
- Advanced algorithms are needed to "unfold" the energy spectra

\[ N(L) = \int R(E_n, L) \Phi(E_n) dE_n \]
Upcoming Measurement Campaign
Fissile Samples in Ispra, Italy, June 2010

- Measurements of MOX powder (2 kg total mass) will be performed using capture-gated and traditional scintillators as well as $^{3}$He tubes
- Cross-correlation, pulse height, and multiplicity data will be acquired

Mass fractions of MOX samples:
- O-16, 16.4%
- Pu-238, 0.0%
- Pu-239, 11.1%
- Pu-240, 4.7%
- Pu-241, 0.5%
- Pu-242, 0.3%
- Am-241, 0.1%
- U-235, 0.5%
- U-238, 66.1%
Upcoming Measurement Campaign
Los Alamos LANSCE Facility, July/August 2010

- Previous experiments at LANSCE have measured the fission neutron energy spectrum of $^{235}\text{U}$ and $^{239}\text{Pu}$ above 1 MeV
- A significant fraction of the neutrons from fission lies below 1 MeV – these measurements will extend the data down to approximately 100 keV
- Measurements will be performed using a DNNG-developed digital data-acquisition and pulse-shape-discrimination system
New Courses Available in NERS

- **Detection Techniques for Nuclear Nonproliferation**
  - Nuclear nonproliferation; homeland security
  - Introduction to the physics of nuclear fission
  - Monte Carlo simulations for nuclear nonproliferation applications
  - Passive and active inspection of SNM
  - Detectors and safeguards instruments
  - Winter 2008 – 17 students
  - Fall 2009 – 19 students

- **Nuclear Safeguards**
  - Collaboration with the Oak Ridge National Lab Safeguards Lab user facility
  - History of nuclear safeguards
  - International safeguards policy
  - Nondestructive assay techniques
  - Typical safeguards instruments for neutron and gamma-ray detection
  - Data analysis for nuclear material identification and characterization
  - Fall 2009 – 17 students

Detection for Nuclear Nonproliferation Group

Los Alamos National Laboratory
April 22, 2010
Summary and Conclusions

- Nuclear nonproliferation and homeland security challenges require the development of new detectors, electronics, and algorithms for SNM detection and characterization
- Our effort at UM is a three-pronged approach to identifying suitable technology: new detectors, new electronics, and new algorithms
  - Several new scintillation detectors have been developed and evaluation is currently underway
  - A scalable electronics platform is being developed: initial tests indicate two-fold improvement in SNM detection probability
  - Cutting-edge analysis algorithms are under development to allow reliable fast neutron spectroscopy for SNM identification and classification
Detection for Nuclear Nonproliferation Group

Department of Nuclear Engineering and Radiological Sciences - University of Michigan

Group Leader: Sara Pozzi

**Group Members**
- Marek Flaska, Assistant Research Scientist
- Shaun Clarke, Assistant Research Scientist
- Andreas Enqvist, Postdoctoral Researcher
- Eric Miller, Graduate Student
- Jennifer Dolan, Graduate Student
- Shikha Prasad, Graduate Student
- Jeff Katalenich, Graduate Student
- Christopher Lawrence, Graduate Student
- Alexis Poitras-Riviere, Graduate Student
- Mark Bourne, Graduate Student
- Bill Walsh, Graduate Student
- 8 Undergraduate Students

**Collaborators – National**
- Robert Haight, Los Alamos National Laboratory
- Alan Hunt, Idaho Accelerator Center
- Donald Umstadter, University of Nebraska
- Peter Vanier, Brookhaven National Laboratory
- John Mattingly, Sandia National Laboratory
- Andrey Gueorguev, ICx Radiation

**Collaborators – International**
- Imre Pazsit, Chalmers University of Technology, Sweden
- Enrico Padovani, Polytechnic of Milan, Italy
- Paul Scoullar, Southern Innovation, Australia
- Peter Schillebeeckx, JRC Geel Belgium
- Senada Avdic, University of Tulsa, Bosnia