Experimental Campaign at the Device Assembly Facility

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1North Carolina State University
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Objective

- **Objective**: provide CVT students, post-docs, and faculty with the opportunity to conduct hands-on experiments with Category I (weapons usable) special nuclear material (SNM)

- CVT worked with LANL to plan and execute Cat-I SNM experiments at the NNSS Device Assembly Facility (DAF) in Summer 2015

- July 6 – 9, 2015, CVT conducted some of the first-ever university-led experiments with Cat-I SNM at DAF
Device Assembly Facility (DAF)

- Located about 90 minutes northwest of Las Vegas
- Operated by NSTec for NNSA
- DAF can support critical and subcritical measurements of
  - Highly-enriched uranium (HEU) metal and oxide
  - Weapons-grade plutonium (WGPu) metal and oxide
  - Neptunium metal
## Fissionable and Reflector Materials Allowed in Construction of Multiplying Assembly

<table>
<thead>
<tr>
<th>Fissionable Material</th>
<th>Mass Limit</th>
<th>Reflector Material</th>
<th>Type</th>
<th>Thickness Restriction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pu in metal/compounds/dry residues</td>
<td>≤ 3,000 g</td>
<td>Copper</td>
<td>A</td>
<td>Total thickness of these reflectors shall not exceed 1 inch</td>
</tr>
<tr>
<td>$^{233}$U in metal/compounds/dry residues</td>
<td>≤ 3,000 g</td>
<td>Nickel</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>Pu in oxide</td>
<td>≤ 4,400 g</td>
<td>Stainless Steel 304</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>$^{233}$U in oxide</td>
<td>≤ 4,400 g</td>
<td>Tungsten</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>$^{235}$U in hydride</td>
<td>≤ 3,000 g</td>
<td>Natural Uranium</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>$^{239}$U in metal/compounds (excluding hydride)/dry residues</td>
<td>≤ 10,000 g</td>
<td>Depleted Uranium</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>$^{237}$Np Sphere</td>
<td>~6 kg Np</td>
<td>Cadmium</td>
<td>B</td>
<td>The total combined thickness of Type A and B reflectors shall not exceed 1 inch if Type A reflectors are present. If no Type A reflectors are used, an unlimited thickness of Type B reflectors may be used.</td>
</tr>
<tr>
<td>BeRP Ball</td>
<td>~4.5 kg Pu</td>
<td>Carbon Steel</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>Rocky Flats Shells (1-24)</td>
<td>~13.7 kg HEU</td>
<td>Iron</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>One Thor Core Piece</td>
<td>~2-4 kg Pu</td>
<td>Lead</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lucite</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Polyethylene</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Borated Polyethylene</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Manganese</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Boroflex</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Aluminum</td>
<td>C</td>
<td>Unlimited thickness of these materials in any combination may be used.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Thorium</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mock HE1</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mock HE2</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mock HE3</td>
<td>C</td>
<td></td>
</tr>
</tbody>
</table>
Participants

NC State
• John Mattingly (faculty, lead) and Jonathan Mueller (post-doc)

Michigan
• Zhong He (faculty), David Goodman (student), Michael Streicher (student), Sara Pozzi (faculty), Kyle Polack (student), Michael Hamel (student)

ORNL
• Jason Newby

LANL
• Jesson Hutchinson (PIC, lead), Derek Dinwiddie (PIC), Donnette Lewis, Kenny Valdez, Lenny Trujillo, Clemente Garcia, Mark Mitchell, Scott Gardner, and Jeff Favorite (POC)

Left to right: Jonathan Mueller, Michael Hamel, Sara Pozzi, Kyle Polack, John Mattingly, David Goodman, Jason Newby, Zhong He, and Michael Streicher
Experiments

SNM sources:
• BeRP ball: 4.5 kg WGPu metal sphere
• Rocky Flats shells: 13 kg HEU metal shells
• Thor core (central piece): 4 kg WGPu metal “disk”

Reflectors/shielding:
• Bare (none)
• Polyethylene
• Iron
• Tungsten

Instruments:
• Fast neutron coded aperture imager (ORNL/SNL)
• Dual particle scatter imager (U of M)
• Polaris/Orion Compton scatter gamma imagers (U of M)
BeRP ball
Rocky Flats shells
Thor core
Coded Aperture Imager
Exploiting fission chain-reaction dynamics

\[ E_p > \frac{1}{2} m_n \left( \frac{d}{\Delta t} \right)^2 \]

\[ E_p \leq \frac{1}{2} m_n \left( \frac{d}{\Delta t} \right)^2 \]

\[ \Delta t = t_n - \left( t_\gamma - \frac{d}{c} \right) \]
Detecting fission chain-reaction neutrons
BeRP Ball and Cf-252
Thor Core
Thor Core in Polyethylene
Dual-Particle Imager

Goals and Objectives

• Evaluate system performance in presence of category-I SNM for disarmament treaties and Non-proliferation Treaty verification

• Acquire benchmark data for continued development of the Dual-Particle Imager

• Identify SNM in the presence of multiple neutron and gamma-ray sources
Dual-Particle Imager

System Design

• EJ-309 organic liquid scintillators
  – Pulse shape discrimination
  – ~15% energy resolution
  – ~1.2 ns time resolution
• NaI(Tl) scintillators
  – ~6% energy resolution
  – ~8 ns time resolution
• CAEN V1720 Digitizers
  – 250 MHz
  – 12-bit resolution
• Custom algorithms
  – Pulse shape discrimination
  – Data acquisition and on-line processing
  – Event correlation
  – Advanced imaging and spectroscopy

Detector purchase funded by DOE-NEUP Award #DE-NE0000324

Combined Compton and neutron scatter camera with two 4 x 4 detector arrays
Dual-Particle Imager

- Possible source location is defined by a cone for each correlated event

- The superposition of many cones creates a hot-spot at the source location

- Photon events assume a full-energy deposition in the NaI(Tl)

- The energy of neutron events is obtained through time of flight
Dual-Particle Imager

- Possible source location is defined by a cone for each correlated event.
- The superposition of many cones creates a hot-spot at the source location.
- Photon events assume a full-energy deposition in the NaI(Tl).
- The energy of neutron events is obtained through time of flight.

\[
\cos \theta_1 = 1 - \frac{m_e c^2 \times E_{d1}}{E_{d2} (E_{d1} + E_{d2})}
\]
Challenges

High Gamma-Ray Flux

- Low energy photons can overload digitizers and contribute to light production in the detectors
- 59.5 KeV photon from $^{241}$Am was most problematic in BeRP ball
- Problem mitigated by using ½” lead shield and higher thresholds for NaI detectors

Preserved counts in this region

½” Pb shadow shield
BeRP Ball
200 cm

Table 8-2. Useful gamma rays in various energy regions
Dual-Particle Imager

BeRP Ball Results

Bare BeRP Ball: Neutron Backprojection

Bare BeRP Ball: Photon Backprojection

Neutron Spectra Comparison

Photon Spectra Comparison
Dual-Particle Imager

Multi-Source Measurement – Photons

- 850-minute measurement of:
  - $\sim 5.2 \times 10^5$ neutrons/second $\delta$-phase plutonium sample shielded by 1.3 cm of lead located at (90°, 85°)
  - $\sim 3 \times 10^5$ neutrons/second $^{252}$Cf source unshielded located at (90°, 109°)
  - $\sim 1 \times 10^6$ neutrons/second AmBe source shielded by 10 cm of lead located at (141°, 85°)
- $\sim 2$-meter standoff for all sources
- $\sim 212,000$ neutrons measured
- $\sim 2,135,000$ photons measured

MLEM Image

Thor Core

$^{252}$Cf

AmBe

Thor Core

$250-415$ KeV from $^{239}$Pu

$600-700$ KeV from $^{239}$Pu and $^{241}$Am
Dual-Particle Imager

Multi-Source Measurement – Neutrons

• 850-minute measurement of:
  ~5.2×10^5 neutrons/second δ-phase plutonium sample shielded by 1.3 cm of lead located at (90°, 85°)
  ~3×10^5 neutrons/second 252Cf source unshielded located at (90°, 109°)
  ~1×10^6 neutrons/second AmBe source shielded by 10 cm of lead located at (141°, 85°)

• ~2-meter standoff for all sources
• ~212,000 neutrons measured
• ~2,135,000 photons measured
Conclusions

• The Dual-Particle Imager provides images and energy spectra for neutron and gamma-rays from SNM

• Measurement of category-I SNM with the Dual-Particle Imager requires mitigation of high gamma-ray flux

• The Dual-Particle Imager can image and discriminate multiple neutron and gamma-ray sources including SNM
Publications


The Dual-Particle Imager is supported in-part by the National Nuclear Security Administration through NA-22 funding opportunity DE-FOA-0000568. It is also funded in-part by the Consortium for Verification Technology under Department of Energy National Nuclear Security Administration award number DE-NA0002534. M.C. Hamel and J.K. Polack are funded in-part by the Sandia National Laboratories Excellence in Engineering Research Fellowship. The prototype system is funded in-part by the Department of Energy, Nuclear Energy University Program, award number DE-NE0000324.
Orion Radiation Measurement Group

• Focus: Room temperature imaging spectrometers
• Research areas include:
  – Reconstruction algorithm development
    • Compton, coded aperture and time encoded imaging
  – Diagnosing semiconductor material imperfections
    • CdZnTe and TlBr
  – Digital readout and pulse processing
  – Practical applications of imaging systems
    • Safeguards, treaty verification and nuclear power
Campaign Systems

• Polaris Separable Plane (SP) System
  – 3 by 3 by 2 array of 2 x 2 x 1.5 cm$^3$ CdZnTe crystals
  – Each crystal further subdivided into 11x11x40 voxels
• **Digital Orion:**
  - 2 by 2 array of (2cm x 2cm x 1.5cm) CdZnTe crystals
  - ASICs digitize triggered and neighboring pixel waveforms
  - Subpixel resolution via induced charge on neighboring pixels
    - $\sim 300\mu m$ at 662keV
    - $\sim 700\mu m$ at 122keV
Rocky Flats Shells with AmBe Driver

AmBe Driver
HEU

3 mm thick Pb
2 mm

Orion

Only 60 keV signal in image pixel
Equal contributions
Only 186 keV signal in image pixel

186 keV

60 keV
THOR Core

- Central slice of THOR core pinhole imaged in several geometries
THOR Core Continued

- Orion single pixel spectrum taken overnight
- $^{240}\text{Pu}$ content measured by 630-670keV spectrum
THOR Core Continued

- $^{240}\text{Pu}$ estimated as 3.63%, actual 5.02%
  - Within 2σ measurement uncertainty

* Spectral analysis done by Scott Garner (LANL)
Campaign Successes

• Imaged HEU gamma-rays using pinhole camera and coded aperture

• Distinguished relative THOR core geometries using pinhole

• Measured THOR core $^{240}\text{Pu}$ content to within 2σ measurement uncertainty
2016 DAF Campaign Opportunity

• There will be a CVT one-week experimental campaign at the DAF again in 2016 (June-July timeframe)

• If you are interested in participating, the due date for applications is October 23, 2015

• Contact Prof. Sara Pozzi or Prof. John Mattingly for the application or more information
Acknowledgements

Thank you to Jesson Hutchinson and Karen Miller for helping us successfully access the DAF and implement our measurements.