Monitoring Using Detection

for ENU4930/6937: Elements of Nuclear Safeguards, Non-Proliferation, and Security

Presented by
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FP&L Endowed Term Professor -- 2007-2010

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Overview

– Introduction

– MC&A

and Nuclear Material Assay

• NNSA Brief - “Beyond Guns, Gates and Guards: An Integrated Approach to Nuclear Material Security”

– Analytical Methods

• Fissile Material Detection Methods
  – U and Pu

– Countering Illicit Trafficking: IAEA

– Summary
Nuclear Material Control and Accounting (MC&A)

- MC&A are important measures to consider when operating a large plant
- If a plant processes 80 MT of Pu in a year
  - This amounts to on the order of 10,000 MT of fuel (enough fuel from 70 large power reactors)
  - If 0.01% is “Material Unaccounted For” (MUF)
    - Then the MUF mass is 8 kg—1 SQ of IAEA material!
  - Physical security measures are important...
  - Analytical methods are also fundamental to process control and material accountability

IAEA, June 2010
SNM Detection Research

• Perform design and assess performance of detector monitoring systems
  – Generate modeling tools, optimize cross sections, verify source terms
  – Assess of n, gamma radiation from SNM using 3-D Transport Simulations
  – Design Passive/Active probe scenarios
  – Sn and Monte Carlo Models
Nuclear Material Control and Accounting (MC&A)

• Physical / Access Protection
  – Physical Protection:
    • $G^3 = “Gates, Guns, Guards”$
  – Facility Access control using IT Information
    • Video images: valuable information as soon as the camera captures fraud, attempted theft or injury
    • Alarms: electronic signals that convey important information about a door opening or temperature dropping
    • Electronic requests from a card reader: Reported back to the access control server are information the accuracy of which is mission critical to most companies.

• Analytical Validation methods for MC&A
  – Laboratory facilities, Quality Control Methods

From USNRC, April 2010
IAEA Principal Analytical Methods Laboratory

- Located in Seibersdorf, Austria
  - 35 km southeast of IAEA Vienna HQ, Austrian Research Center
  - Established in 1962, staff of 180
    - 30% professionals /
    - 40% technicians / 30% support staff
  - Contributes to the implementation of Safeguards, Nuclear Safety and Security, and Technical Co-operation.

- Main activities are
  - Scientific and analytical services, Research and development
  - Training of scientists from developing countries
  - Assessments and Management of Terrestrial Environments
  - Supporting Quality in Environ. Analytical Techniques in Member States
  - Network of Analytical labs (NWAL) support analysis

From IAEA.org
Analytical Methods – Gamma spectroscopy

– Most radioactive nuclides emit unique gamma radiation
  • “gamma lines” interact with photoelectric effect to yield photopeaks
  • Scattering via Compton scattering, and if energy is >1.02 MeV, pair production
  • Record pulse height vs energy deposited in the detector; unique collection of gamma lines can be attributed
    – known emissions to specific isotopes using an isotope matching/ID software
  • Scintillator detectors interact to yield a light pulse to create a cascade of electrons in dynodes
Analytical Methods – Gamma spectroscopy

• Gamma rays interact with scintillator to yield a light pulse to create a cascade of electrons in dynodes
  – Scintillation photons incident on photocathode liberate electrons through the *photoelectric effect*
  – Photoelectrons then accelerated by a strong electric field in the PMT; as photoelectrons accelerate, they collide with electrodes in the tube (known as dynodes) releasing additional electrons
  – This increased electron flux is further accelerated with succeeding electrodes, causing multiplication (by ~1E4)
    • Amplified charge burst arrives at the output electrode of the tube.
• PMT gain is amount of amplified charge; so output signal is proportional to the energy deposited by the gamma ray in the scintillator.
Analytical Methods – Gamma spectroscopy

- A. The Full-Energy Photopeak
- B. Compton Background Continuum
- C. The Compton Edge
- D. The “Compton Valley”
- E. Backscatter Peak
- F. Excess-Energy Region
- G. Low-Energy Rise

\[ E' = \frac{m_o c^2}{1 - \cos(\varphi) + \left(m_o c^2 / E\right)} \]
Analytical Methods – Gamma spectroscopy

- Conventional Approach
**ASEDRA**

Advanced Synthetically Enhanced Detector Resolution Algorithm

- **How does it work?**
  - Read spectrum, background, detector E, FWHM calibrations
  - *No other a-priori detail*
  - Denoise background and spectrum, low energy tailing
  - Process spectrum using Detector Response Functions derived from radiation transport, E-broadening, “typical” shielding sets
  - Adaptable to any detector material

- Spurious peaks in Compton Continuum possible when shielding differs from DRF’s – *Solved with SmartID...*
PuBe – heavily shielded (>6 mfp, 15g WGPu)  
1 min count, 2x2 NaI(Tl)

ASEDRA finds 14 peaks ranging in energy from 50.9 – 647.6keV

SmartID scores $^{239}$Pu as the most probable isotope (with ease!)

<table>
<thead>
<tr>
<th>Nucleide</th>
<th>EI</th>
<th>PI</th>
<th>FOMI</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{239}$Pu</td>
<td>9.197</td>
<td>10.000</td>
<td>72.0374</td>
<td>1.000</td>
</tr>
<tr>
<td>$^{241}$Am</td>
<td>5.024</td>
<td>4.151</td>
<td>25.8621</td>
<td>0.143</td>
</tr>
<tr>
<td>$^{148m}$Pm</td>
<td>1.995</td>
<td>4.649</td>
<td>23.0330</td>
<td>0.032</td>
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<tr>
<td>$^{143}$Ce</td>
<td>2.075</td>
<td>2.942</td>
<td>18.0537</td>
<td>0.018</td>
</tr>
</tbody>
</table>

$^{60}$Co & $^{137}$Cs mixed  
3 min count, 2x2 NaI(Tl)

ASEDRA finds 5 peaks ranging in energy from 31.6 – 1324.3KeV

SmartID scores $^{60}$Co and $^{137}$Cs as the most probable isotope pair

<table>
<thead>
<tr>
<th>Nucleide#1</th>
<th>Nucleide#2</th>
<th>PISum</th>
<th>FOMISum</th>
<th>SumScore</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{60}$Co</td>
<td>$^{137}$Cs</td>
<td>0.975</td>
<td>9.908</td>
<td>1.000</td>
</tr>
<tr>
<td>$^{60}$Co</td>
<td>$^{240}$Pu</td>
<td>0.975</td>
<td>13.819</td>
<td>0.717</td>
</tr>
<tr>
<td>$^{137}$Cs</td>
<td>$^{240}$Pu</td>
<td>0.670</td>
<td>10.392</td>
<td>0.655</td>
</tr>
<tr>
<td>$^{60}$Co</td>
<td>$^{124}$Ce</td>
<td>0.075</td>
<td>22.412</td>
<td>0.422</td>
</tr>
</tbody>
</table>
### U Identification

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Gamma-Ray Energy (keV)</th>
<th>Specific Intensity (gamma/s·g of isotope)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{232}$U</td>
<td>129.1</td>
<td>$6.5 \times 10^8$</td>
</tr>
<tr>
<td></td>
<td>270.5</td>
<td>$3.0 \times 10^7$</td>
</tr>
<tr>
<td></td>
<td>327.8</td>
<td>$2.7 \times 10^7$</td>
</tr>
<tr>
<td>$^{233}$U</td>
<td>119.0</td>
<td>$3.9 \times 10^4$</td>
</tr>
<tr>
<td></td>
<td>120.8</td>
<td>$3.2 \times 10^4$</td>
</tr>
<tr>
<td></td>
<td>146.4</td>
<td>$6.6 \times 10^4$</td>
</tr>
<tr>
<td></td>
<td>164.6</td>
<td>$6.4 \times 10^4$</td>
</tr>
<tr>
<td></td>
<td>245.3</td>
<td>$3.8 \times 10^4$</td>
</tr>
<tr>
<td></td>
<td>291.3</td>
<td>$5.8 \times 10^4$</td>
</tr>
<tr>
<td></td>
<td>317.2</td>
<td>$8.3 \times 10^4$</td>
</tr>
<tr>
<td>$^{234}$U</td>
<td>120.9</td>
<td>$5.4 \times 10^5$</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>143.8</td>
<td>$7.8 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>163.4</td>
<td>$3.7 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>185.7</td>
<td>$4.3 \times 10^4$</td>
</tr>
<tr>
<td></td>
<td>202.1</td>
<td>$8.0 \times 10^2$</td>
</tr>
<tr>
<td></td>
<td>205.3</td>
<td>$4.0 \times 10^3$</td>
</tr>
</tbody>
</table>

In equilibrium with $^{234}$mPa

- $^{238}$U: 742.8, 7.1
- $^{236}$U: 766.4, $2.6 \times 10^1$
- $^{238}$U: 786.3, 4.3
- $^{234}$Pb: 1001.0, $7.5 \times 10^1$
Gamma signature Comparison
of 1y and 50y HEU, 25 kg

1 Yr since separation
50 Yrs since separation

Sjoden calculation
UF$_6$ Flow Assay Monitors

Useful in an enrichment plant

(The Am-241 source (60 keV gamma) is in place as a reference for a transmission source through the gas)
A ball of plutonium emits neutron and gamma radiation intrinsic and induced sources... it forms a complex mosaic of multiplication, moderation, shielding, scattering and interaction... a challenging detection problem.

Plutonium was first synthesized in 1940 by a team led by Glenn T. Seaborg and Edwin McMillan at the University of California, Berkeley laboratory by bombarding uranium-238 with deuterons. McMillan named the new element after Pluto, and Seaborg suggested the symbol Pu as a joke. Trace amounts of plutonium were subsequently discovered in nature. Discovery of plutonium became a classified part of the Manhattan Project to develop an atomic bomb during World War II. --Los Alamos Science 26: 56–61; below—Table of Nuclides, Firestone
Pu Assay in Reprocessing

The short-lived U-237 daughter rapidly reaches secular equilibrium with Pu-241 after ~2 months, and U-237 is often used as an assay for Pu

Use this information to verify the Pu-241 activity information in the table above...
Pu Gamma Signature using Ge

Spectrum: 14% Pu-240 and 1.2% Am-241

Note WGPu is <7% Pu-240
"Pu Gamma Signature"

Gamma energies and specific activities for Pu

<table>
<thead>
<tr>
<th>Region (keV)</th>
<th>$^{238}\text{Pu}$</th>
<th>$^{239}\text{Pu}$</th>
<th>$^{240}\text{Pu}$</th>
<th>$^{241}\text{Pu}$</th>
<th>$^{241}\text{Am}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(keV)</td>
<td>(γ/s·g)</td>
<td>(keV)</td>
<td>(γ/s·g)</td>
<td>(keV)</td>
</tr>
<tr>
<td>40-60</td>
<td>43.48</td>
<td>$2.49 \times 10^8$</td>
<td>51.63</td>
<td>$6.19 \times 10^5$</td>
<td>45.23</td>
</tr>
<tr>
<td>90-105</td>
<td>99.86</td>
<td>$4.59 \times 10^7$</td>
<td>98.78</td>
<td>$2.80 \times 10^4$</td>
<td>104.24</td>
</tr>
<tr>
<td>120-450</td>
<td>152.68</td>
<td>$6.05 \times 10^6$</td>
<td>129.29</td>
<td>$1.44 \times 10^5$</td>
<td>160.28</td>
</tr>
<tr>
<td></td>
<td>$203.54$</td>
<td>$1.28 \times 10^4$</td>
<td>$245.01$</td>
<td>$1.28 \times 10^4$</td>
<td>$375.04$</td>
</tr>
<tr>
<td></td>
<td>$413.71$</td>
<td>$3.42 \times 10^4$</td>
<td>$645.97$</td>
<td>$3.42 \times 10^2$</td>
<td>$642.48$</td>
</tr>
<tr>
<td>450-800</td>
<td>766.41</td>
<td>$1.39 \times 10^5$</td>
<td>645.97</td>
<td>$3.42 \times 10^2$</td>
<td>717.72</td>
</tr>
</tbody>
</table>

$^a$Uranium-237 daughter of $^{241}\text{Pu}$ with $^{241}\text{Pu}$-$^{237}\text{U}$ equilibrium.
Pu Gamma Assay in Liquids

Gamma energies from selected lines are used to determine Pu assay ....

![Pu Gamma Assay System Diagram]

### Ratios used in Los Alamos plutonium isotopic system

<table>
<thead>
<tr>
<th>Isotopic Ratio</th>
<th>Gamma-Ray Energy of Samples (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Aged</td>
</tr>
<tr>
<td>238/241</td>
<td>152.7/148.6</td>
</tr>
<tr>
<td>239/241</td>
<td>345.0/332.4</td>
</tr>
<tr>
<td>240/241</td>
<td>203.5/208.0</td>
</tr>
<tr>
<td>241/239</td>
<td>160.3/164.6</td>
</tr>
<tr>
<td>Am/239</td>
<td>169.6/171.3</td>
</tr>
</tbody>
</table>

*a A weighted average of the two ratios is used.
*b The $^{241}$Am is usually too low to measure.
“Pu Neutron Signature”

Neutron detection is a challenge

Significant reliance on characterization of neutron signatures from Pu in reprocessing applications is made on He-3 gas, which is in short supply. Currently all large scale applications of He-3 have been placed on hold awaiting a presidential commission decision on the priority of the different areas of need.

Sjoden Calculation/ Private Communication
Analytical Methods – Other methods

• Besides gamma spectrometry for solids and liquids...
  – Neutron passive counting (Pu only)
  – Neutron multiplicity counting (Pu only)
  – Active neutron interrogation (induced multiplication)
  – Delayed neutron counting
  – Calorimetry (Pu and heavy actinides, T; p.53 text)
    • Used a lot for Pu scrap, small quantities; requires hours
  – Fission product content in fuel <-> burnup
  – Cerenkov & Mass spectrometry
Countering Illicit Trafficking: Indicators and Warnings

- Indicators & warnings are
  - “the ‘bottom line’ of intelligence”
- Indicators (indications) are observables or activities related to a particular threat or challenge
  - Fed into the decision making process
- ‘Warning’ itself is “a process of communicating judgements about threats ... to decision makers”
  - “communications must be received and understood in order for leaders to take action.”
  - An effective warning involves both communication and timeliness

Counteracting Illicit Trafficking: Concept of Warning

• Other realities to consider
  – ‘more facts’ and first-rate sources do not necessarily produce ‘more warnings’
  – intelligence warnings are useless unless some action is taken on them”

• Concept of warning has three levels:
  – (a) At the **strategic** level, warning focuses on “determining who the enemy is and what his capabilities are”
  – (b) **Operational** warning focuses on “the enemy’s modes or operations of attack” and how these can be detected “before being put into action”
  – (c) **Tactical** warning focuses on warnings that an adversary “is executing his attack plans”

• Warning levels must be evaluated based on modus operandi of the group carrying out illicit acts...

MO of Al Qaeda

- Consider Al Qaeda affiliated groups:
  - trend towards *increasingly lethal terrorist events* over the past ten years
  - apparent preference for *suicide operations*
  - lack of restraint with actions designed to have ‘*mass effect*’ (*mass casualties, destruction & disruption*)
  - lack of warnings
  - preference for economic & transportation (air, surface & maritime) targets
  - history of launching concurrent attacks
  - Major uncertainty appears on ‘capability’ level and how terrorist groupings will solve technical thresholds.
  - This places into clear perspective the centrality of *acquiring tactical level information on terrorist procurement of the necessary materials and technical knowledge*.
Countering Illicit Trafficking: IND Threat

- The possibility that a terrorist group will acquire sufficient nuclear material suitable for constructing and detonating an IND is the greatest threat we face.

- The consequences if detonated in a populated area would be truly catastrophic in their immediate impact and would have far reaching and unpredictable future consequences.

- For this reason alone, measures to prevent such an event must be our highest priority”
Countering Illicit Trafficking: Indicators and Warnings

Dhiren Barot -- Al Qaeda Operative, now imprisoned

- Documented proposals for radiological terrorism
- He notes they were primarily ‘weapons of mass disruption, dislocation or effect’ and that decontamination and rebuilding costs could be ‘immense’ “perhaps billions of dollars (sic)”
- Drawing upon the consequences of an accident in France involving 900 smoke detectors, he proposed burning or exploding a large number of smoke detectors (he suggests 10 000) containing americium.
- In his estimation, the “fear and chaos that this would spread would be large scale and on a long term basis (sic).”
- Barot recommended the use of smoke detectors because they were easy to acquire.

Countering Illicit Trafficking: ITDB

- **IAEA’s Illicit Trafficking Database (ITDB)**
  - an information system which includes information dissemination and analysis,
  - 12th year of operation, 99 states participating
- **Scope is intentionally broad**
  - Covers all types of radioactive material, all quantities and all unauthorized activities including
    - thefts and losses, interdictions and recoveries, sales and attempted sales, unauthorized movements and disposals
  - information on 1266 incidents reported by States since 1993
    - Other incidents reported in open sources, but await confirmation or denial by the States involved
  - Between 2002 & 2006, reported incidents rose by 385%
  - Some of the increase in numbers of reported incidents may be an indicator of success in efforts to improve security.

Countering Illicit Trafficking: ITDB

• Consider Current IND threat events logged in ITDB:
  – Incidents involving weapons usable material, HEU/Pu, rare
    • Little/no grounds for complacency
  – Some cases in the early 1990s involved kilogram quantities
    • Not seen this since; recent cases involved gramm quantities
  – Some incidents are/appear to be linked: e.g. HEU seized in both France and Bulgaria
    • Possibility that the materials offered for sale and/or recovered, were samples drawn from larger caches which as yet are unrecovered.
    • Alternatively, linked cases possible evidence of a weakness in security at the facility of origin
  – Linked events: Already led to some thefts and may be exploited again??

Countering Illicit Trafficking: ITDB

- Majority uranium cases reported to ITDB involve LEU or source material... of little direct use in themselves
  - Require processing beyond the capabilities of a terrorist group to become so.
  - Symptomatic of failures or vulnerabilities MCA measures at the facility
- Radioactive sources involved in incidents range through all categories of material; from the ‘very dangerous’ to the ‘not dangerous’, according to the IAEA’s categorization scale.
  - Material suitable for malicious use can be extended if the desired consequences go beyond the deterministic
  - ... Include psychological, social, economic and other considerations unrelated to destructive power or even the power to contaminate.
  - Of the 1266 incidents reported to the ITDB by States, 825 involved radioactive sources although the radioisotope involved, or its activity level, is not always known.

Countering Illicit Trafficking: ITDB

- Of all 825 Radioactive sources incidents:
  - Some such as $^{192}$Ir have relatively short half-lives and can be discounted once they have aged sufficiently
  - 1/3 involved $^{137}$Cs sources
    - usually in moisture density and level gauges
    - medical applications.
  - The activity levels involved are usually not very high
    - 1 Bq = 1 dis/s
    - hundreds of MBq to tens of GBq
    - have potential for malicious use either individually or through accretion

Countering Illicit Trafficking: ITDB

- Some incidents reported to the ITDB have involved suspected or real malicious intent...
  - Example--Germany, 2004: a suspected member of a terrorist organization reportedly showed interest in acquiring nuclear material and in Belgium in 2005, small quantities of UF4 powder were mailed to various government and international officials in Brussels.
  - There is also some evidence of the involvement of organized groups in illicit trafficking and other unauthorized activities--Terrorist groups or organized crime

- “To address the trafficking problem and, thereby, reduce or eliminate the related threat, we must address the causes...”

Counteracting Illicit Trafficking: SAFE Framework

• The SAFE framework
  – “appropriate, focused and layered trade security measures will actually facilitate the movement of legitimate trade across national borders and thereby protect the global economy.”
  – “security and facilitation” are coupled
  – The SAFE framework has four core elements:
    • —Advance electronic manifest information
    • —A consistent risk management approach
    • —Use of non-intrusive detection equipment on high risk outbound export cargo prior to loading on a conveyance for exportation. The request will come from the nation importing the cargo
    • —Enhanced trade facilitation for legitimate trade that meets certain security standards.

• The SAFE framework is built on two pillars:
  • —Customs to customs network arrangements
  • —Customs to business partnerships.

Summary

• We have reviewed a “Broad Scope” of topics regarding fissile material accountability, detection, and trafficking issues ....
  – MC&A and Nuclear Material Assay
  – Analytical Methods
    • Fissile Material Detection Methods
      – U and Pu
  – Countering Illicit Trafficking: IAEA
Tomorrow: 230 pm

• Dr Terry Hawkins, LANL
Questions?