Nondestructive Assay of Spent Fuel for International Safeguards

Marc Humphrey

January 16, 2013
International Nuclear Safeguards

- International nuclear safeguards comprise a set of technical measures to verify that civil nuclear materials are not diverted to undeclared uses.
- Measures include inspections, nuclear material accountancy, containment and surveillance activities, and design information verification.
- Carried out by the International Atomic Energy Agency (IAEA) subject to terms of safeguards agreements.
Objective: To develop the policies, concepts, technologies, expertise, and international infrastructure necessary to strengthen and sustain the international safeguards system as it evolves to meet new challenges.

“We need more resources and authority to strengthen international inspections.”

*President Barack Obama*
Next Generation Safeguards Initiative
Safeguards Technology Development

• Sponsor safeguards technology development projects at U.S. National Laboratories

• Transition advanced technologies with medium-term safeguards applications from the laboratory into the field

• Organize field trials with international and domestic partners

• Strengthen safeguards technology development infrastructure at the U.S. National Laboratories

$14 million budget
11 National Laboratories
~ 35 projects in 2013
Spent Fuel Safeguards – Status Quo
• Qualitative verification of spent fuel using fission product gammas
• Measures total neutrons and gross gammas to “verify” operating history of assembly (initial enrichment, burnup, cooling time)
• Measures intensity of near ultraviolet Cerenkov light in a spent fuel pond to detect and deter pin diversion (“partial defect”)
NGSI Spent Fuel NDA Project
Safeguards Objectives

• Primary Goal – to enable direct and independent quantification of Pu mass in spent fuel with an uncertainty of better than 5%
  – Input accountability at reprocessing facilities
  – Shipper/receiver difference
  – Special inspections

• Secondary Goal – to improve the toolkit of safeguards inspectors
  – Improved partial defect detection
  – Assure integrity of transport (e.g., fingerprinting)
  – Recovery from loss of “continuity-of-knowledge” (e.g., by determining initial enrichment, burn-up, cooling time and multiplication)
  – Improved understanding of the limits of spent fuel NDA
• Underlying premise:
  
  While no existing NDA technique is capable of determining plutonium content singlehandedly to acceptable accuracy, plutonium quantification can be achieved through integration of several NDA techniques with complementary features.

• Five-year effort, begun in 2009:
  
  – Modeling and peer review (2009-2010)
  – Down-selection and system integration (2011)
  – Prototype development and field tests (2012-2014)
• Systematic evaluation of 14 NDA techniques:

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<thead>
<tr>
<th>Neutron</th>
<th>Passive</th>
<th>Active</th>
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<tbody>
<tr>
<td>Total Neutron</td>
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<tr>
<td>Passive Neutron Albedo Reactivity</td>
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<td>Differential Die-Away</td>
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<tr>
<td>Self-integration Neutron Resonance Densitometry</td>
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<td>Delayed Neutrons</td>
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<tr>
<td>Differential Die-Away Self-Interrogation</td>
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<td>Lead Slowing Down Spectrometer</td>
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<td>Coincident Neutron</td>
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<td>Neutron Resonance Transmission Analysis</td>
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<td>Gamma</td>
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<td>X-Ray</td>
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• Simulated response of each against a common library of spent fuel assemblies

Differential Die-Away

Delayed Neutron
Phase 1
Modeling and Peer Review

- External committee provided in-depth review of each technique

<table>
<thead>
<tr>
<th>General Characteristics</th>
<th>PG</th>
<th>XRF</th>
<th>SINRD</th>
<th>DDSI</th>
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<tr>
<th>Pin Diversion Sensitivity* (High, Med, Low)</th>
<th>PG</th>
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| Priority for More Work | 4 | 5 | 1 | 2 | 8 | 3 | 7 | 6 | 9 |
- External committee provided in-depth review of each technique

<table>
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<tr>
<th>General Characteristics</th>
<th>DDA</th>
<th>DN</th>
<th>DG</th>
<th>LSDS</th>
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<tr>
<td>Cost (High, Med, Low)</td>
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<td>H</td>
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<td>H</td>
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<tr>
<td>Practical Implementation (Accuracy)</td>
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<td>High</td>
<td>Low</td>
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</table>

| Quantification Ability for Assemblies     |     |     |     |      |      |      |      |      |
| Elemental Pu                              | N   | N   | N   | N    | N   | N    | N    | N    |
| ²³⁸Pu                                    | N   | N   | Maybe | Maybe | Y   | Y    | Y    | N    |
| ²³⁹U                                    | N   | N   | Maybe | Maybe | Y   | Y    | Y    | N    |
| ²⁴⁰Pu                                    | N   | N   | N    | Maybe | Y   | Maybe | Y    | N    |
| ²⁴¹Pu                                    | Y   | Y   | Y    | Maybe | Y   | Maybe | N    | Y    |
| FP absorbers                             | N   | N   | Maybe | N    | Maybe | Maybe | Maybe | N    |
| Other actinide absorbers                 | N   | N   | Maybe | N    | Maybe | Maybe | Maybe | N    |
| ²³⁸Pu eff Quantification Penetrability (# rows) | 9   | 9   | 5    | 9    | 9    | 5-7  | <1   | 9    |
| Burmp                                    | N   | N   | N    | N    | N    | N    | N    | N    |
| Initial Enrichment                       | N   | N   | N    | N    | N    | N    | N    | N    |
| Cooling Time                             | N   | N   | N    | N    | N    | N    | N    | N    |

| Pin Diversion Sensitivity² (High, Med, Low) |     |     |     |      |      |      |      |      |
| Outer Region (rows 1-2)                   | M   | M   | H   | M    | M    | H    | None | M    |
| Middle Region (rows 3-5)                  | M   | M   | M   | M    | M    | M    | None | M    |
| Center Region (rows 6-9)                  | M   | M   | L   | M    | M    | L    | None | M    |

| Independence of (for Fissile Mass Quantification) |     |     |     |      |      |      |      |      |
| Burmp                                    | N   | N   | Y   | Y    | Y    | Y²   | Y    | N    |
| Initial Enrichment                       | N   | N   | Y   | Y    | Y    | Y²   | Y    | N    |
| Cooling Time                             | N   | N   | Y   | Y    | Y    | Y²   | Y    | N    |

| Priority for More Work                   | 2   | 2   | 1   | 5    | 6    | 4    | 3    | 3    |
• Down-selection criteria:
  – Quality of signal (e.g., dynamic range, penetration)
  – Hardware maturity
  – Simplicity/applicability
  – Robustness
  – Complementary features (hardware or physics)
Phase 2
Down-selection and System Integration

Differential Die-Away

Delayed Neutron
# Phase 2

Down-selection and System Integration

<table>
<thead>
<tr>
<th>System</th>
<th>Techniques</th>
<th>Key Attributes</th>
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</thead>
</table>
| 1      | - Passive Neutron Albedo Reactivity (PNAR)  
- Self-Interrogation Neutron Resonance Densitometry (SINRD)  
- Passive Gamma / Total Neutron | - Lightweight  
- Relatively low cost  
- Short measurement time  
- Robust |
| 2      | - Californium Interrogation Passive Neutron (CIPN)  
- Self-Interrogation Neutron Resonance Densitometry (SINRD)  
- Passive Gamma / Total Neutron | - Lightweight  
- Relatively low cost  
- Short measurement time  
- Robust |
| 3      | - Differential Die-Away Self Interrogation (DDSI)  
- Self-Interrogation Neutron Resonance Densitometry (SINRD)  
- Passive Gamma / Total Neutron | - Relatively heavy  
- Intermediate cost  
- Longer measurement time  
- Robust |
| 4      | - Delayed Neutron (DN)  
- Differential Die-Away (DDA)  
- Delayed Gamma (DG)  
- Passive Gamma / Total Neutron | - Relatively heavy  
- Relatively high cost  
- Longer measurement time  
- Less robust  
- Potential for high accuracy |
### Prototype development schedule:

<table>
<thead>
<tr>
<th>Technique</th>
<th>Fabrication</th>
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<tr>
<td>Self-integration Neutron Resonance Densitometry (SINRD)</td>
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<td>$^{252}\text{Cf}$ Interrogation with Prompt Neutron (CIPN)</td>
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Phase 3
Prototype Development and Field Trials

Field trial schedule:

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• Potential benefits to facility operators:
  – Determination of burn-up credit (so fuel can be stored and shipped more efficiently)
  – Optimization of reactor core reloading
  – Optimization of assembly selection for reprocessing
  – Determination of heat load in a geological repository

Measurement of multiplication, IE, BU, and CT could be integrated into normal fuel management
• Routine safeguards measurements for spent fuel assemblies rely on indirect measurements, computer simulation, and operator-supplied information.

• New technologies would improve input accountancy, recovery from loss of continuity-of-knowledge, or containment measures.

• While no single NDA technique can likely determine plutonium content singlehandedly to acceptable accuracy, integration of several techniques will help.

• Project will also advance our understanding of capabilities and limitations in the area of spent fuel NDA.
Several Universities and International Collaborators
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