Antineutrino Reactor Monitoring in the Context of IAEA Safeguards

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Civilian and military nuclear fuel cycles can overlap

To geological repository

Low-enriched Uranium (LEU)

Natural uranium

High-enriched Uranium (HEU)

Nuclear explosives production

"Closed" Cycle

"Open" Cycle

Uranium or Mixed Uranium/Plutonium Fuel Rods

Reactor Fuel Fabrication

Plutonium

Reprocessing

Fuel Rods Contain Plutonium

To geological repository

Radioactive Waste

Natural Uranium

Uranium

LLNL-PRES-759422
The International Atomic Energy Agency

- Created in 1957 in response to Eisenhower’s 1953 Atoms for Peace proposal
  - Dual role: *facilitating* and *verifying* peaceful use of atomic energy

- An independent inter-governmental organization within the UN family
  - Unique relationship with the UN Security Council
  - 170 Member States as of April 2018

- Its Statute authorizes the IAEA to establish "safeguards"
A technical verification system embedded in a political and legal framework

- THE POLITICAL FRAMEWORK – the Agency’s Board of Governors and its General Conference

- THE LEGAL FRAMEWORK – safeguards agreements

(Note: This slide was adapted from Richard Hooper, former Director of IAEA’s Safeguards Concepts and Planning Division)
As originally conceived, IAEA safeguards did not necessarily apply to all nuclear activities in a state.

- Before the NPT entered into force in 1970, IAEA safeguards agreements typically applied only to specific facilities, materials, and equipment, usually as a condition of supply.

- The NPT, however, requires non-nuclear weapons states parties to conclude with the IAEA comprehensive safeguards agreements that apply to all nuclear material in all peaceful activities.
  - 174 States* have NPT safeguards agreements in force.

* and Taiwan, China.
The IAEA has three high-level safeguards objectives under NPT comprehensive safeguards agreements

- To detect diversion of declared nuclear materials
- To detect misuse of declared nuclear facilities for undeclared production
- To detect undeclared nuclear facilities, materials, and activities anywhere in the state
Performance goals for detection of diversion

- Article 28 of the standard text of NPT safeguards agreements establishes the objective of:
  - “timely detection of the diversion of significant quantities of nuclear material from peaceful nuclear activities . . . and deterrence of such diversion by the risk of early detection”

- The IAEA had to decide, as a matter of policy:
  - How much nuclear material is a significant quantity?
  - How soon must detection occur to be timely?
  - What detection probability provides acceptable deterrence?
Nuclear material categories

- **Indirect-use material** (natural or low-enriched uranium) is nuclear material that requires further enrichment or transmutation for use in nuclear weapons

- **Direct-use material** (Pu, HEU, U-233, or mixtures containing them)
  - **Irradiated direct-use material** (e.g., plutonium contained in irradiated fuel) requires chemical processing in shielded facilities to remove fission products
  - **Unirradiated direct-use material** (e.g., separated Pu, MOX, high-enriched UF$_6$), and facilities capable of producing such material, are the highest priority for safeguards detection
Safeguards inspection goals vary with material category

<table>
<thead>
<tr>
<th>Material category</th>
<th>Examples</th>
<th>Quantity goal</th>
<th>Timeliness goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indirect-use material</td>
<td>LEU fresh fuel</td>
<td>75 kg U-235 content</td>
<td>1 year</td>
</tr>
<tr>
<td>Irradiated direct-use material</td>
<td>Irradiated fuel in reactor cores, spent fuel pools, or dry storage</td>
<td>8 kg Pu, 25 kg U-235 as HEU</td>
<td>3 months*</td>
</tr>
<tr>
<td>Unirradiated direct-use material</td>
<td>High-enriched UF₆, fresh MOX fuel, HEU fresh fuel</td>
<td>8 kg Pu, 25 kg U235 as HEU</td>
<td>1 month</td>
</tr>
</tbody>
</table>

*In states where the IAEA has established high confidence in the absence of undeclared nuclear activities, the timeliness goals for less sensitive materials (i.e., not for unirradiated direct-use material) may be relaxed further.*
Nuclear material category and form (bulk or “item”) influence safeguards priority and effort

<table>
<thead>
<tr>
<th>Type of facility</th>
<th>Nuclear material category</th>
<th>Bulk or item form</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uranium conversion plant</td>
<td>Indirect-use</td>
<td>Bulk</td>
</tr>
<tr>
<td>Enrichment plant</td>
<td>Most have the potential to produce unirradiated direct-use material</td>
<td>Bulk</td>
</tr>
<tr>
<td>Fuel fabrication plant (NU or LEU)</td>
<td>Indirect-use</td>
<td>Bulk</td>
</tr>
<tr>
<td>Most reactors (w/o MOX)</td>
<td>Irradiated direct-use</td>
<td>Item</td>
</tr>
<tr>
<td>Reprocessing plant</td>
<td>Unirradiated direct-use</td>
<td>Bulk</td>
</tr>
<tr>
<td>MOX fuel fabrication plant</td>
<td>Unirradiated direct-use</td>
<td>Bulk</td>
</tr>
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</table>
Antineutrino detectors have the potential to measure reactor power and fissionable material content.
Of 715 nuclear facilities under safeguards worldwide in 2017, more than half were reactors

- 257 power reactors
  - 217 light-water reactors
  - 33 on-load refueled reactors
  - 6 reactors of other types

- 153 research reactors and critical assemblies

- Of 209,000 significant quantities (SQ) of nuclear material under safeguards, more than 75% was in the form of plutonium contained in spent fuel and in reactor cores

- Reactors accounted for about a third of all IAEA person-days of inspection effort in 2017

- From a safeguards perspective, most reactors have the advantage that nuclear material is in “item” form rather than “bulk” form

Source: IAEA 2017 Annual Report, Annex, Tables A4 and A5
Scenarios for diversion or misuse at power reactors

- Removal of fuel rods or assemblies from the fresh fuel storage area (note that some LWRs use MOX fuel)
- Removal of fuel assemblies from the core
- Irradiation of undeclared fuel assemblies or other uranium target material in the core to produce undeclared plutonium
- Removal of fuel rods or assemblies from the spent fuel pool
- Removal of fuel rods or assemblies from a consignment when they leave the reactor facility or subsequently

Source: International Atomic Energy Agency, International Safeguards in the Design of Nuclear Reactors, IAEA Nuclear Energy Series No. NP-T-2.9, p.18
For each scenario, the IAEA takes into account potential concealment methods

- For example:

<table>
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<tr>
<th>Diversion scenario</th>
<th>Concealment methods</th>
<th>Safeguards measures</th>
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<tr>
<td>Removal of fuel assemblies from the reactor core</td>
<td>Substitution with dummies, falsifying records, borrowing from another location</td>
<td>Item counting, item identification, seals, optical surveillance, spent fuel bundle counters, core discharge monitors, simultaneous inspections</td>
</tr>
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Source: International Atomic Energy Agency, International Safeguards in the Design of Nuclear Reactors, IAEA Nuclear Energy Series No. NP-T-2.9, p.18
## Diversion/misuse scenarios

<table>
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<th>Misuse/diversion scenarios</th>
<th>Concealment methods</th>
<th>Safeguards measures</th>
</tr>
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<tr>
<td>Removal of fuel rods or assemblies from the fresh fuel storage area</td>
<td>Substitution with dummies, falsifying records, borrowing fuel rods or assemblies from another location</td>
<td>Item counting, item identification, application of seals, non-destructive assay (NDA) measurements, simultaneous inspections</td>
</tr>
<tr>
<td>Removal of fuel assemblies from the core</td>
<td>Substitution with dummies, falsifying records, borrowing fuel assemblies from another location</td>
<td>Item counting, item identification, seals, optical surveillance, spent fuel bundle counters, core discharge monitors, simultaneous inspections</td>
</tr>
<tr>
<td>Irradiation of undeclared fuel assemblies or other material in or near the core and recovery of the plutonium</td>
<td>Undeclared design changes allowing targets to be introduced into the core</td>
<td>Seals, optical surveillance, NDA measurements, spent fuel bundle counters, core discharge monitors, power monitoring, design information verification</td>
</tr>
<tr>
<td>Removal of fuel rods or assemblies from the spent fuel pool</td>
<td>Substitution with dummies, falsifying records, borrowing fuel rods or assemblies from another location</td>
<td>Item counting, item identification, seals, optical surveillance, NDA measurements, spent fuel bundle counters, simultaneous inspections</td>
</tr>
<tr>
<td>Removal of fuel rods or assemblies from a consignment when they leave the facility or subsequently</td>
<td>Substitution with dummies in the consignment, understating the number of assemblies shipped and substitution with dummies in the spent fuel pool</td>
<td>Verification of content of shipping container, sealing of shipping container before shipment and verification of content at receiving facility</td>
</tr>
</tbody>
</table>

Typical IAEA safeguards measures at LWRs

- Application of tamper-indicating **seals** (to reactor head, equipment hatches, transfer canal), unattended **optical surveillance** of spent fuel pool

- Examination of accounting and operating **records and reports** and supporting documents

- **Physical inventory verification** (especially during open-core period)
  - Verify fresh fuel (item counting, item ID, non-destructive assay)
  - Verify seals, use temporary surveillance during open core period
  - Verify core fuel
  - Verify spent fuel (item counting, Cerenkov viewing device)
  - Verify contents of containers/transfers
  - Confirm absence of unrecorded production

- **Interim inspections** (possibly random) between refueling to meet timeliness goals for detecting diversion of spent fuel (and MOX, if applicable)

- Verification of facility **design information**
Typical containment and surveillance (C/S) arrangements for a light-water power reactor

Verifying the presence of LEU in a VVER fresh fuel assembly via gamma-ray spectrometry
Sealed bolt on reactor pressure vessel head
A Cerenkov viewing device aids verification of the contents of the spent fuel pool and open core
CVD images for various fuel types
[Source: J. Whitlock, AECL, “CANDU Proliferation Resistance,” 27 May 2008]
Retrieving data flashcard from a surveillance camera used to monitor refueling operations
Resealing the surveillance camera housing
A high-level summary of safeguards technical measures at nuclear reactors*

- **Power reactors:**
  - **Off-load-refueled reactors (e.g., PWRs/VVERs, BWRs):**
    - Assay of all fresh fuel (Item counting, item identification, NDA)
    - Inspector presence during open core periods (NDA/C/S)
    - Monitoring of spent fuel in pools and dry cask storage (C/S, NDA)
  - **On-load-refueled reactors (e.g., CANDU):**
    - Assay of all fresh fuel (NDA, counting, IDs)
    - Continuous monitoring of fuel flow (qualitative NDA, discharge monitors, transfer monitors)
    - Monitoring of spent fuel in pools and dry casks (C/S, NDA)

- **Research Reactors and Critical Assemblies:**
  - Assay of all fuel and targets (NDA, counting, IDs, weight)
  - Thermohydraulic **power monitoring** for reactors > 25 MWt

* Borrowed from a presentation by Sergey Zykov, IAEA, at AAP 2014, Paris
The IAEA appears to be relatively satisfied with its current safeguards approach at most reactors

- The IAEA sees higher priorities for its limited safeguards budget. Examples include:
  - Safeguarding enrichment, reprocessing* and Pu fuel fabrication plants, which handle (or can produce) unirradiated direct-use material in bulk form
  - Detecting undeclared nuclear facilities and activities
  - And at most reactors, one area for improvement is strengthening detection of diversion of spent fuel from storage, where antineutrino monitoring doesn’t help much

* Note, however, that antineutrino monitoring, if coupled with expanded operator declarations and improved core modeling, potentially could Pu content on predict per-assembly basis, narrowing uncertainties due to shipper-receiver differences at reprocessing plants. (See A. Bernstein, T.E. Shea, N.S. Bowden, et al., “Antineutrino-Based Reactor Monitoring for Future IAEA Safeguards Applications,” Pro., INMM 53rd Annual Meeting, Orlando, 15-19 July 2012
So as recognized in several recent AAP workshops, the potential nonproliferation value of antineutrino reactor monitoring appears to lie not so much in routine LWR power reactor safeguards but instead in more specialized applications...
... for example:

- At reactors burning Pu fuels, confirmation of core composition as an extra check against diversion of fresh Pu fuel by substitution of undeclared LEU fresh fuel
- **After loss of COK** on the integrity of reactor head seals, timely confirmation that core composition remains unchanged
- Monitoring **certain reactor types** (e.g., MSRs, very-long-lifetime core reactors)
- A more spoof-resistant means (than thermohydraulic monitors) for confirming the declared power history of certain large research reactors
- Confirming burnup of excess weapons plutonium pursuant to an arms control agreement
- Perhaps a **future transparency measure at fusion reactors** to confirm absence of nuclear material targets?
- **Far-field confirmation of non-operation of a shut-down reactor** pursuant to an agreement that does not provide for on-site verification
- **Far-field detection of the operation of an undeclared reactor**
Safeguards implementation in 2017

What did we achieve in 2017?

We concluded that for

- **70 States**
  all nuclear material remained in peaceful activities.

- **103 States**
  declared nuclear material remained in peaceful activities.

- **3 States**
  nuclear material, facilities or other items to which safeguards had been applied remained in peaceful activities.

- **5 States**
  nuclear material in selected facilities to which safeguards had been applied remained in peaceful activities.

How did we get there?

Our legal framework

182 States with safeguards agreements in force

132 States with additional protocols in force

Our verification process

Conducted
2,843 in-field verifications

13,744 days in the field

Verified
24,300 seals
installed on nuclear material, facility critical equipment or IAEA’s safeguards equipment at nuclear facilities

Acquired
556 commercial satellite images

Remotely monitored
130 facilities

Deployed
991 non-destructive assay systems for the measurement of nuclear material

Our resources

139.3 million
+23.1 million extra budgetary

Our coverage

208,889 significant quantities of nuclear material

1,298 nuclear facilities and locations outside facilities

Collected
483 environmental samples

599 nuclear material samples

1,541 surveillance cameras connected to nuclear facilities

946 staff & contractors from 96 countries