Antineutrino Reactor Monitoring in the Context of IAEA Safeguards

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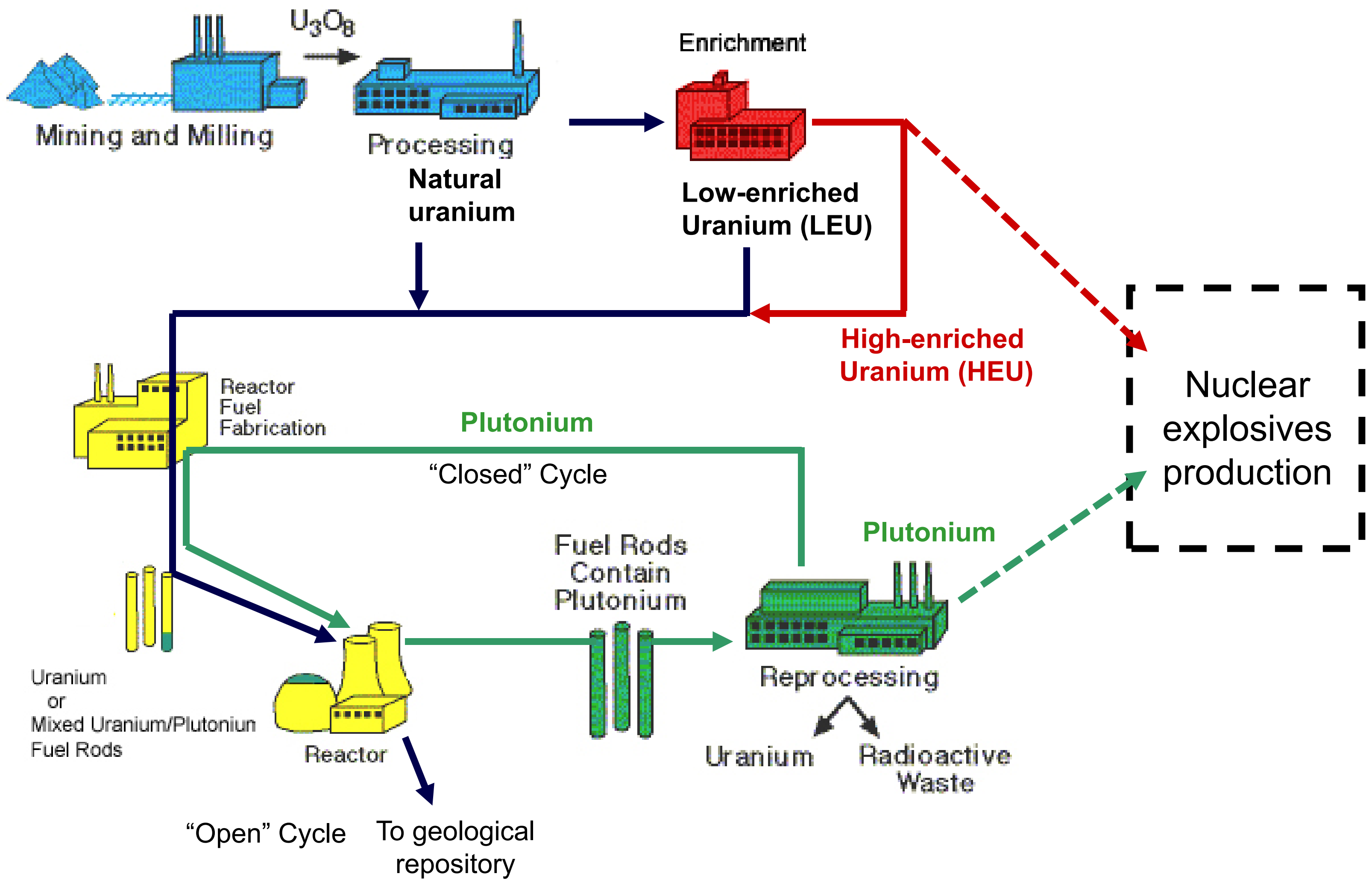
Civilian and military nuclear fuel cycles can overlap



The International Atomic Energy Agency

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 Safegaurds 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

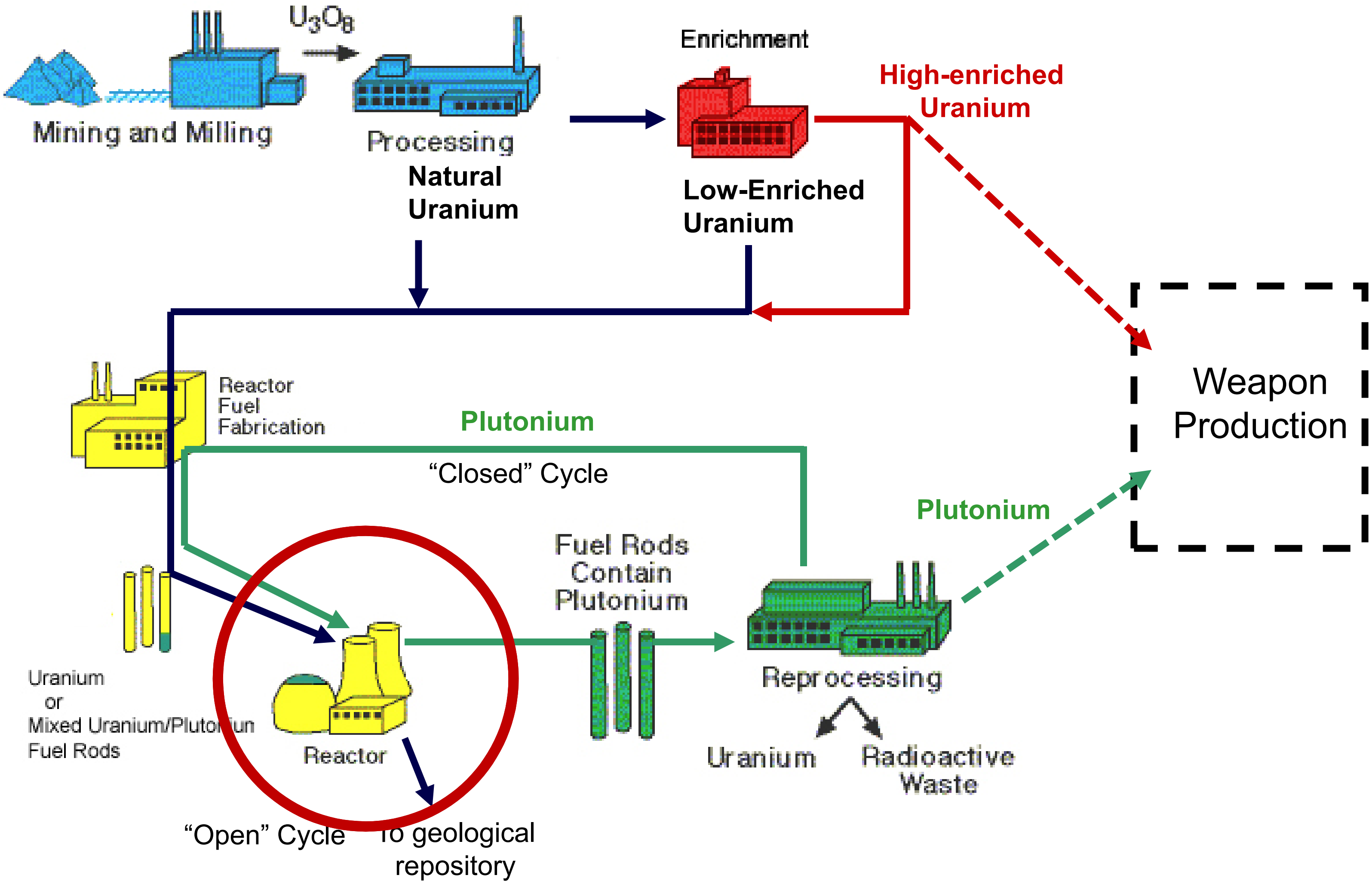
Material category	Examples	Quantity goal	Timeliness goal
Indirect-use material	LEU fresh fuel	75 kg U-235 content	1 year
Irradiated direct-use material	Irradiated fuel in reactor cores, spent fuel pools, or dry storage	8 kg Pu, 25 kg U-235 as HEU	3 months*
Unirradiated direct-use material	High-enriched UF_6, fresh MOX fuel, HEU fresh fuel	8 kg Pu, 25 kg U235 as HEU	1 month

*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

Type of facility	Nuclear material category	Bulk or item form
Uranium conversion plant	Indirect-use	Bulk
Enrichment plant	Most have the potential to produce unirradiated direct-use material	Bulk
Fuel fabrication plant (NU or LEU)	Indirect-use	Bulk
Most reactors (w/o MOX)	Irradiated direct-use	Item
Reprocessing plant	Unirradiated direct-use	Bulk
MOX fuel fabrication plant	Unirradiated direct-use	Bulk

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 2107 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:

Diversion scenario	Concealment methods	Safeguards measures
Removal of fuel assemblies from the reactor core	Substitution with dummies, falsifying records, borrowing from another location	Item counting, item identification, seals, optical surveillance, spent fuel bundle counters, core discharge monitors, simultaneous inspections

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

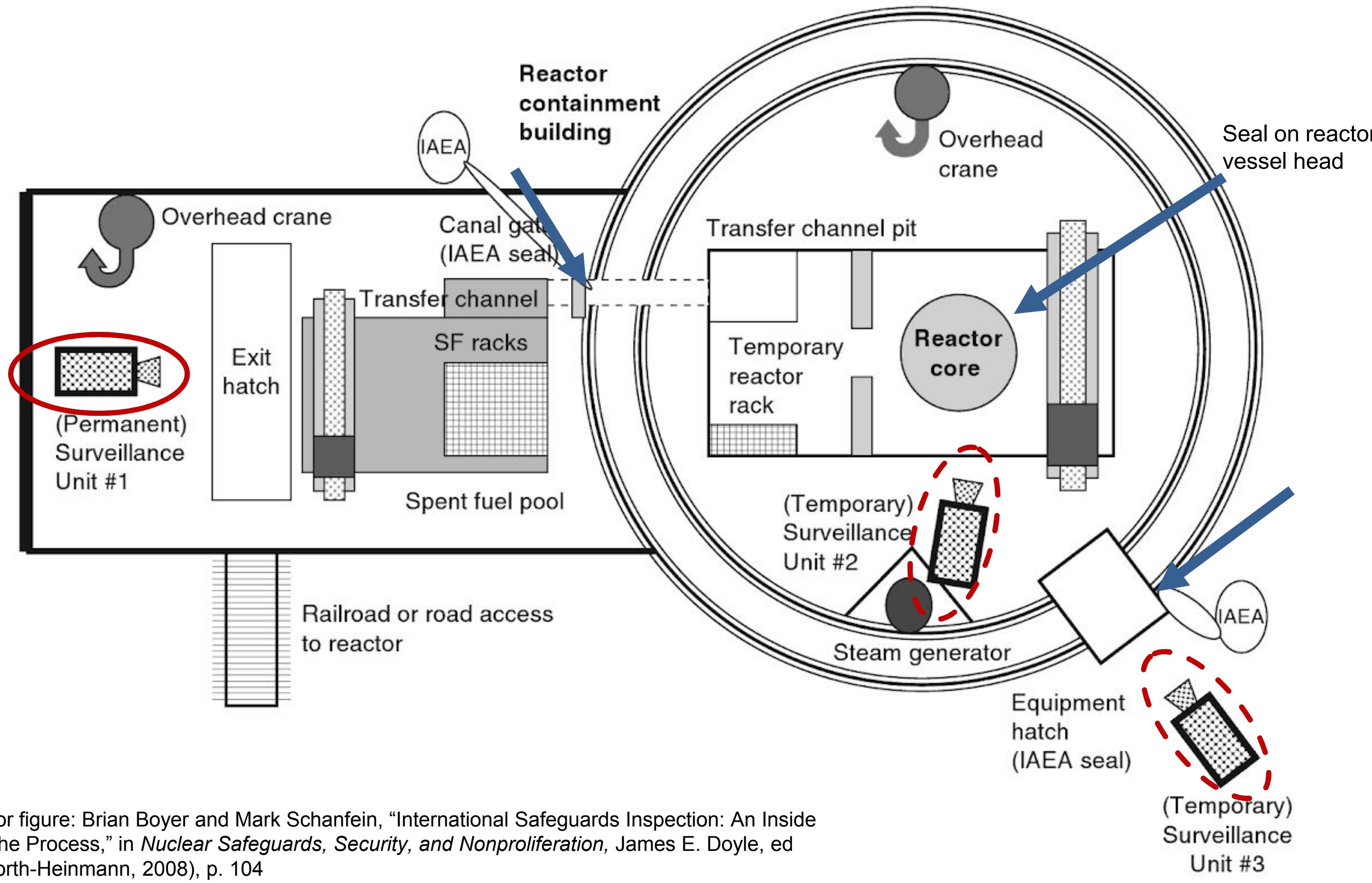
Misuse/diversion scenarios	Concealment methods	Safeguards measures
Removal of fuel rods or assemblies from the fresh fuel storage area	Substitution with dummies, falsifying records, borrowing fuel rods or assemblies from another location	Item counting, item identification, application of seals, non-destructive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

Source: International Atomic Energy Agency, International Safeguards in the Design of Nuclear Reactors, IAEA Nuclear Energy Series No. NP-T-2.9, p.18

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



Source for figure: Brian Boyer and Mark Schanfein, "International Safeguards Inspection: An Inside Look at the Process," in *Nuclear Safeguards, Security, and Nonproliferation,* James E. Doyle, ed (Butterworth-Heinmann, 2008), p. 104

Verifying the presence of LEU in a VVER fresh fuel assembly via gamma-ray spectrometry

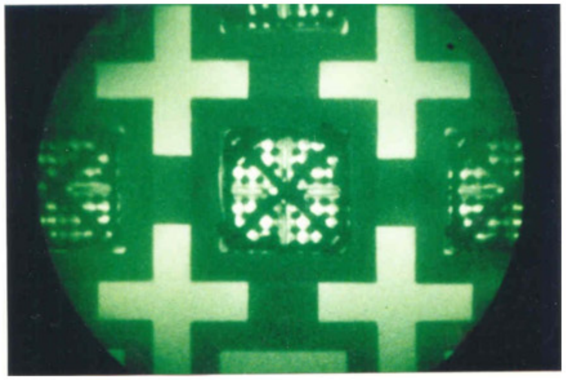
Image: IAEA

Sealed bolt on reactor pressure vessel head

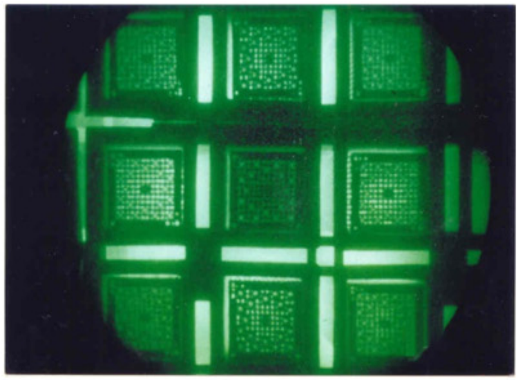
A Cerenkov viewing device aids verification of the contents of the spent fuel pool and open core

CVD images for various fuel types

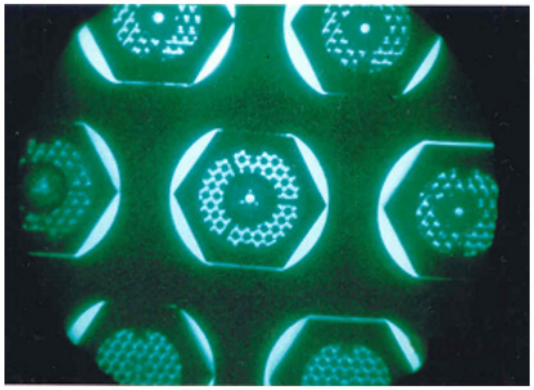
[Source: J. Whitlock, AECL, "CANDU Proliferation Resistance," 27 May 2008



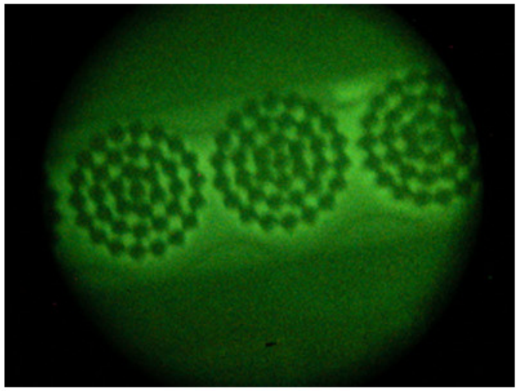
BWR Fuel



PWR Fuel



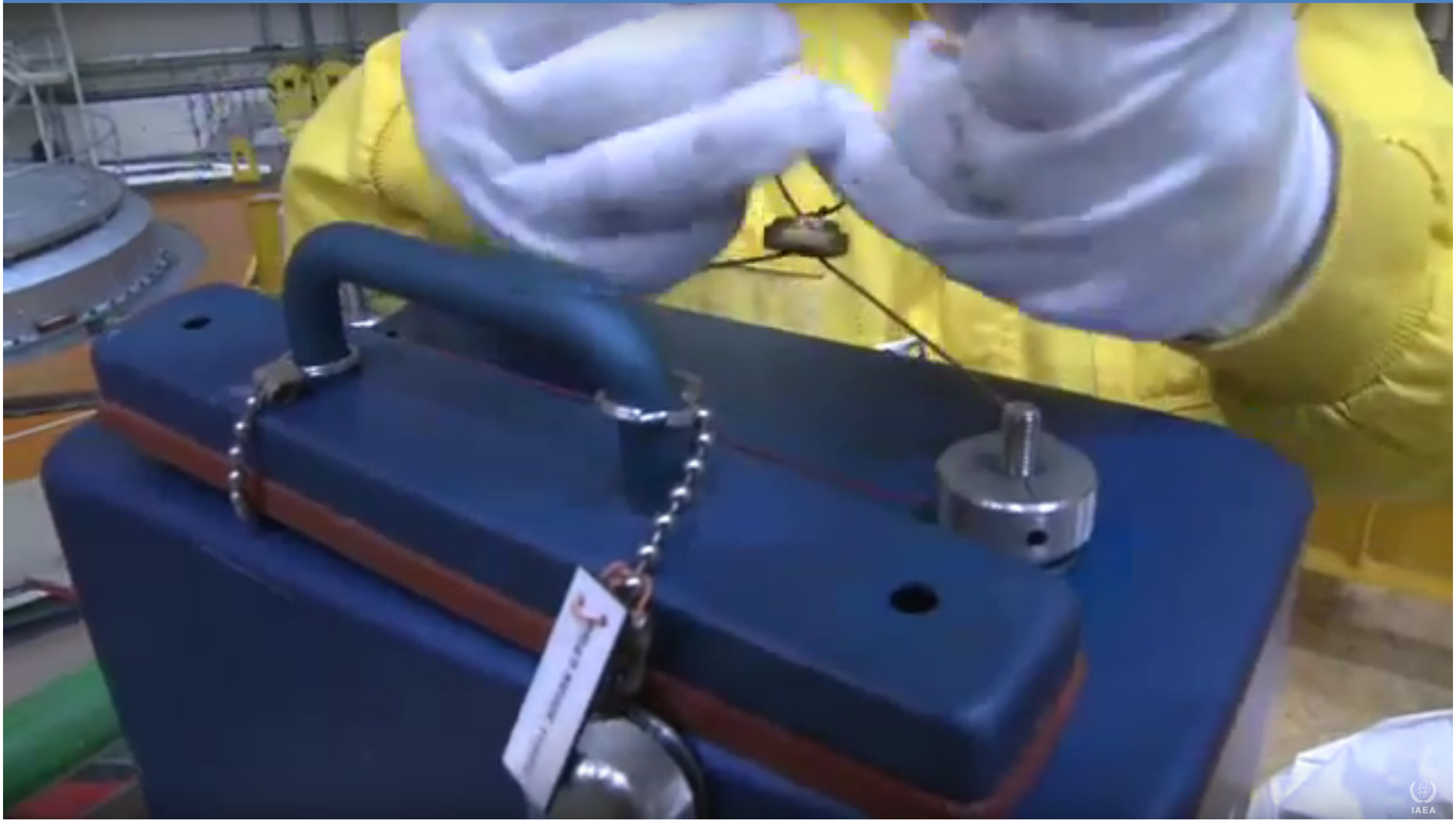
VVER Fuel



CANDU Fuel

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**

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Safeguards implementation in 2017

Helping prevent the spread of nuclear weapons

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 coverage

208,889 significant quantities of nuclear material

1,298 nuclear facilities and locations outside facilities

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

IAEA

Collected **483** environmental samples | **599** nuclear material samples

Acquired **556** commercial satellite images

Remotely monitored **130** facilities

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

1,541 surveillance cameras connected to nuclear facilities

Our resources

139.3 million
+23.1 million extra budgetary

946
staff & contractors
from 96 countries

Source: IAEA, https://www.iaea.org/sites/default/files/18/04/sg-implementation-2017.pdf