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Introduction to Nuclear Safeguards: Nondestructive Analysis

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Idaho National Laboratory is a multiprogram laboratory operated by Battelle Energy Alliance for the United States Department of Energy under contract DE-AC07-05ID14517.

Safeguards in Context

*"… the objective of safeguards is the **timely detection** of diversion of **significant quantities** of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or of other nuclear explosive devices or for purposes unknown, and deterrence of such diversion by the risk of early detection."*

"To this end the Agreement should provide for the use of material accountancy as a safeguards measure of fundamental importance, with containment and surveillance as important complementary measures."

"The Agreement should provide that the technical conclusion of the Agency's verification activities shall be a statement, in respect of each material balance area, of the amount of material unaccounted for over a specific period, giving the limits of accuracy of the amounts stated. "

-IAEA, INFCIRC 153

Key Definitions

Timely detection – the time required to convert different forms of nuclear material to the components of a nuclear explosive device.

- For metallic Pu and HEU conversion time is estimated as 7-10 days; IAEA detection goal is **1 month**
- For pure unirradiated compounds of these materials such as oxides or nitrates conversion time is estimated as 1-3 weeks; IAEA detection goal is **1 month**
- For Pu or HEU in irradiated fuel conversion time is estimated as 1-3 months, IAEA detection goal is **3 months**
- For low-enriched uranium conversion time is estimated as 1 year, , IAEA detection goal is **1 year**

Significant quantity (SQ) – the approximate quantity of nuclear material in respect of which, taking into account any conversion process involved, the possibility of manufacturing a nuclear explosive device cannot be excluded.

- For plutonium (<80% ^{238}Pu) the SQ is 8 kg
- For ^{233}U the SQ is 8 kg
- For highly enriched uranium (HEU) the SQ is 25 kg of ^{235}U
- For low-enriched uranium (LEU) the SQ is 75 kg of ^{235}U

Ref: "IAEA Safeguards Monitoring Systems & Science and Technology Challenges for International Safeguards" & "Are IAEA Safeguards on Plutonium Bulk-Handling Facilities Effective?"

Method of Safeguarding

<u>Safeguards Techniques:</u>

1. Environmental Sampling (ES)
2. Containment and Surveillance (C/S)
3. Nondestructive Assay (NDA)
4. Destructive Assay (DA)

} *material accountancy as a safeguards measure of fundamental importance*

Balancing the books … material unaccounted for (MUF)

$$\boldsymbol{MUF \equiv \left(BI + I - R - EI\right)}$$

$\boldsymbol{BI}$ = beginning inventory

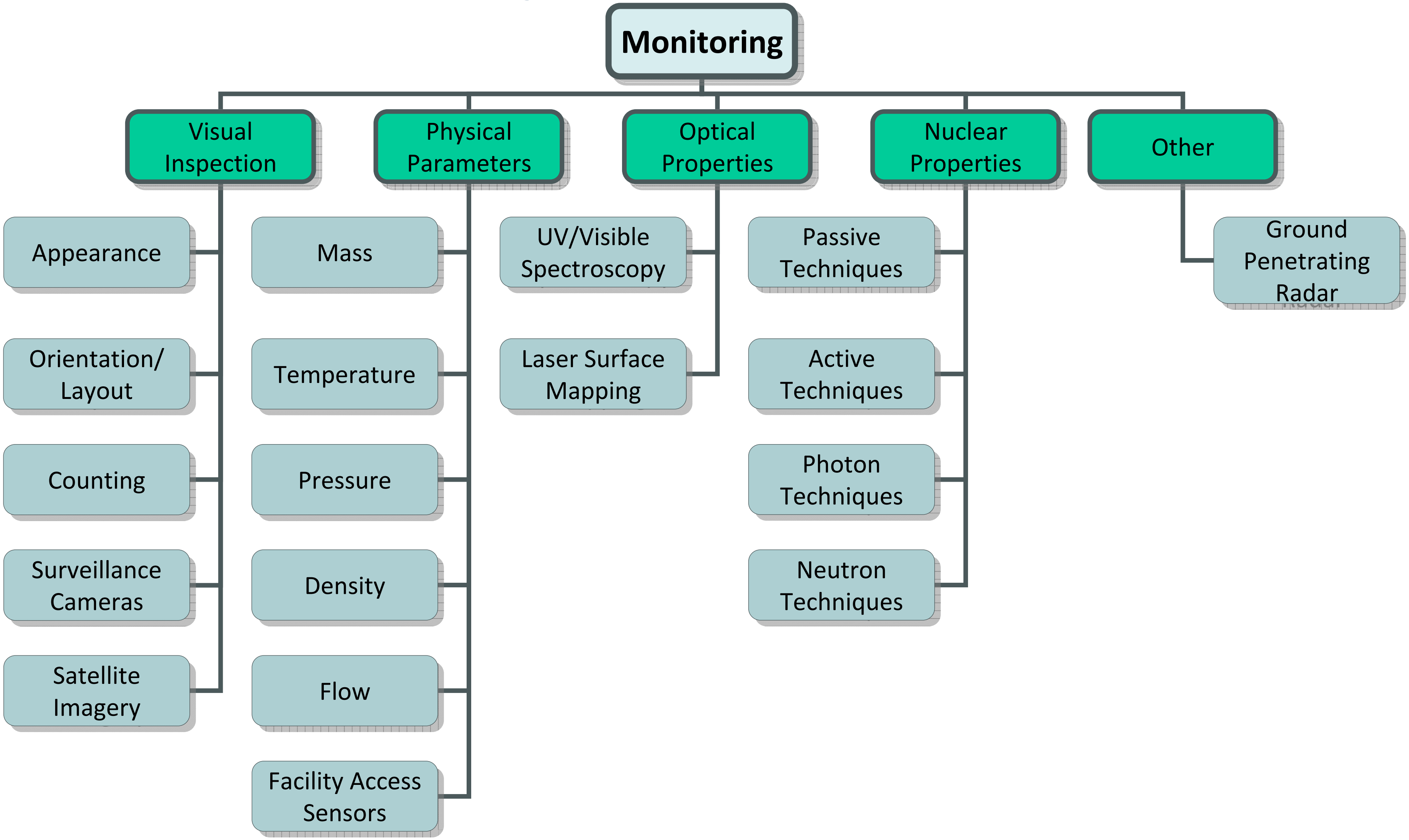
$\boldsymbol{I}$ = new inputs into a system

$\boldsymbol{R}$ = removals from a system

$\boldsymbol{EI}$ = ending inventory

Ref: "Nuclear Safeguards, Security, and Nonproliferation"

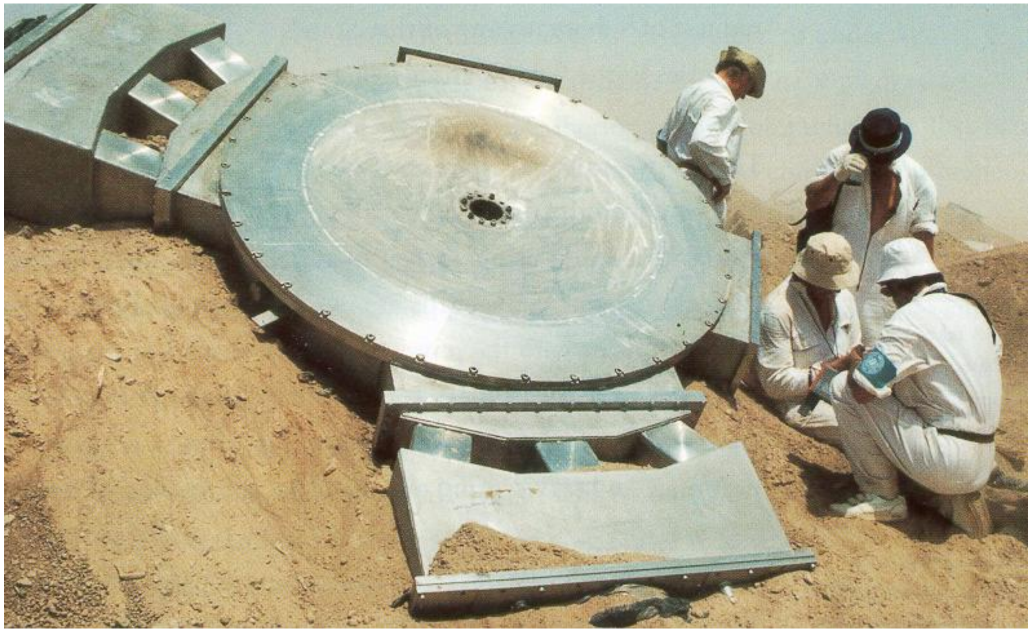
Nondestructive Analysis – A Broad Definition



Visual Inspections

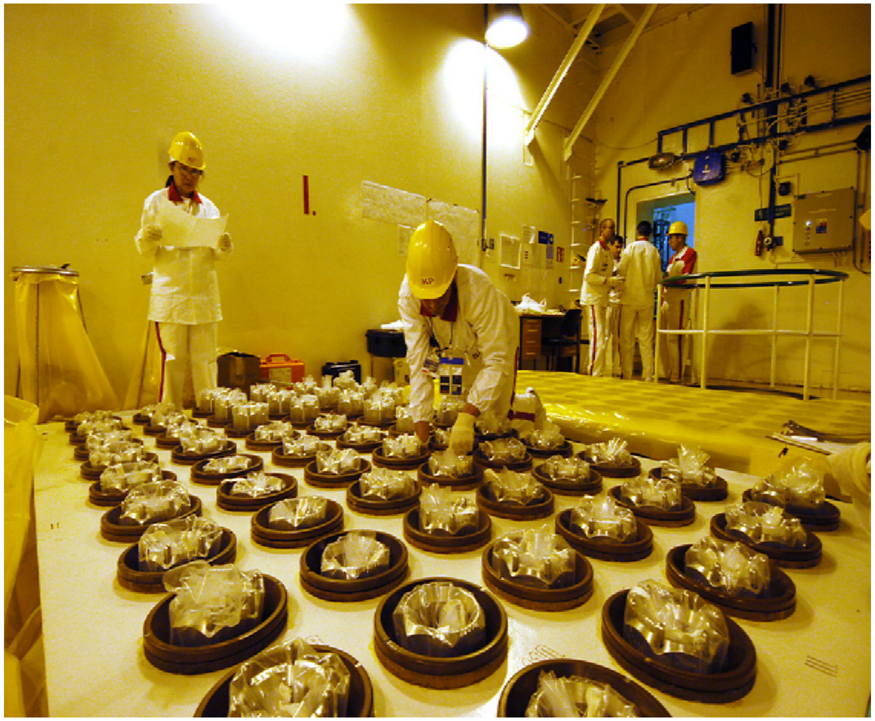
Visual inspections are the easiest, cheapest, most commonly performed type of safeguard assessments and visual observation by skilled and knowledgeable inspectors is a key part of safeguards. However, visual inspections are not foolproof and misdirection, obfuscation, concealment, and other methods of deception can limit the overall usefulness of visual inspections in many cases.

This photo was taken in the Iraqi desert after the 1991 Gulf War; it shows inspectors examining a component of an electromagnetic isotope separator, part of a covert uranium enrichment program unknown prior to the war.



Ref: "International Nuclear Safeguards INMM Tutorial"

Simple Counting



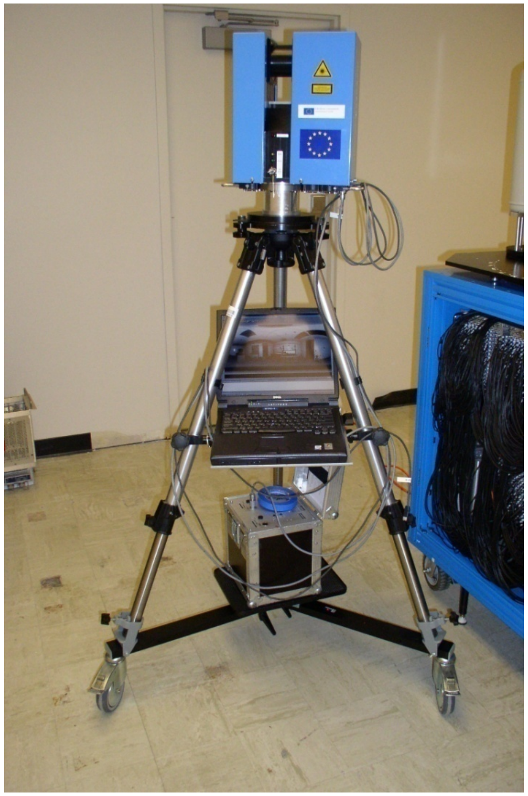
Things that are counted …

- *Fuel pins, rods, assemblies, canisters*
- *UF_6 containers*
- *Waste storage containers*
- *Pipes, valves, …*

Ref: "IAEA Safeguards Equipment"

Design Information Verification (DIV)

3DLRFD - Laser DIV Tool



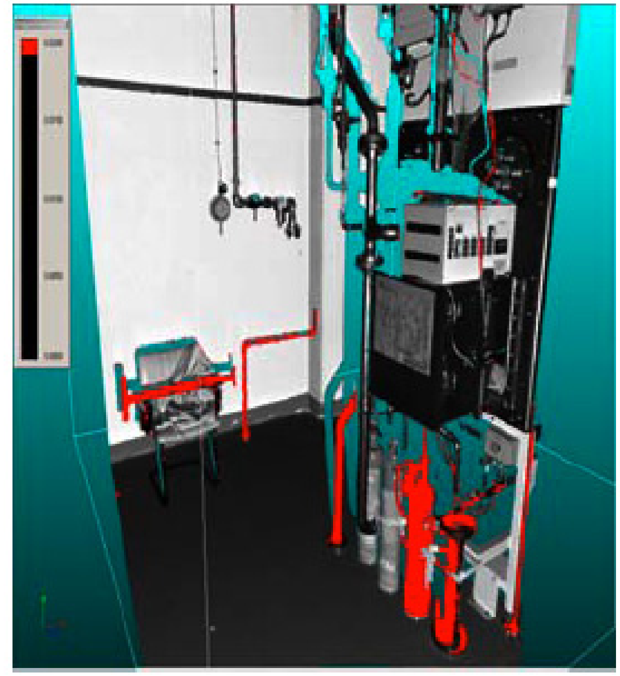
Nuclear processing facilities can be very complex; DIV confirms a facility is laid out to achieve the declared task(s), and nothing more. Next generation "change detection" tools can help identify modifications after initial DIV.

Ref: "IAEA Safeguards Equipment" & "Modern Safeguards Systems"

Design Information Verification (DIV) Example

Reference Image

New Image

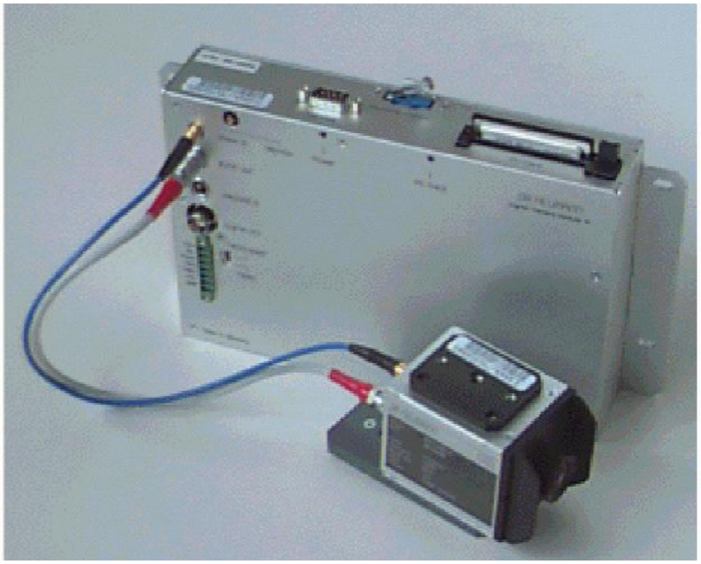


Differences Highlighted

Data here shows changes in a facility and its equipment detected using the 3DLRFD (3DLR) system. *The red points indicate objects that have shifted position beyond a set tolerance level.*

Ref: "Addressing Verification Challenges"

Surveillance Cameras



Current IAEA surveillance systems are based on the DCM14 digital camera module.

- Scene change detection
- Image compression
- Image/data authentication & encryption
- Power management & battery back-up
- External triggers
- State of health
- Removable image and data recording media

Surveillance is used to:

- Detect and/or confirm all movements of nuclear material and spent fuel containers
- Confirm that containment is maintained
- Confirm that information related to locations and quantities of nuclear material is valid
- Confirm IAEA devices are not tampered with
- Ensure the absence of undeclared operations
- Continuously monitor a specific activity for a short period of time

Ref: "IAEA Safeguards Equipment"

Special Nature of Safeguard Surveillance Cameras

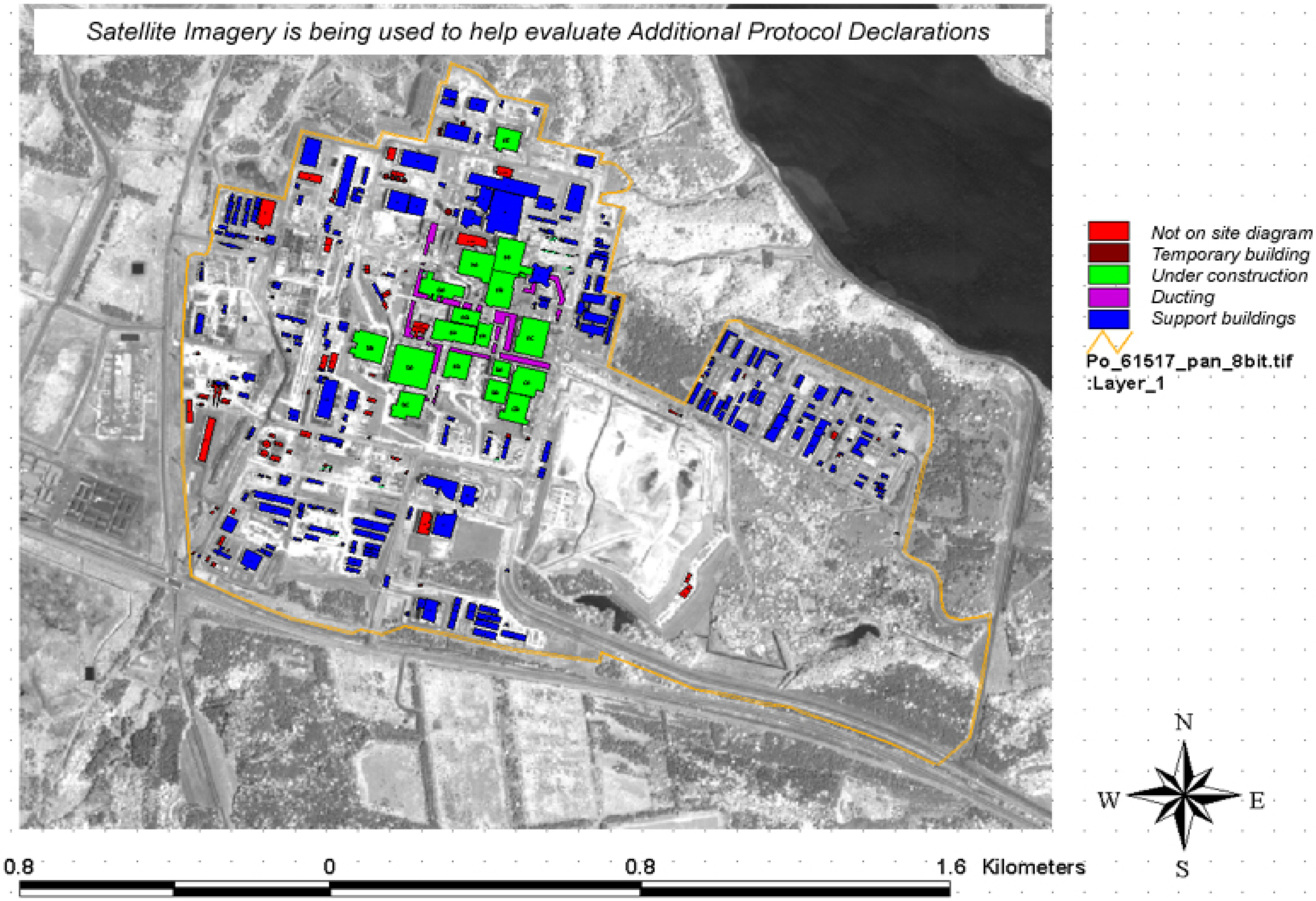
As with nearly all safeguards instrumentation the cameras used for monitoring and surveillance are specialized and custom made

- Tamper resistant/tamper indicating
- Data authentication
- Self powered
- Redundancy

Installation of an IAEA camera in an HEU down blending facility in Kazakhstan

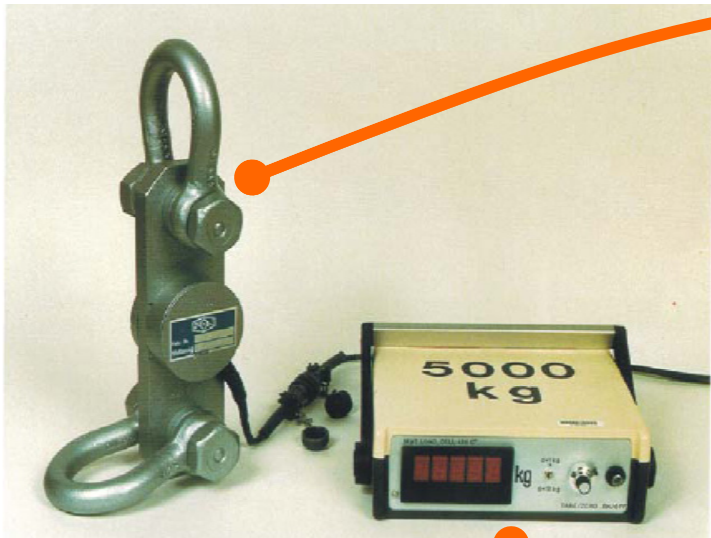
Ref: "IAEA Safeguards Equipment" & "Addressing Verification Challenges"

Satellite Imagery

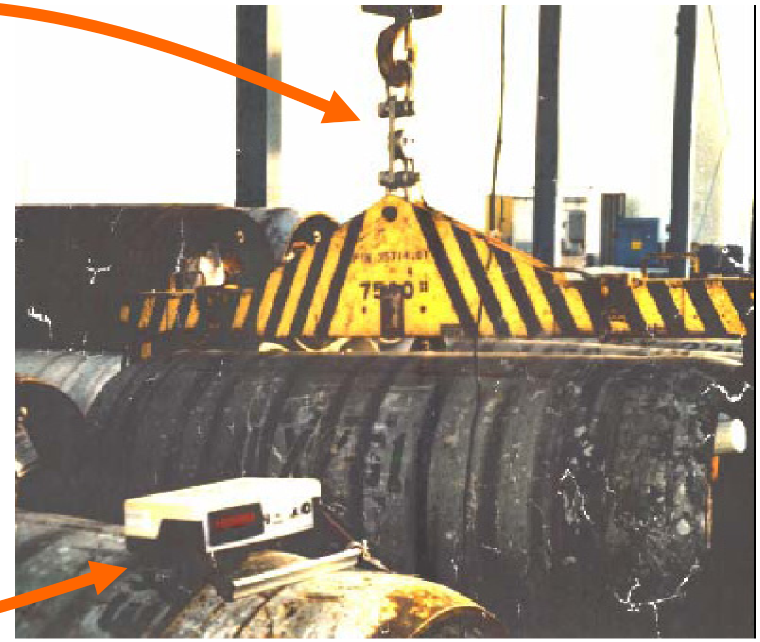


Ref: "IAEA Safeguards Equipment"

Physical Parameters – "Simple" Mass Measurements



Load Cell Based Weighing System (LCBS)



LCBS being used to weigh a UF_6 cylinder

Ref: "IAEA Safeguards Equipment"

Monitoring Materials in Storage

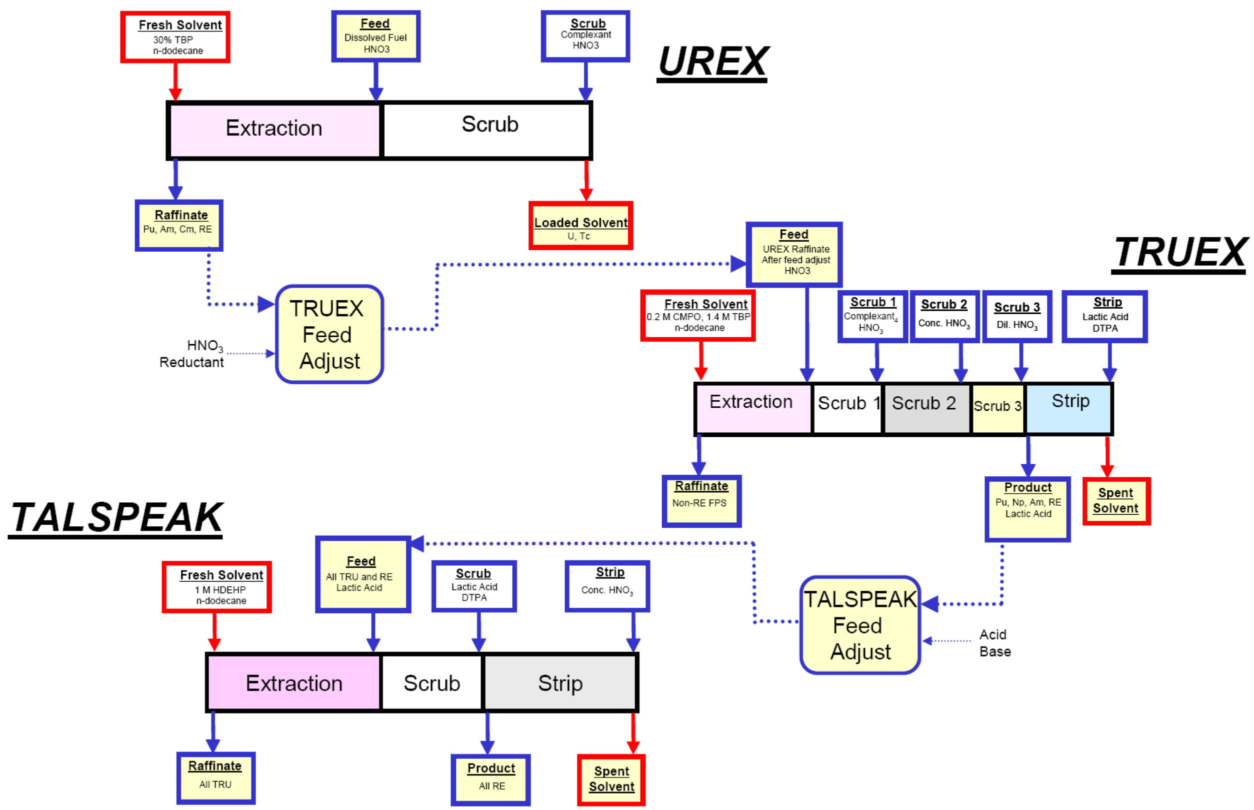
The continuous automated vault inventory system (CAVIS) from Oak Ridge National Laboratory installed at the All-Russian Scientific Research Institute of Experimental Physics (VNIEEF) in 1997-1998.

The CAVIS equipment monitors material mass using a load cell, local radiation fields, and the material serial number.

Ref: "Modern Safeguards Systems"

Process Monitoring: Mass, Temperature, Pressure, Density, Flow

The UREX+1a demonstration flowsheet



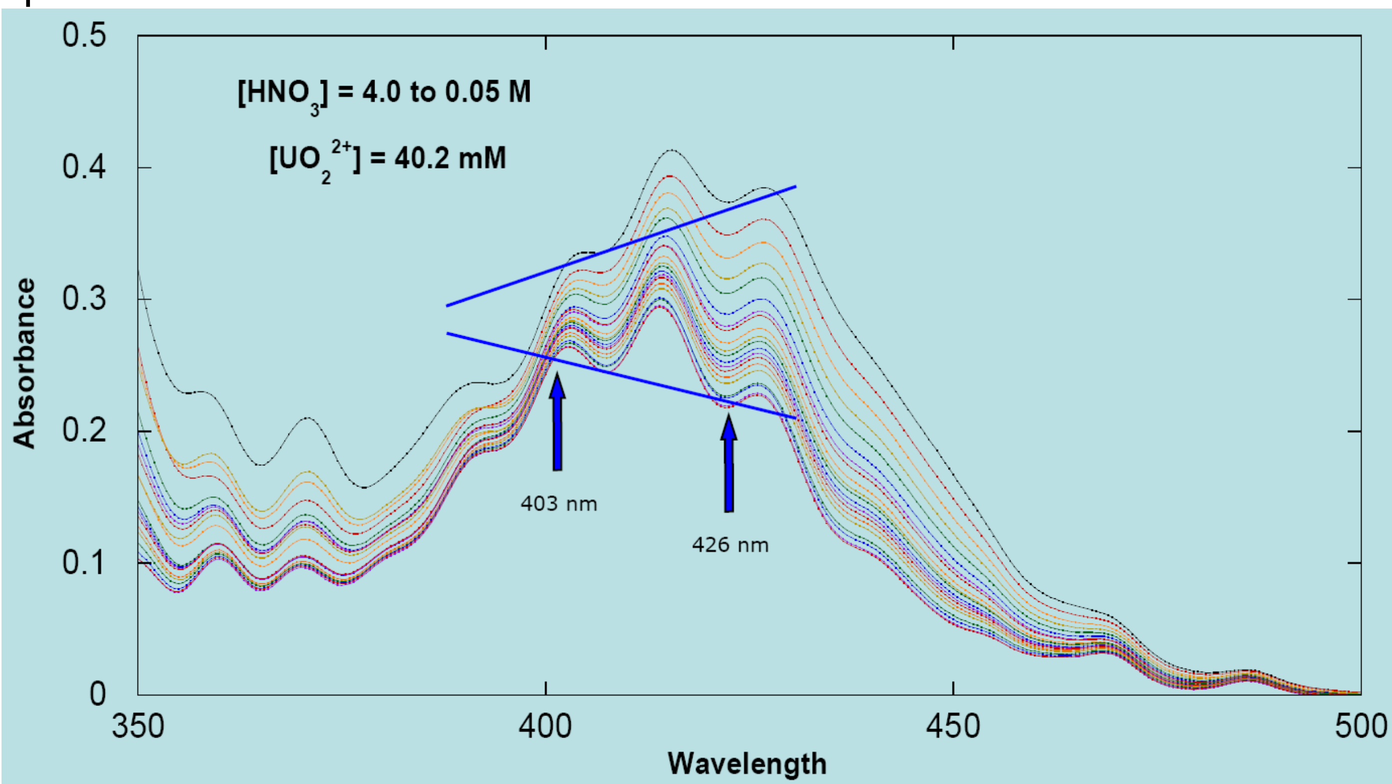
Ref: "Preliminary Results of the Lab-Scale Demonstration of the UREX+1a Process Using Spent Nuclear Fuel"

Many measurement opportunities exist within the entire nuclear fuel cycle including during mining, enrichment, fuel fabrication, spent fuel reprocessing, waste disposal, and all of the steps in between these processes.

Traditional industrial control system measurements can be used for both process quality and safeguards.

Optical Techniques – UV/Vis Spectroscopy (for Process Monitoring)

An important safeguards challenge is to perform real-time process monitoring in aqueous reprocessing, a very hostile and challenging environment. Laser based ultraviolet/visible spectroscopy may help in this area, providing a non-contact method for assaying chemical species in solution



This plot shows the UV/Vis spectrum of UO_2 (features at 403 nm and 426 nm) for varying nitric acid strengths.

Data like this can be used to assay the uranyl concentration in aqueous processes in near real time.

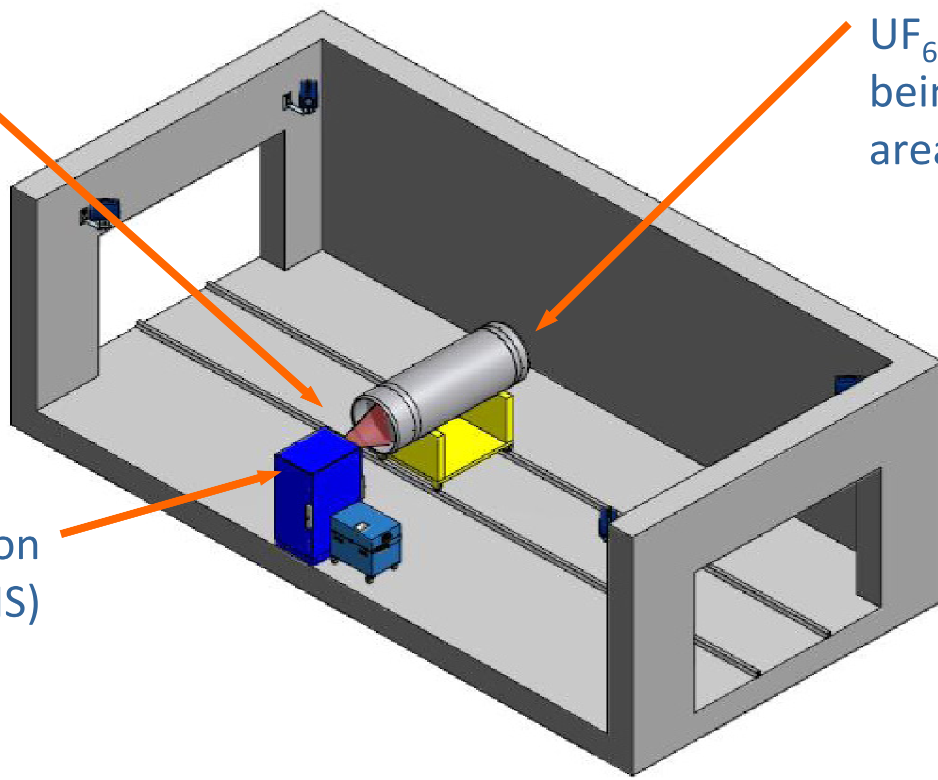
Ref: "Fuel Cycle Separations Group An Overview"

Laser Surface Profiling

More sophisticated optical inspection tools are under development, including a laser item identification tool to detect signs of tampering and to be sure items are correctly labeled and have not been switched.

Laser is used to map and record surface morphology of canister, unique like a human fingerprint

UF_6 storage container being moved from one area to another

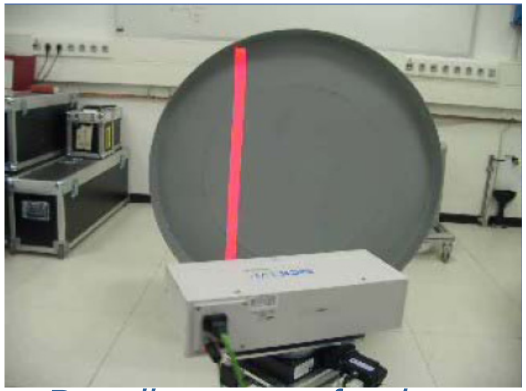


Laser Item Identification System (L2IS)

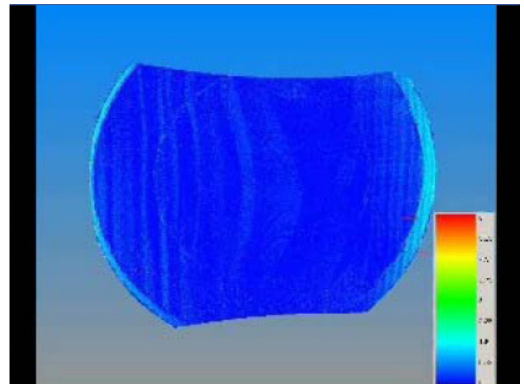
Ref: "Laser Based Applications: Existing and Future Solutions"

Laser Surface Profiling Example

Example: detection of tampering with a storage drum using laser surface mapping



Baseline scan of a drum



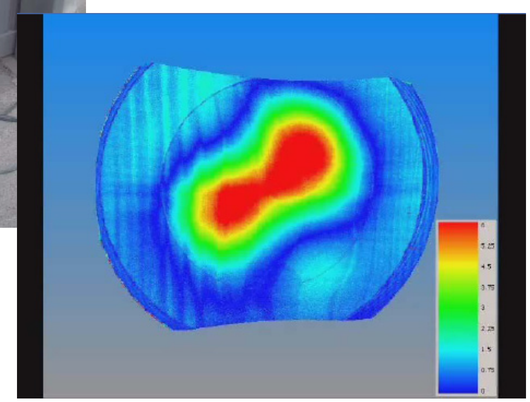
Drum Surface morphology

Tamper

Patch & weld

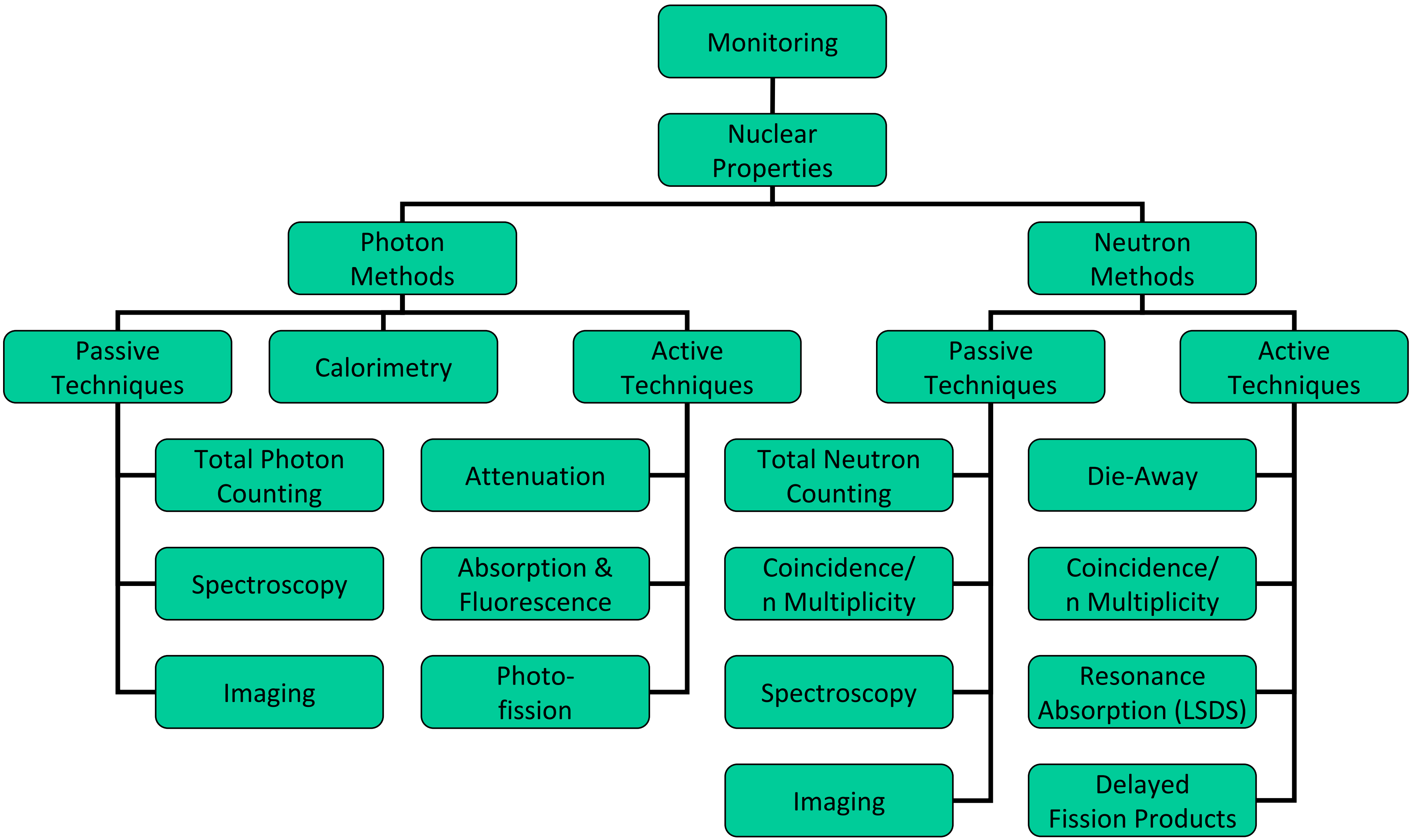
Paint

Re-scan detects changes



Ref: "Laser Based Applications: Existing and Future Solutions"

Nuclear Nondestructive Assay Techniques



The Passive Gamma-Ray Signatures

Isotope	Energy (keV)	Activity (γ/g-s)	Mean Free Path (mm) (High-Z, ρ)	(Low-Z, ρ)
^{234}U	120.9	9.35×10^4	0.23	69
^{235}U	143.8	8.40×10^3	0.36	73
	185.7	4.32×10^4	0.69	80
^{238}U	766.4	2.57×10^1	10.0	139
	1001.0	7.34×10^1	13.3	159
^{238}Pu	152.7	5.90×10^6	0.40	75
	766.4	1.387×10^5	9.5	139
^{239}Pu	129.3	1.436×10^5	0.27	71
	413.7	3.416×10^4	3.7	106
^{240}Pu	45.2	3.80×10^6	0.07	25
	160.3	3.37×10^4	0.45	76
	642.5	1.044×10^3	7.4	127
^{241}Pu	148.6	7.15×10^6	0.37	74
	208.0	2.041×10^7	0.86	83
^{241}Am	59.5	4.54×10^{10}	0.14	38
	125.3	5.16×10^6	0.26	70

These materials are dense; self-shielding is not negligible

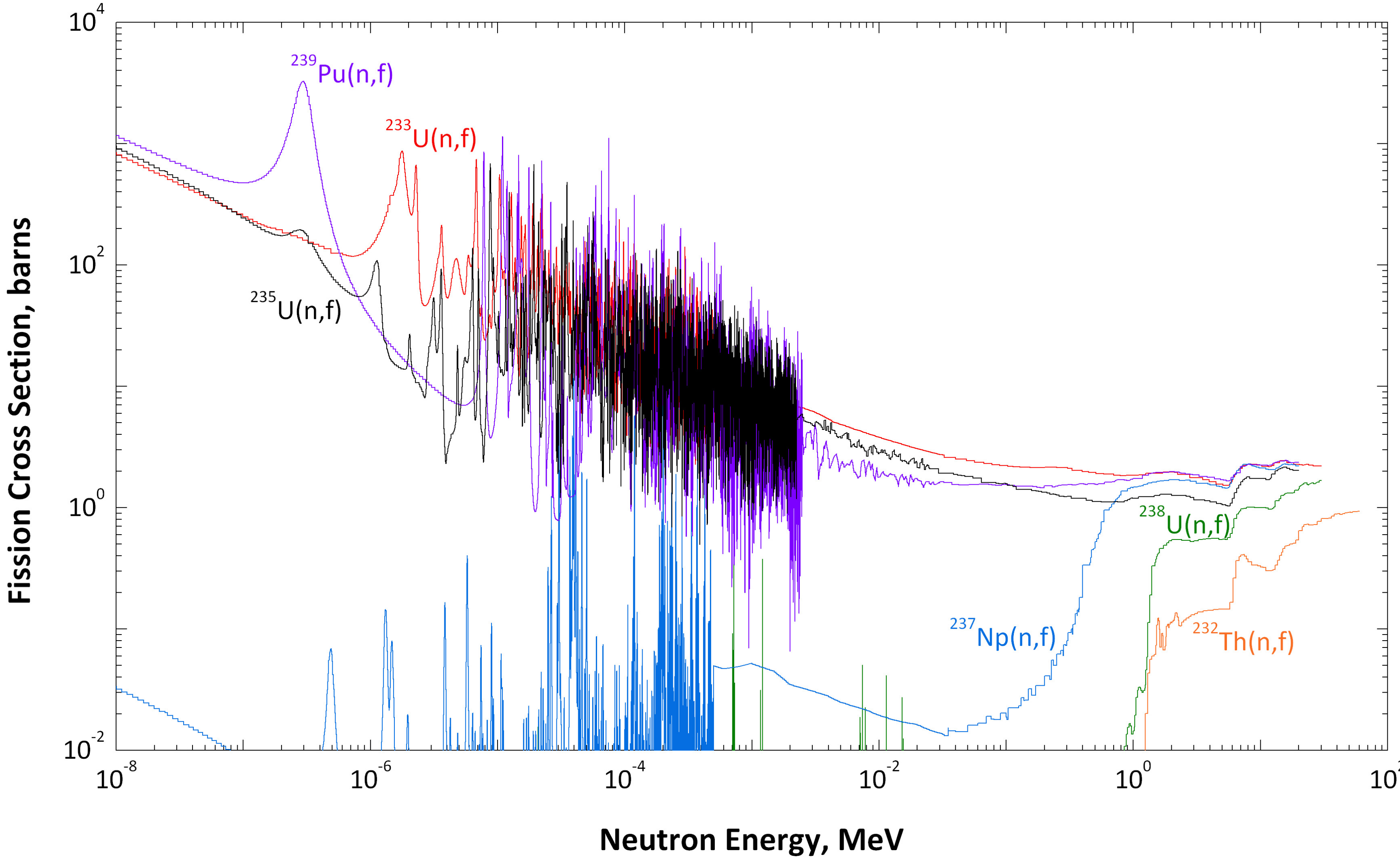
Ref: "Panda Book"

The Passive Neutron Signatures

Isotope	Half Life	Spontaneous Fission Yield (n/s-kg)	Spontaneous Fission Multiplicity ν	Induced Thermal Fission Multiplicity ν
^{232}U	71.7 yr	1,300	1.71	3.13
^{233}U	1.59×10^5 yr	0.86	1.76	2.4
^{234}U	2.45×10^5 yr	5.02	1.81	2.4
^{235}U	7.04×10^8 yr	0.299	1.86	2.41
^{236}U	2.34×10^6 yr	5.49	1.91	2.2
^{238}U	4.47×10^9 yr	13.6	2.01	2.3
^{237}Np	2.14×10^6 yr	0.114	2.05	2.70
^{238}Pu	87.7 yr	2.59×10^6	2.21	2.9
^{239}Pu	2.41×10^4 yr	21.8	2.16	2.88
^{240}Pu	6.56×10^3 yr	1.02×10^6	2.16	2.8
^{241}Pu	14.35 yr	50 ±	2.25	2.8
^{242}Pu	3.76×10^5 yr	1.72×10^6	2.15	2.81
^{244}Cm	18.1 yr	1.08×10^{10}	2.72	3.46
^{252}Cf	2.65 yr	2.34×10^{15}	3.757	4.06

Ref: "Panda Book", values with ± have significant uncertainty

The Neutron Fission Cross Sections



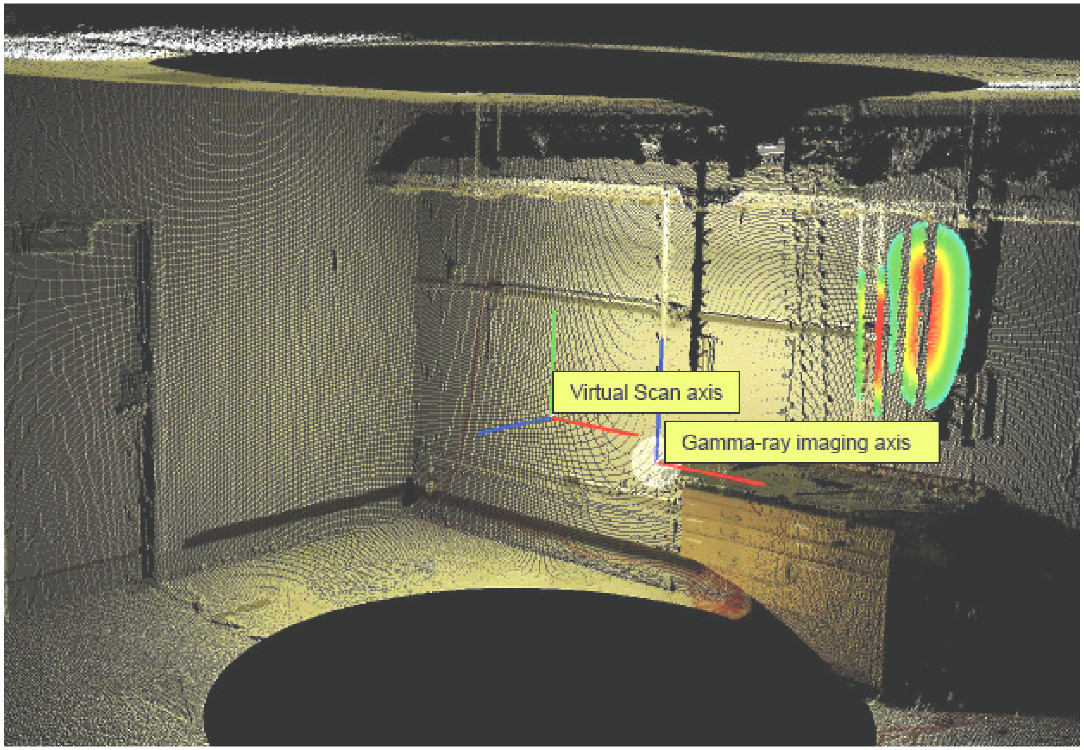
A Note on Radiation Detection

- ***This seminar does not explain how radiation detectors work***
  - Within 60-90 minutes a proper discussion of the science and engineering involved in radiation detection and measurement would not be possible
  - It is worth noting that almost all (but there are a few exceptions) radiation detectors indirectly infer the presence of radiation based on its interaction in a sensor, and the subsequent conversion of the energy of that reaction to an electrical signal

3DLR + A Gamma-Ray Imager

Here a Compton imager developed by LLNL is being used together with the 3DLR system to generate spatial maps combined with radiation field intensity plots.

To the right gamma-ray contour plots are shown over the visual 3D image data; radioactive material is contained within a few pipes on the wall.



Ref: "New and Novel Non-destructive Neutron and Gamma-Ray Technologies Applied to Safeguards"

Digital Cherenkov Viewing Device (DCVD)

The DCVD photographs Cherenkov light, the "blue glow" seen in water cooled reactors and spent fuel storage pools, which is used for safeguards monitoring.

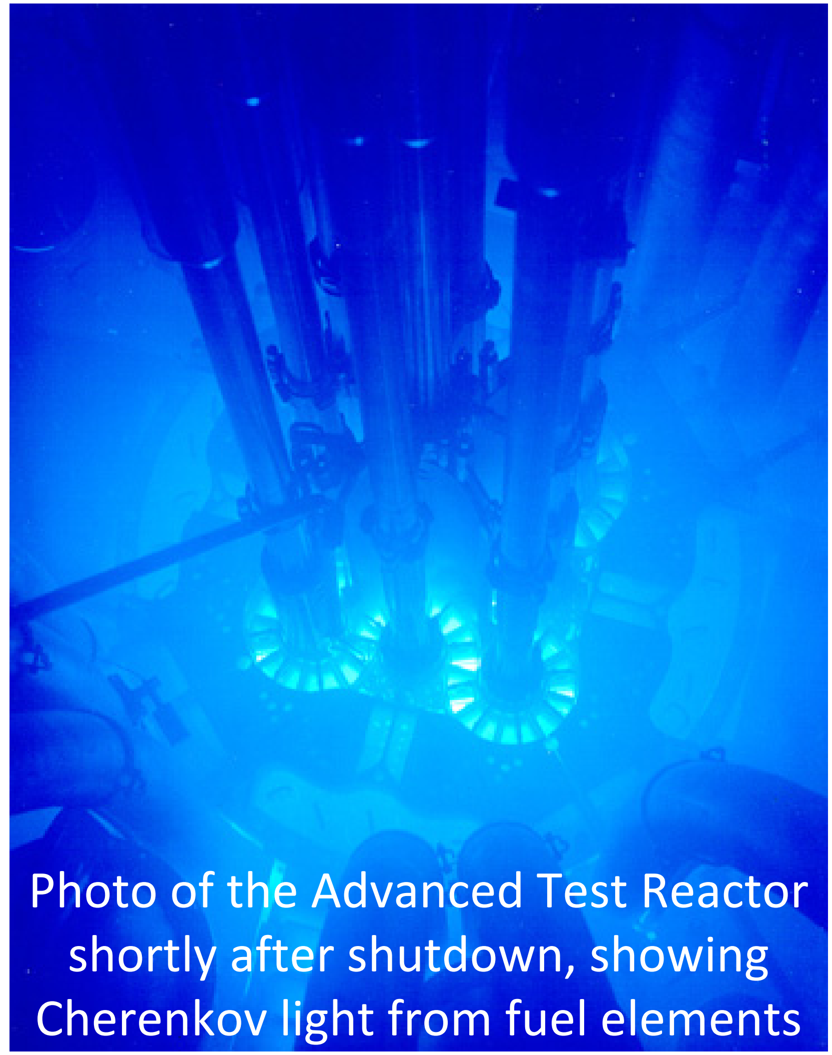
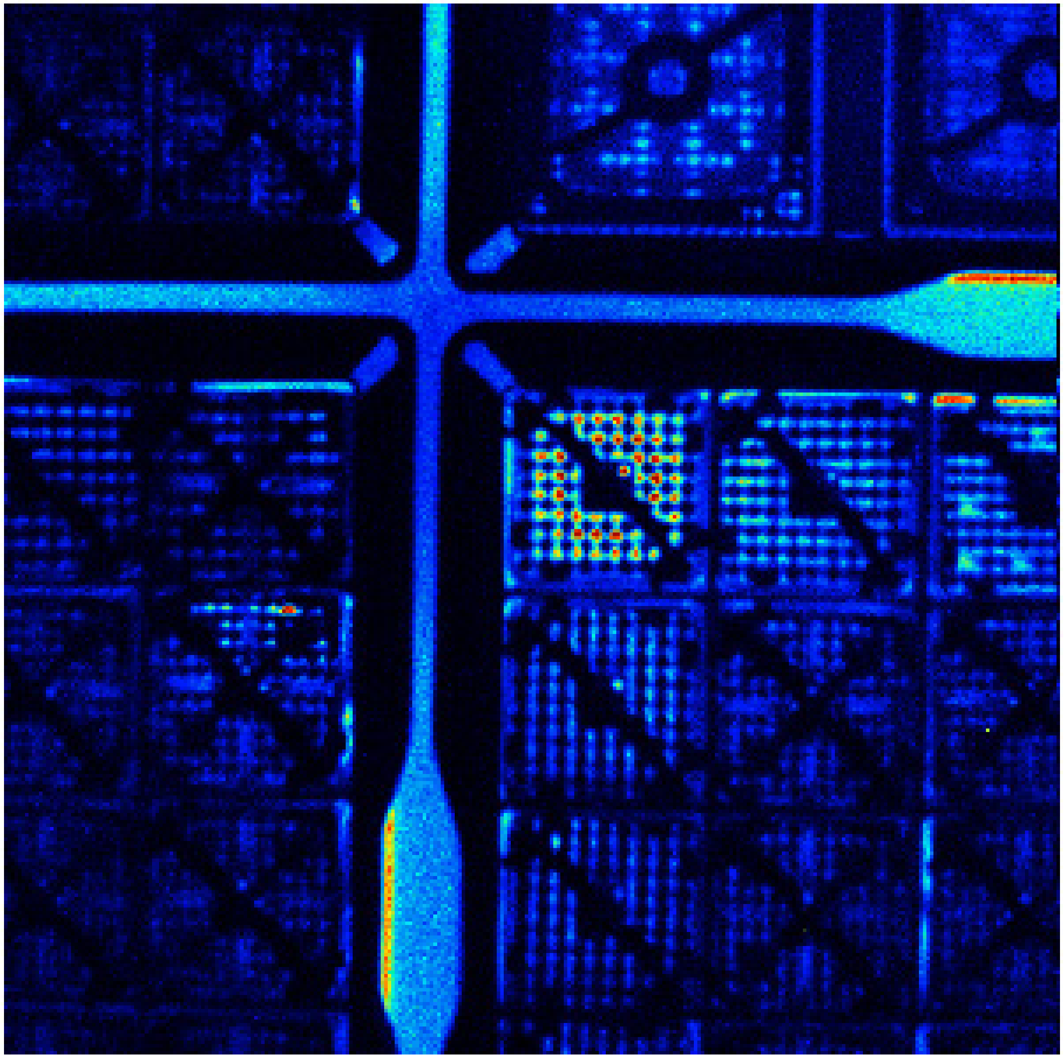


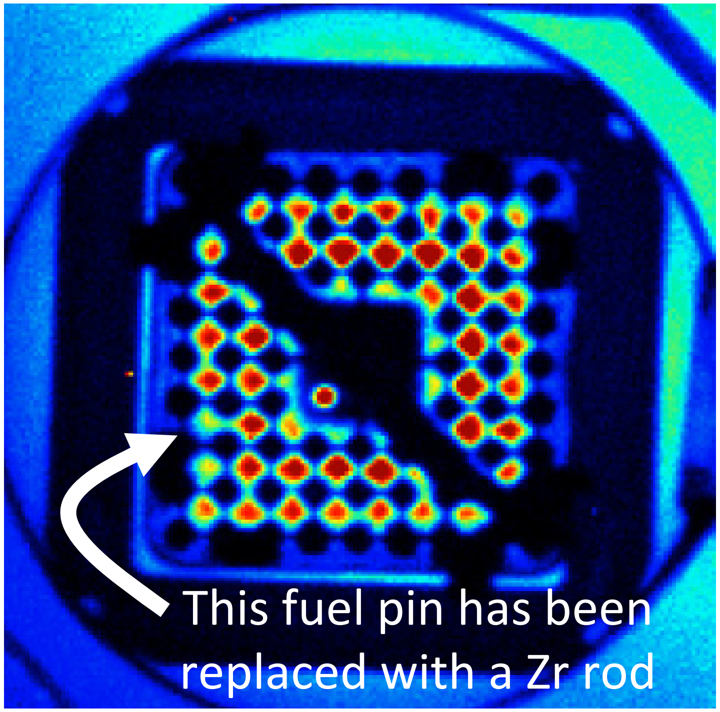
Photo of the Advanced Test Reactor shortly after shutdown, showing Cherenkov light from fuel elements

Ref: "Addressing Verification Challenges" & "Status on Two Novel IAEA Canadian Support Programme Technologies"

DCVD Images



Field of view of a 40,910 MWd/t BWR spent fuel element after 6 years of cooling using an 80 mm focal length UV lens.



Ref: "Addressing Verification Challenges" & "Status on Two Novel IAEA Canadian Support Programme Technologies"

HM-5 Hand Held Assay Probe

Portable handheld gamma detectors for detecting presence and identifying nuclear and other radioactive materials

Ref: "IAEA Safeguards Equipment"

Mini Multichannel Analyzer (MMCA)

Self contained analysis system for analysis of gamma rays using either NaI scintillator detectors or CdZnTe solid-state semiconductor detectors

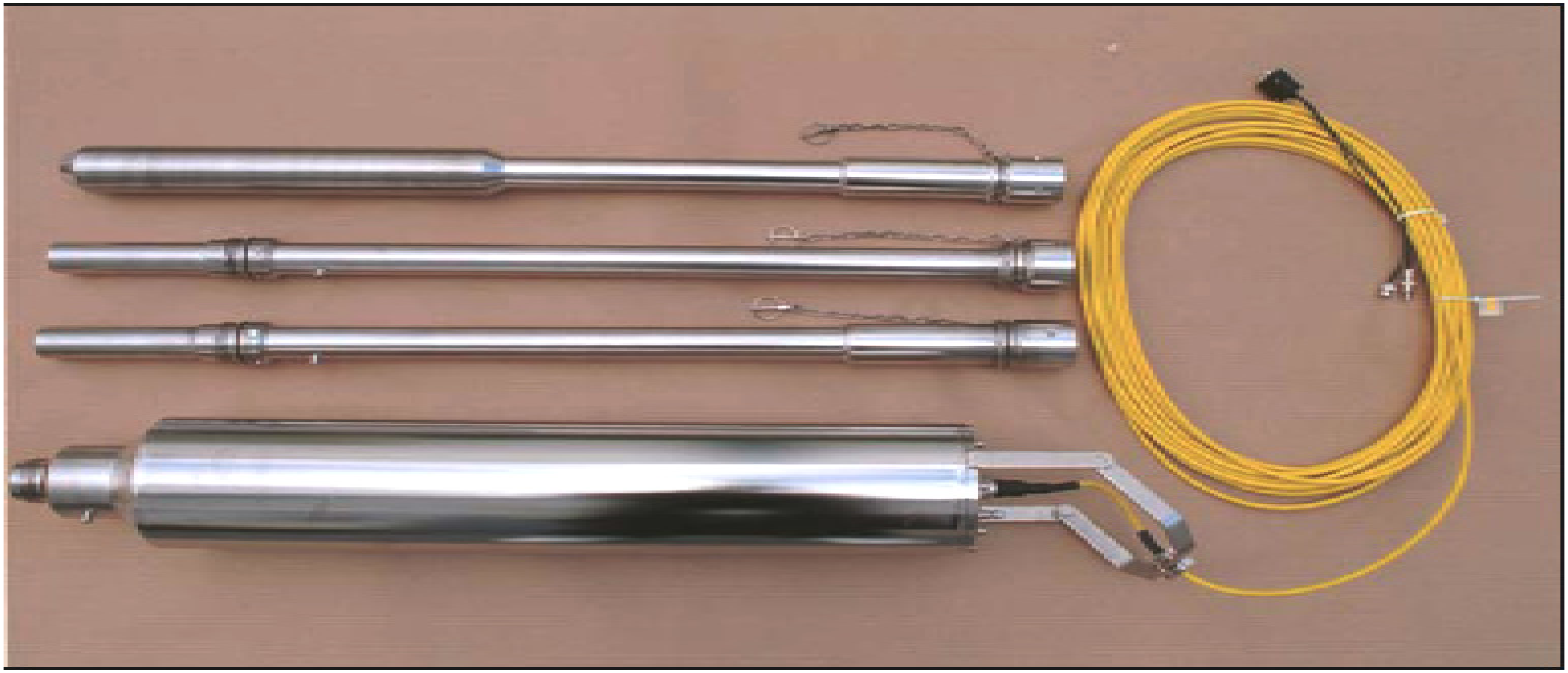
Ref: "IAEA Safeguards Equipment"

Irradiated Item Attribute Tester (IRAT)

A variant of the MMCA instrument for spent fuel verification, detecting the presence/absence of Cs-137

Ref: "IAEA Safeguards Equipment"

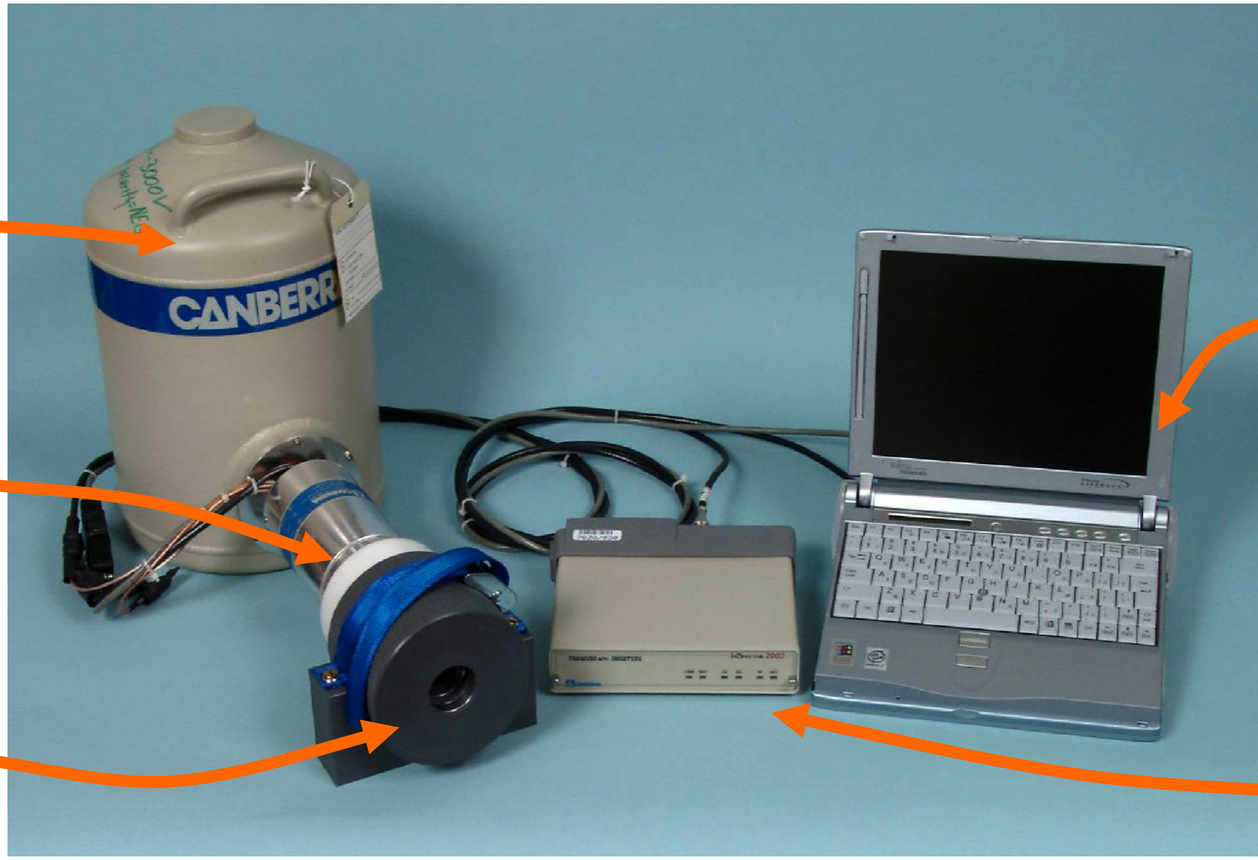
Spent Fuel Attribute Tester (SFAT)



A variant of the MMCA instrument for spent fuel verification detecting the presence/absence of Cs-137, with multiple tools for insertion into fuel assemblies

Ref: "IAEA Safeguards Equipment"

InSpector-2000 MCA



Multi-channel analyzer system with a high-purity Ge (HPGe) detector for isotopic analysis of uranium enrichment and plutonium isotopics

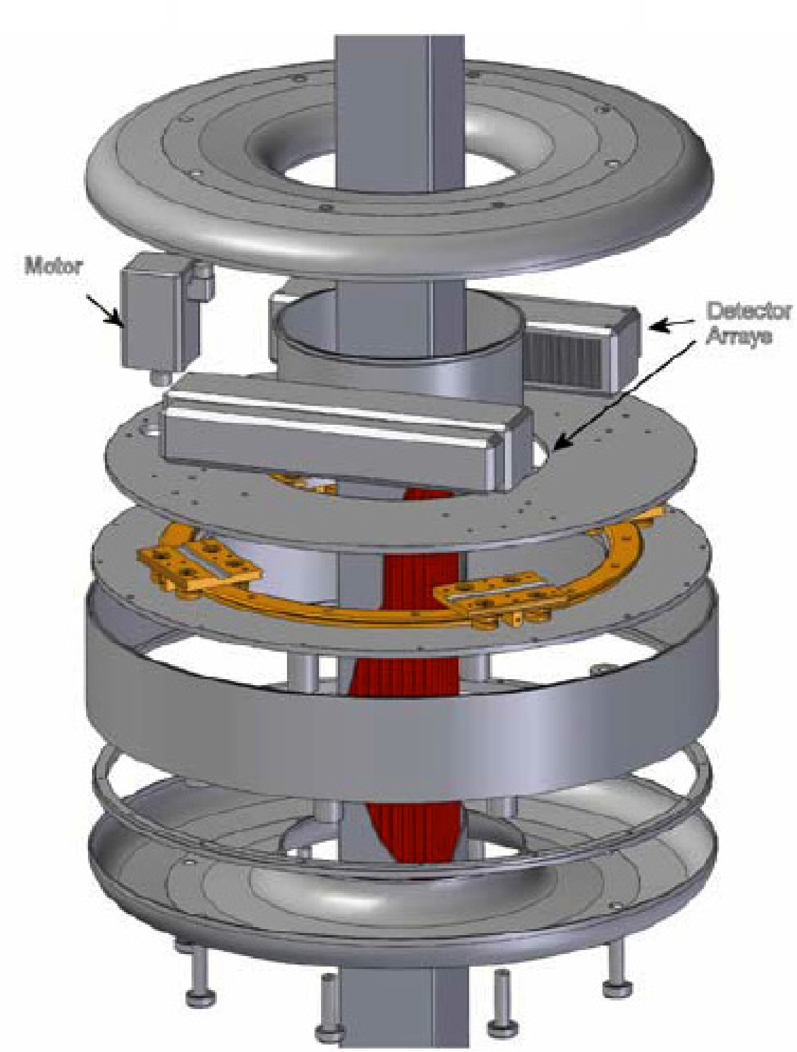
Ref: "IAEA Safeguards Equipment"

In-Situ Object Counting System (ISOCS)

Numerically calibrated off-the-shelf gamma-ray spectrometry system adopted by the IAEA in 2003 for LEU hold up and waste measurements

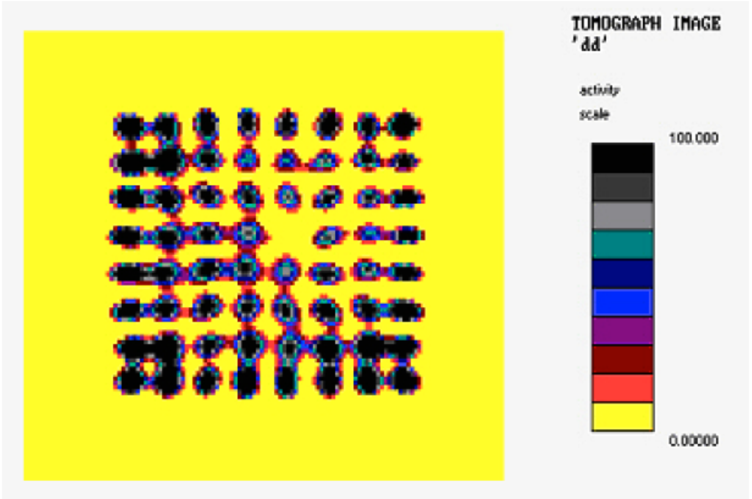
Ref: "IAEA Safeguards Equipment"

Passive Gamma Emission Tomography



Exploded view of tomographic imager developed in Finland for analyzing BWR or PWR fuel bundles and detecting missing fuel pins or fuel pin defects.

Simulations predict that the detection of a single inner missing pin of 17x17 type assembly is detected with high (> 96%) probability in optimal geometry and reasonably low noise conditions.

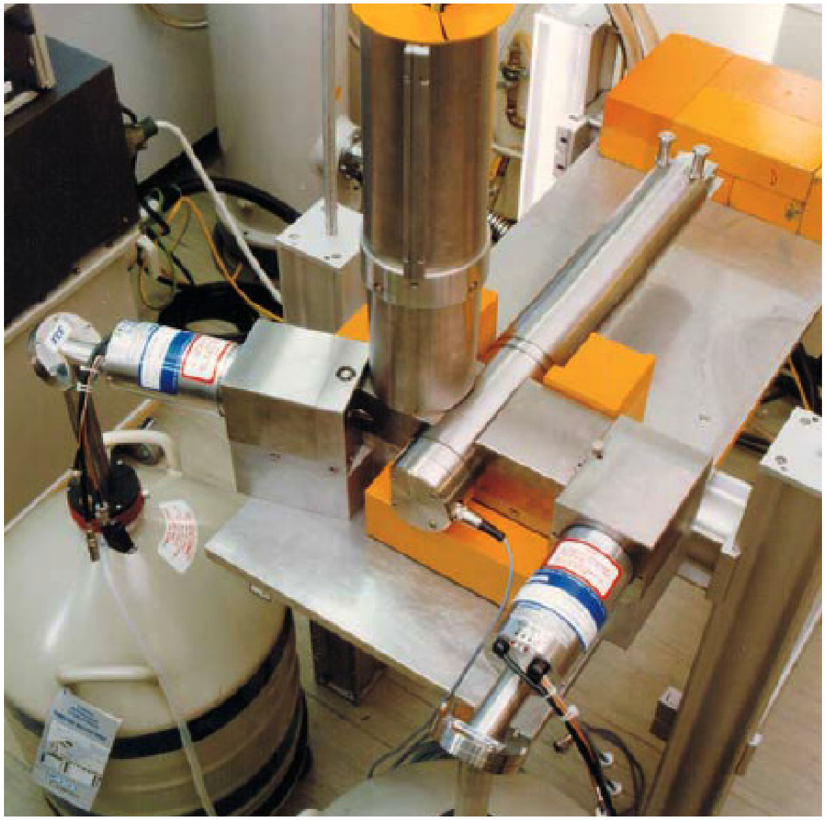


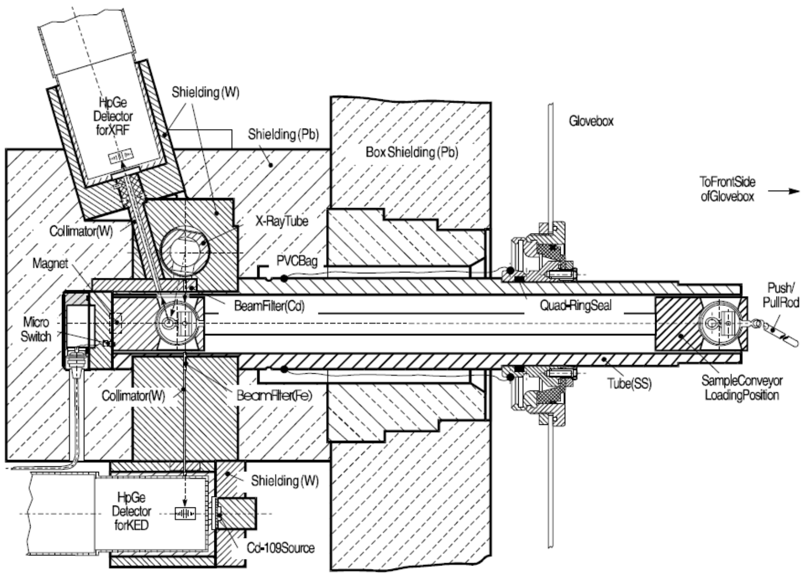
Simulations for an 8 x 8 BWR assembly with a missing pin.

Ref: "Addressing Verification Challenges"

Hybrid K-Edge/XRF Densitometry

- An instrument for assaying uranium and plutonium concentrations in liquid process streams
- X rays in in the 150-keV range, near the uranium K-edge absorption line, are transmitted through a pipe; a measurement of the attenuation of these x rays provides data on the uranium concentration (typical process contain ~50-250 g/L uranium)
- A separate detector is used to measure x-ray fluorescence from plutonium and uranium in the solution





Ref: "Photon Absorption/Excitation Techniques" & http://www.canberra.com/pdf/Products/Systems_pdf/hybridk.pdf

Calorimetry

A measurement of the thermal power of a sample, calorimetry can be used to quantify the mass of plutonium when additional details about the relative fraction of different plutonium isotopes is known.

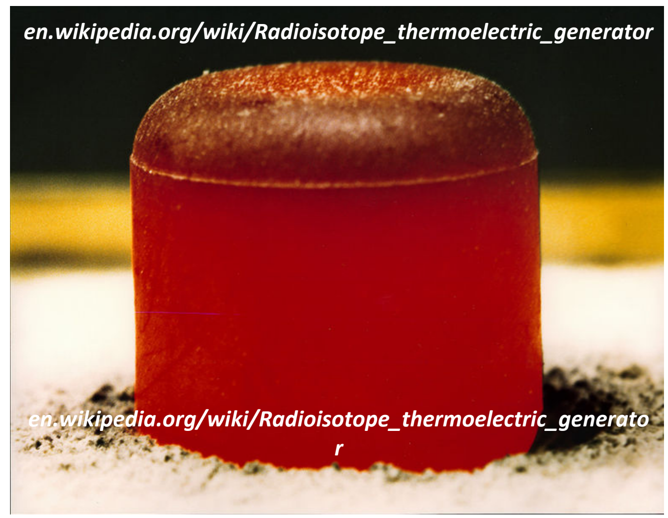
- Calorimetry assays are independent of sample geometry, nuclear material distribution in the sample, and matrix material composition
- Heat standards are directly traceable to National Standards and plutonium standards are not needed
- The assay is comparable to chemical assay in precision and accuracy if the isotopic composition is well known
- The assay is applicable to a wide range of material forms and plutonium can be measured in the presence of uranium.

Ref: "Non Destructive Assay" - esarda2.jrc.it/internal_activities/WC-MC/Web-Courses/07-NDA-Peerani.pdf

Specific Power of Key Isotopes

Isotope	Primary Decay Mode	Specific Power (mW/g)
^{238}Pu	α	567.57
^{239}Pu	α	1.9288
^{240}Pu	α	7.0824
^{241}Pu	β	3.412
^{242}Pu	α	0.1159
^{241}Am	α	114.2
^{3}H	β	324

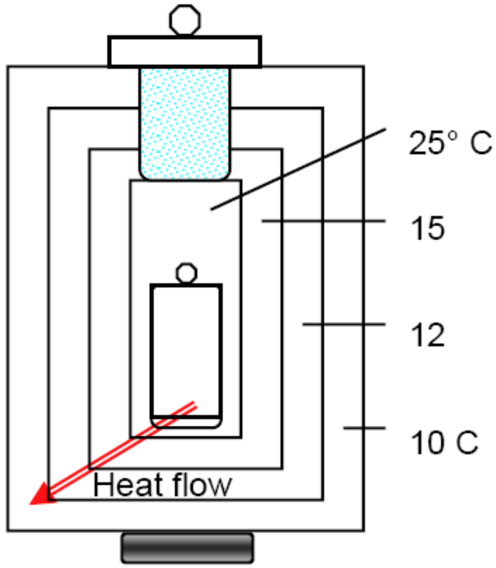
The very high specific power for ^{238}Pu explains the use of this isotope in radioisotope thermoelectric generators (RTGs), which are long-life power sources used in deep-space exploration vehicles



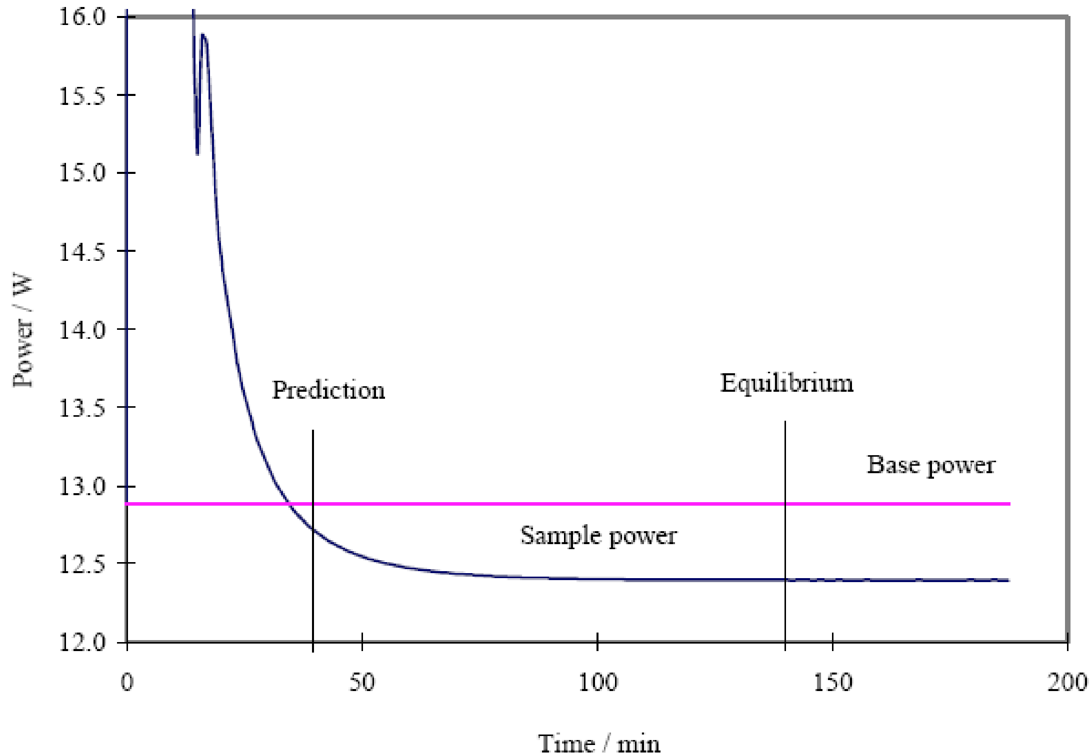
This is a photo of a ^{238}Pu fuel pellet of the type used in the NASA Cassini and Galileo probes; it produced 62 W of heat

Ref: "Non Destructive Assay," citing Hyde, E. K., "The Nuclear Properties of the Heavy Elements, III, Fission Phenomena," Dover Publications, New York, New York (1971), and Evans, R. D., "The Atomic Nucleus", McGraw-Hill Book Co., New York, New York (1955)

Calorimeter Equipment



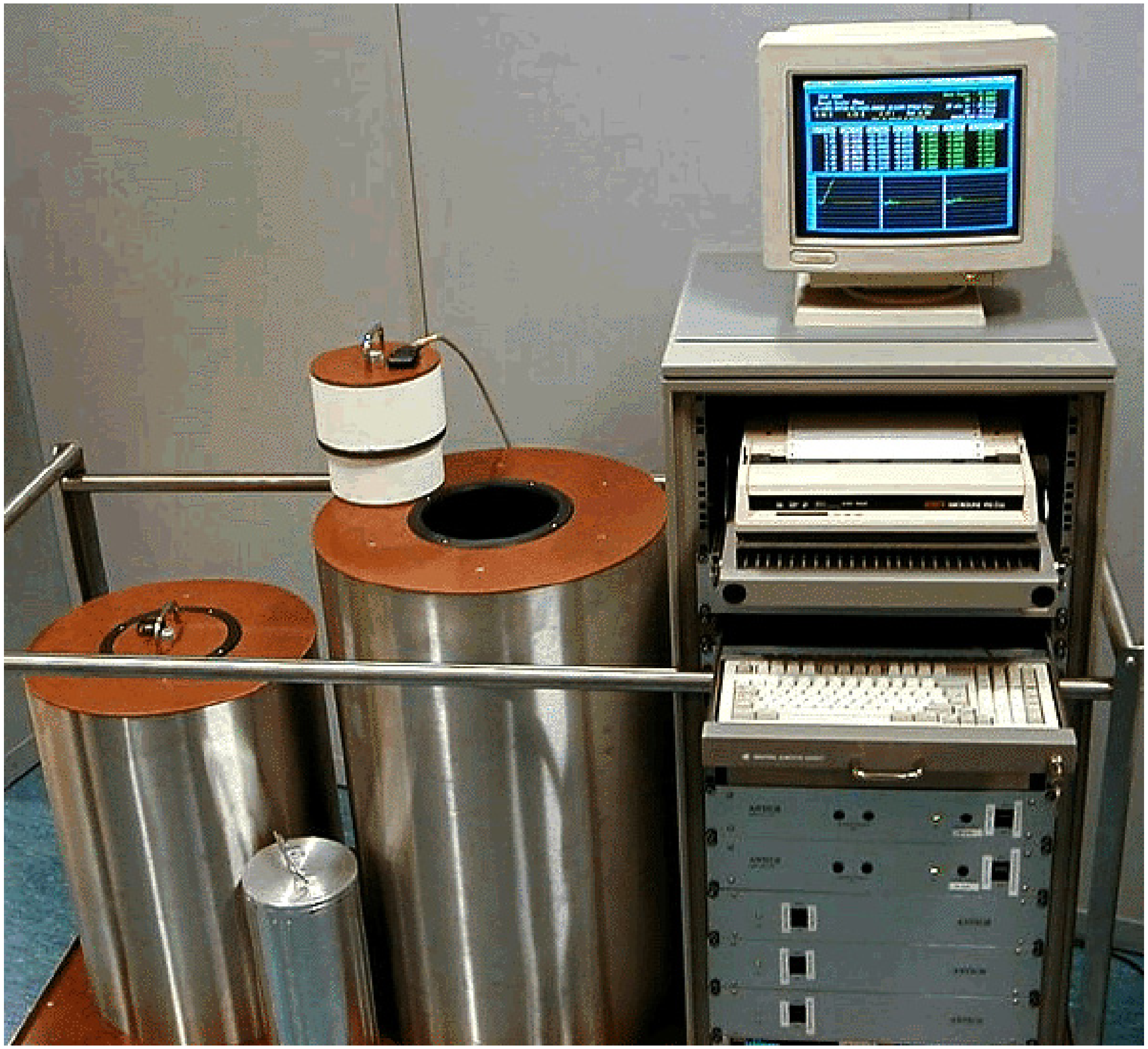
Schematic view of an isothermal calorimeter



First, the empty calorimeter is heated and the power required to maintain a particular equilibrium temperature level is determined (pink line). Then, a self-heating sample is placed inside the calorimeter and the new power level needed to maintain the same equilibrium temperature is determined (blue line).

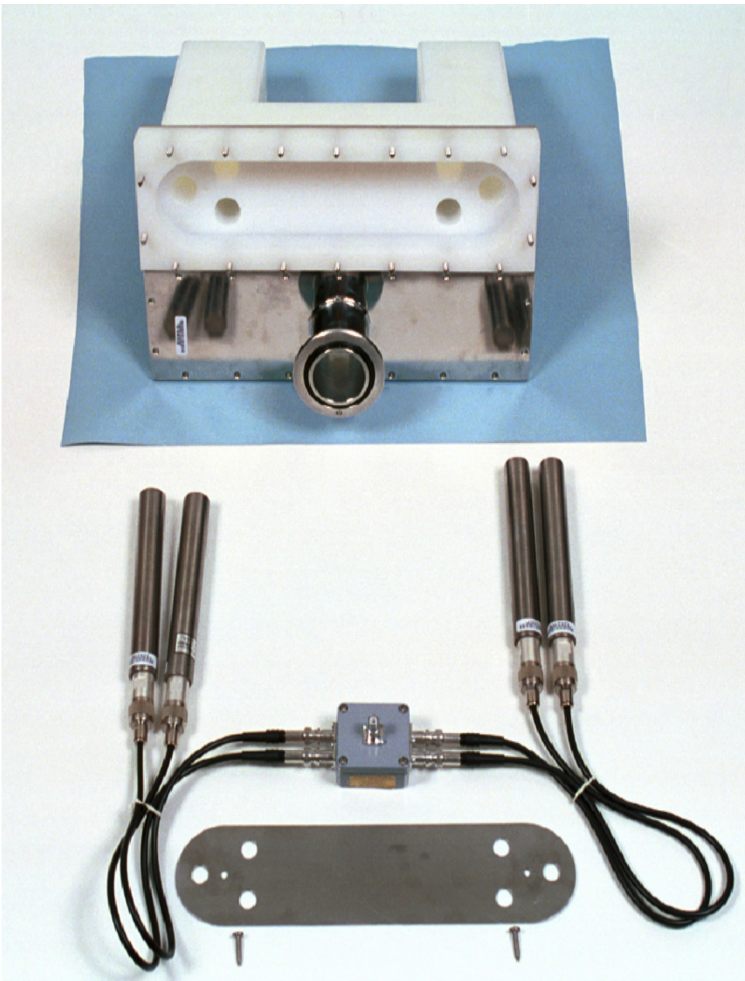
Ref: "Non Destructive Assay" - esarda2.jrc.it/internal_activities/WC-MC/Web-Courses/07-NDA-Peerani.pdf

Plutonium Air-Flow Calorimeter



Ref: "Non Destructive Assay" - esarda2.jrc.it/internal_activities/WC-MC/Web-Courses/07-NDA-Peerani.pdf

Fork Detector (FDET)



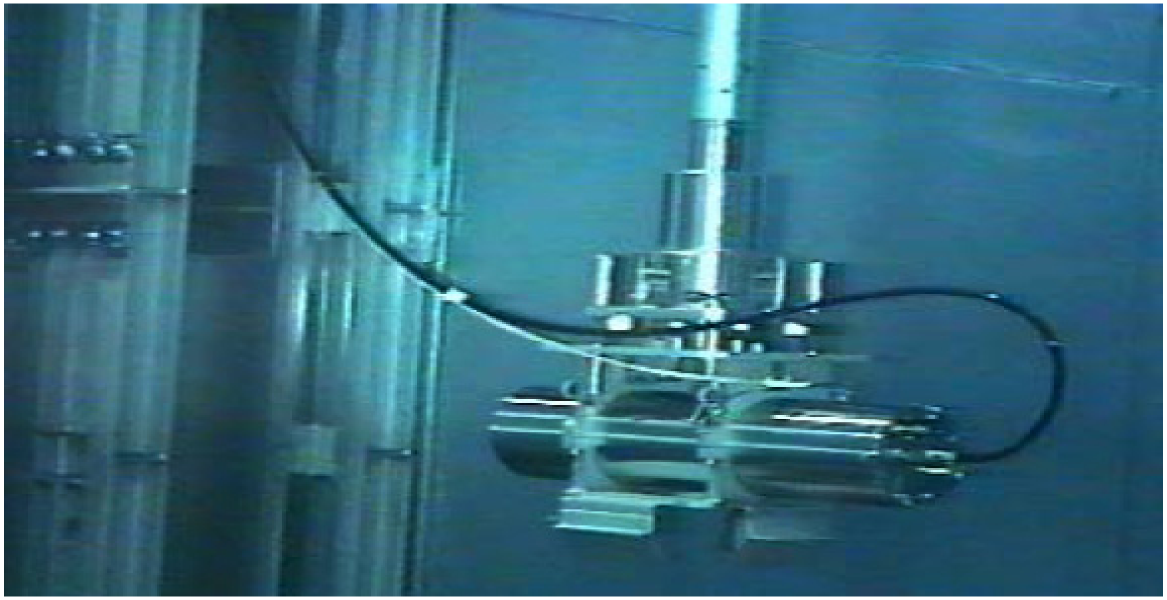
Neutron detectors are housed in a submersible "fork" assembly that is lowered into spent fuel storage pools. SF assemblies are raised and placed between the forks; analysis is performed to assay/verify spent fuel burn-up.

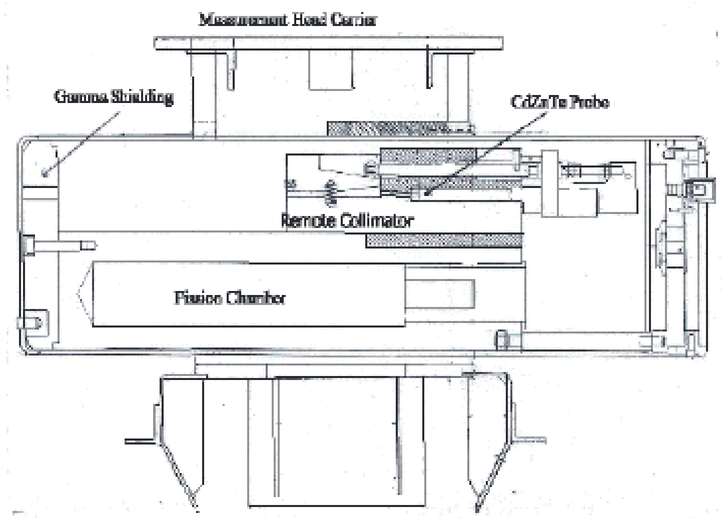
Ref: "IAEA Safeguards Equipment" & "Non Destructive Assay"

SMOPY Underwater Assay Tool

Room temperature gamma-ray spectrometry

- High efficiency
- Compact design, 160 x 600 mm
- Weight 50kg
- Fits fuel handling tool and storage racks
- Positioning accurate within 0.5 cm
- Safeguards MOX Python





Ref: "IAEA Safeguards Equipment"

Neutron Coincidence & Multiplicity

- Fission (spontaneous or induced) produces multiple neutrons per event – neutron multiplicity
- Performing time-correlated measurements of neutrons from a test object can be used to distinguish fission neutrons from other neutron sources, such as the (α,n) neutron signature present in oxide fuels
- If estimates of the plutonium isotopic distribution are available then accurate mass determinations may be made of the plutonium in a sample
- Larger masses of fissionable material are subject to multiplication, which can produce "long-duration" chains of fission neutrons following a first neutron from either spontaneous fission or cosmic-ray produced neutrons

High Efficiency Passive Counter (HEPC)

Large objects may be placed within the box. Embedded within the box's polyethylene walls are numerous neutron detectors. Overall, the box is a high-efficiency neutron detector. Passive neutron measurements are taken and analyzed to determine neutron multiplicity. Assay estimates may be made of the total plutonium content of the materials inside the box.

Ref: "Non Destructive Assay"

High Level Neutron Coincidence Counter (HLNC)

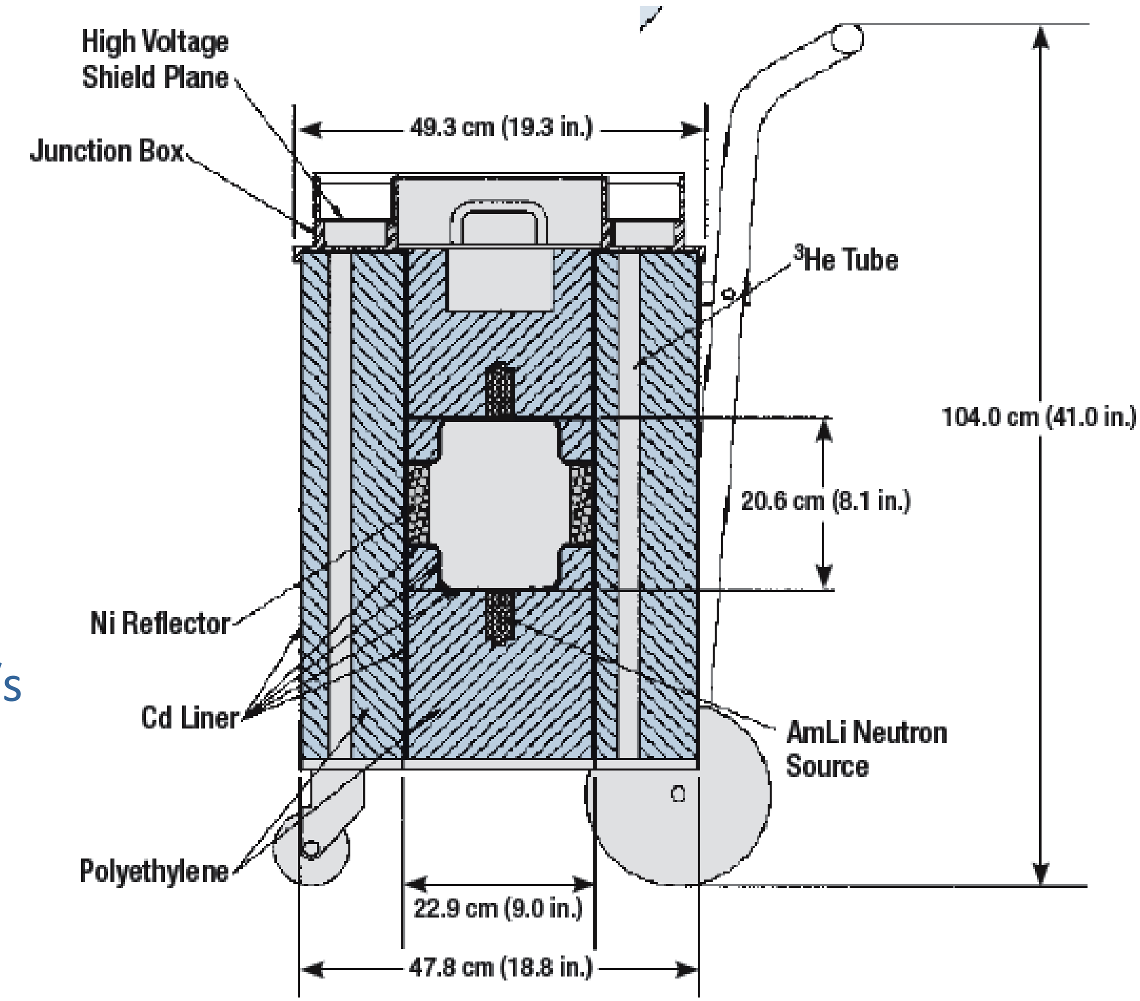
Neutron coincidence counter, with He-3 detectors and coincidence counter electronics for verification of Pu bearing materials

Ref: "IAEA Safeguards Equipment"

Active Well Coincidence Counter (AWCC)

AmLi neutron source: 5 x 10^4 n/s

Sensitivity limit: 1 g (Defined as net coincidence signal equal to three sigma of background for 1000 second count.)

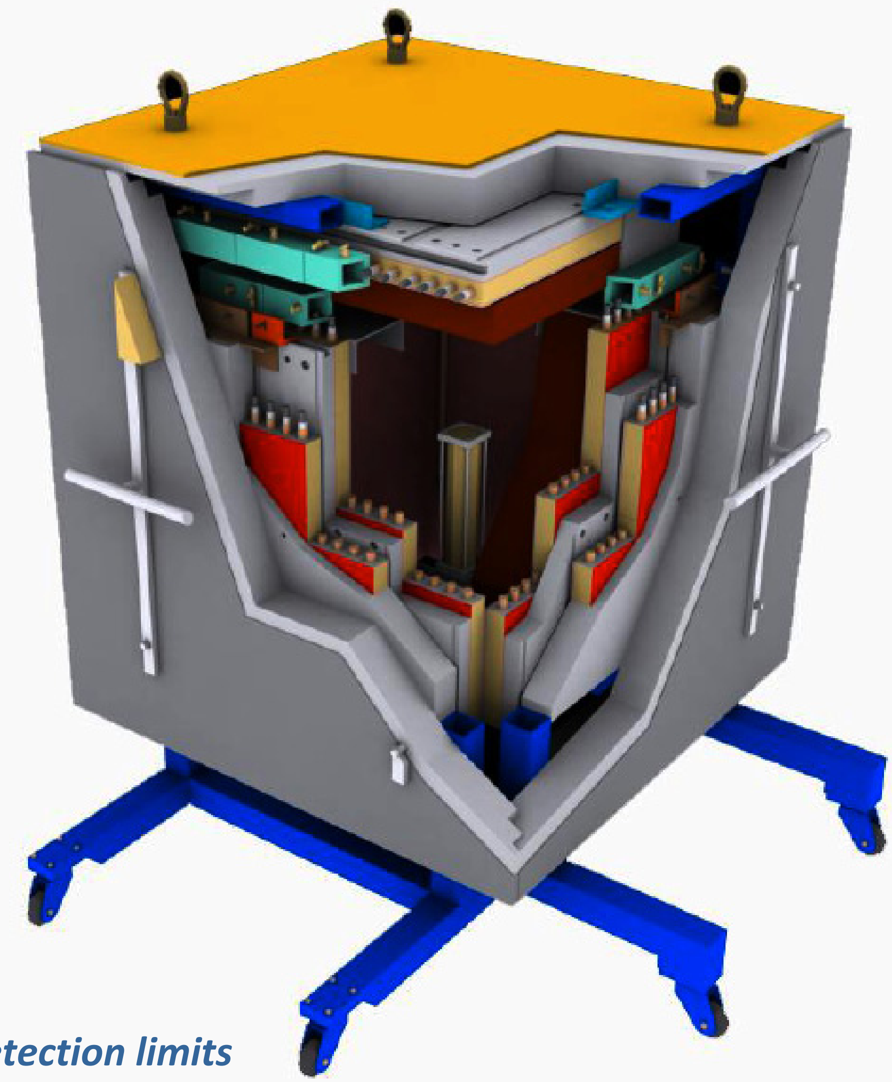


Ref: "www.canberra.com/products/715.asp"

Pulsed Neutron Interrogation Test Assembly (PUNITA

The mass of small amounts of fissile materials is determined by the active neutron correlation technique. The device incorporates a commercial pulsed neutron generator and a large graphite mantle surrounding the sample cavity.

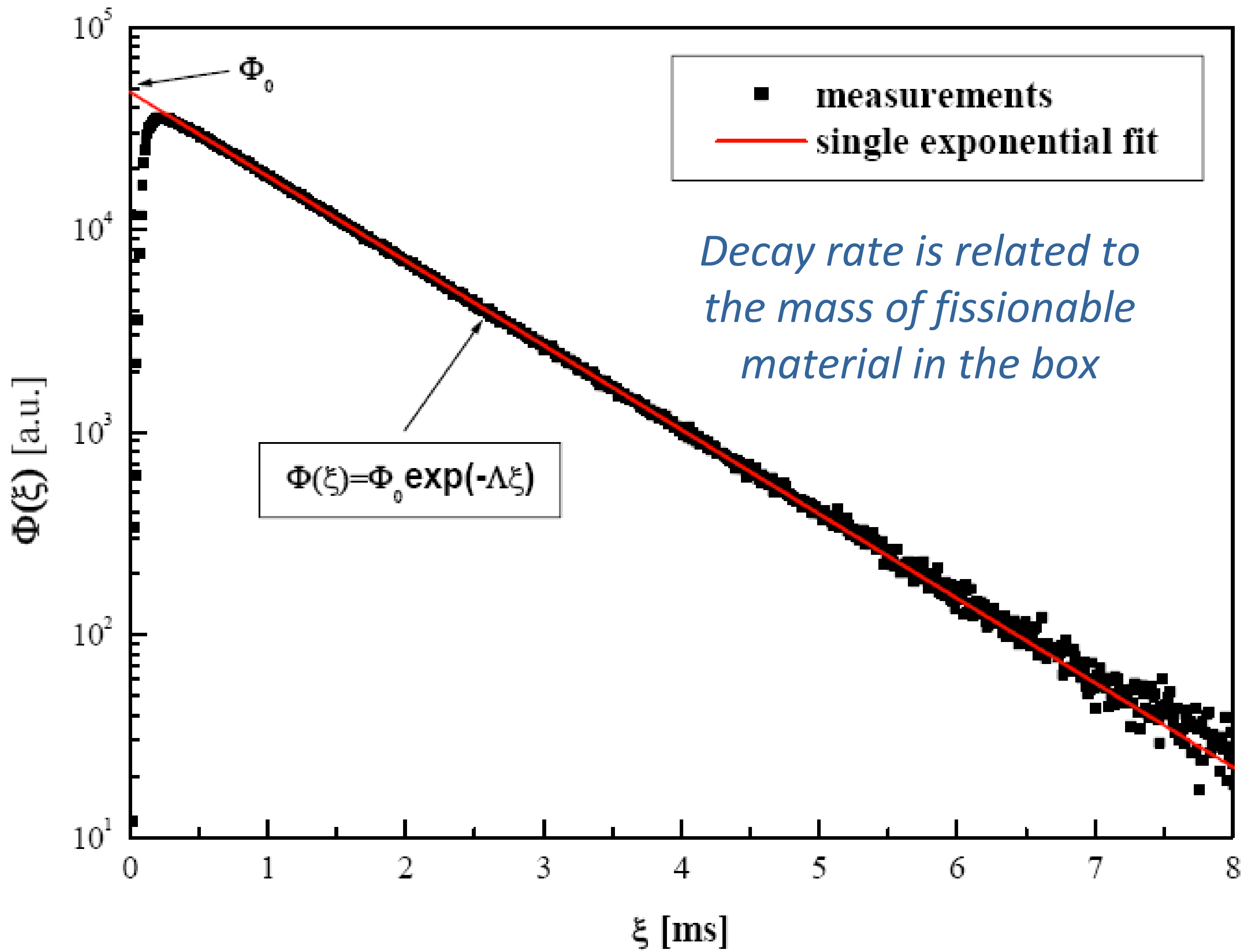
A high thermal neutron flux with a long lifetime is achieved inside the sample cavity; neutrons emitted from fission events in the sample are detected in a fashion similar to standard passive neutron correlation (multiplicity) counting.



~mg detection limits

Ref: "Addressing Verification Challenges"

PUNITA Data



Ref: "Addressing Verification Challenges"

Other Instruments for Safeguards

Beyond the examples shown in this presentation there are many other nondestructive analysis tools used in support of the safeguards mission.

Advances in nanotechnology, robotic systems, image analysis, remote sensing, sensor networks, human behavior studies, etc. may all be found useful towards improving the technological support to nonproliferation efforts in the future.

Ground Penetrating Radar for DIV

Ref: "Addressing Verification Challenges"

Final Remarks

"In regard to nuclear proliferation and arms control, the fundamental problem is clear: Either we begin finding creative, outside-the-box solutions or the international nuclear safeguards regime will become obsolete."

-M. ElBaradei, Washington Post, June 14, 2006, page A23.

References Used to Make this Presentation

- "Nuclear Safeguards, Security, and Nonproliferation," Doyle, J. E. (ed.), Butterworth-Heinemann, Burlington, Mass. (2008).
- "The Structure and Content of Agreements Between The Agency and States Required in Connection with the treaty on the Non-Proliferation of Nuclear Weapons," IAEA Document INFCIRC/153 (Corrected), International Atomic Energy Agency, Vienna, Austria (1972).
- Schanfein, M., "IAEA Safeguards Monitoring Systems & Science and Technology Challenges for International Safeguards," INL/EXT-09-16119 (2009).
- Miller, M., "Are IAEA Safeguards on Plutonium Bulk-Handling Facilities Effective?," http://www.nci.org/k-m/mmsgrds.htm
- "Research and Development Programme for Nuclear Verification 2008-2009," International Atomic Energy Agency, Vienna, Austria (2008).
- "International Nuclear Safeguards INMM Tutorial," Institute of Nuclear Materials Management, http://www.inmm.org/Technical_Divisions/2394.htm#ISD, (http://www.inmm.org/about/tech_div/IS Tutorial_1006CURRENT.ppt)
- Park, W.-S., "The Mission of the IAEA's Department of Safeguards," www.bnl.gov
- Zendel, M. "IAEA Safeguards Equipment," JAEA-IAEA Workshop on Advanced Safeguards Technology for the Nuclear, www-pub.iaea.org/MTCD/Meetings/PDFplus/2007/cn1073/Presentations/4A.4%20Pres_%20Zendel%20-%20IAEA%20Safeguards%20Equipment.pdf
- Pickett, C. A. and Bell, Z., "Modern Safeguards Systems," www.bnl.gov

References Used to Make this Presentation (Cont.)

- Pereira, C., et al., "Preliminary Results of the Lab-Scale Demonstration of the UREX+1a Process Using Spent Nuclear Fuel," www.aiche-ned.org/conferences/aiche2005annual/session_538/AICHE2005annual-538d-Pereira.pdf
- Poirier, S., "Laser Based Applications: Existing and Future Solutions," www-pub.iaea.org/MTCD/Meetings/PDFplus/2007/cn1073/Presentations/4B.4%20Pres_%20Poirier%20-%20Laser%20based%20applications%20Existing%20and%20Future%20Solutions.pdf
- Fuel Cycle Separations Group An Overview, http://radchem.nevada.edu/
- Reilly, D., et al., "Passive Nondestructive Assay of Nuclear Materials," Nuclear Regulatory Commission Report NUREG/CR-5550 (also LA-UR-90-732) (1991). *The PANDA book*
- Gozani, T., "Active Nondestructive Assay of Nuclear Materials," Nuclear Regulatory Commission Report NUREG/CR-0602 (also SAI-MLM-2585) (1981). *The ANDA book*
- Charlton, W. S., and Boyle, D. R., Lecture Notes From Course NUEN 689 "Nuclear Fuel Cycle and Safeguards," Texas A&M University, College Station, Tex.
- www.dilbert.com
- Swinhoe, M., et al., "A Survey on LWR Spent Fuel and Measurement Methods," Los Alamos National Laboratory Report LA-UR-02-7240 (2002).

References Used to Make this Presentation (Cont.)

- Symposium on International Safeguards: Addressing Verification Challenges, International Atomic Energy Agency, Vienna, Austria, 16-20 October 2006, "Addressing Verification Challenges," IAEA Proceedings Series (2007). www-pub.iaea.org/MTCD/publications/PDF/P1298/p1298_posters.pdf, www-pub.iaea.org/MTCD/publications/PDF/P1298/p1298_contributed_papers.pdf
- Dougan, A., "New and Novel Non-destructive Neutron and Gamma-Ray Technologies Applied to Safeguards," JAEA-IAEA Workshop on Advanced Safeguards Technology for the Future Nuclear Fuel Cycle, www-pub.iaea.org/MTCD/Meetings/1073_presentations.asp.
- Zendel, M., "IAEA Safeguards Equipment," JAEA-IAEA Workshop on Advanced Safeguards Technology for the Future Nuclear Fuel Cycle, www-pub.iaea.org/MTCD/Meetings/1073_presentations.asp.
- Kosierb, R., "Status on Two Novel IAEA Canadian Support Programme Technologies," JAEA-IAEA Workshop on Advanced Safeguards Technology for the Future Nuclear Fuel Cycle, www-pub.iaea.org/MTCD/Meetings/1073_presentations.asp.
- Peerani, P. "Non Destructive Assay," Nuclear Safeguards and Nonproliferation Course, ESARDA, Ispra, Italy (2009)
- "Photon Absorption/Excitation Techniques," esarda2.jrc.it/references/Technical_sheets/ts-photoabs-071116.pdf

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