RADIOACTIVITY AND NON PROLIFERATION

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Ecole Joliot-Curie 2017

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- …

OUTLINE

- Introduction about IAEA and Non Proliferation
- Nuclear Power Worldwide and Nuclear Fuel Cycle
- The Fission Process in a Nutshell
- Non Proliferation
- Safeguarding Techniques: NDA, C&S, Remote Monitoring, Environmental Sampling and Nuclear Forensics
- Safeguards Inspections
- New and Novel Technologies: antineutrino detection, reactor simulations and nuclear data

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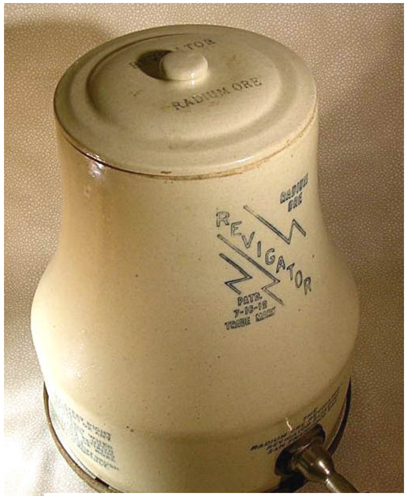
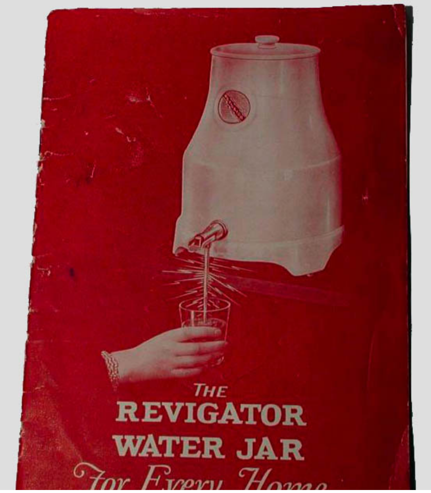
History And Generalities

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W. T. ELDRIDGE, Sugarland Industries, Sugarland, Texas.
JUDGE J. M. MATTHEWS, Harrisburg, Texas.
[illegible] Dallas, Texas.
JOHN M. MATHIS, SR., Attorney, 3509 Montrose Ave., Houston, Texas.
MRS. F. A. BUCKELEW, 5638 Willis Avenue, Dallas, Texas.
DR. H. W. STRAUSS, 1510 Main Street, Houston, Texas.
DR. GENEVIEVE LAUGHLIN, 2108 Live Oak Street, Dallas, Texas.
DR. J. F. KING, 1714 Hawthorn Street, Houston, Texas.
KENNETH W. MAYS, D. D. S., 3104 Main Street, Houston, Texas.
L. J. FLEMING, 318 Central Trust Building, San Antonio, Texas.
R. W. CROWDER, 2307 Ninth Street, Lubbock, Texas.
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Just fill the Revigator at night. The water remains in contact with the radium ore walls 12 hours. By morning the water has returned to that healthful state found only in genuinely fresh water right at the springs. It is flavorless and odorless and is neither a medicine nor a drug. Just that restored element of freshness generated by the tiny explosions that occur

1920-1930's: Radioactive waters, talc, whool for babies, creams, medicine, etc… containing Radium and Thorium !

=> Radioactivity was thought to be curative


EMBELLISSANTE PARCE QUE CURATIVE

3°

SAVON

THO-RADIA

A BASE DE THORIUM
ET DE BAUME DU PÉROU

Par sa pureté, sa douceur et ses vertus hygiéniques, il prémunit contre les altérations de l'épiderme et prépare la voie aux applications de la crème et de la poudre THO-RADIA. Recommandé pour la toilette des bébés.

FORMULE
du Dr Alfred CURIE

Le pain de 100 gr.
3 francs

CHEZ LES PHARMACIENS EXCLUSIVEMENT


4°

DENTIFRICE

THO-RADIA

A BASE DE SELS DE THORIUM

FORMULE
du Docteur Alfred CURIE

Le grand tube :
6 francs

Astringent et bactéricide, il stérilise la cavité buccale, évite et combat les gingivites, prévient la carie et les pyorrhées alvéolaires. Il assainit les dents, laisse dans la bouche une délicieuse impression de fraîcheur, conserve l'éclat, la blancheur et l'intégrité de la dentition.

Pas de joli sourire sans de jolies dents

CHEZ LES PHARMACIENS EXCLUSIVEMENT

…

History And Generalities

- 1942: first chain reaction under the Chicago stadium
- 1945 : Hiroshima and Nagasaki : The Manhattan project is managed by Robert Oppenheimer. Explored 2 possible ways: ^{235}U and ^{239}Pu (element number 94 discovered in 1940 by Glenn Seaborg).
- These 2 bombs weren’t the end of the race… in 1952 and 1953 US et USSR have developed the H-bomb.
- 1951 : 1st electricity production with a reactor in Chicago (EBR 1 from Pu fission, 100kW)
- 1953: Eisenhower’s address « Atoms for peace » in which he proposes the creation of an international body to both regulate and promote the peaceful use of atomic power (nuclear power) ;
- 1954-1956: Negociations btw US and USSR
- Statute of IAEA approved in 1956, came into force in 1957.

The IAEA

Created in 1957, The International Atomic Energy Agency (IAEA) is the UNO Agency in charge of scientific culture spreading in the field of nuclear science.

IAEA is organized in five departments:

- **Nuclear Science And Applications** : covers a broad range of socio-economic sectors, from health, food and agriculture to the environment, water resources and industry. Assists Member States meet their development needs through nuclear science, technology and innovation.
- **Nuclear Energy**: fosters sustainable nuclear energy development by supporting existing and new nuclear programmes around the world. Provides technical support on the nuclear fuel cycle and the life cycle of nuclear facilities, and builds indigenous capability in energy planning, analysis, and nuclear information and knowledge management.

The IAEA

- **Safety and Security**: aims at providing a strong, sustainable and visible global nuclear safety and security framework to protect people, society and the environment from the harmful effects of ionizing radiation.

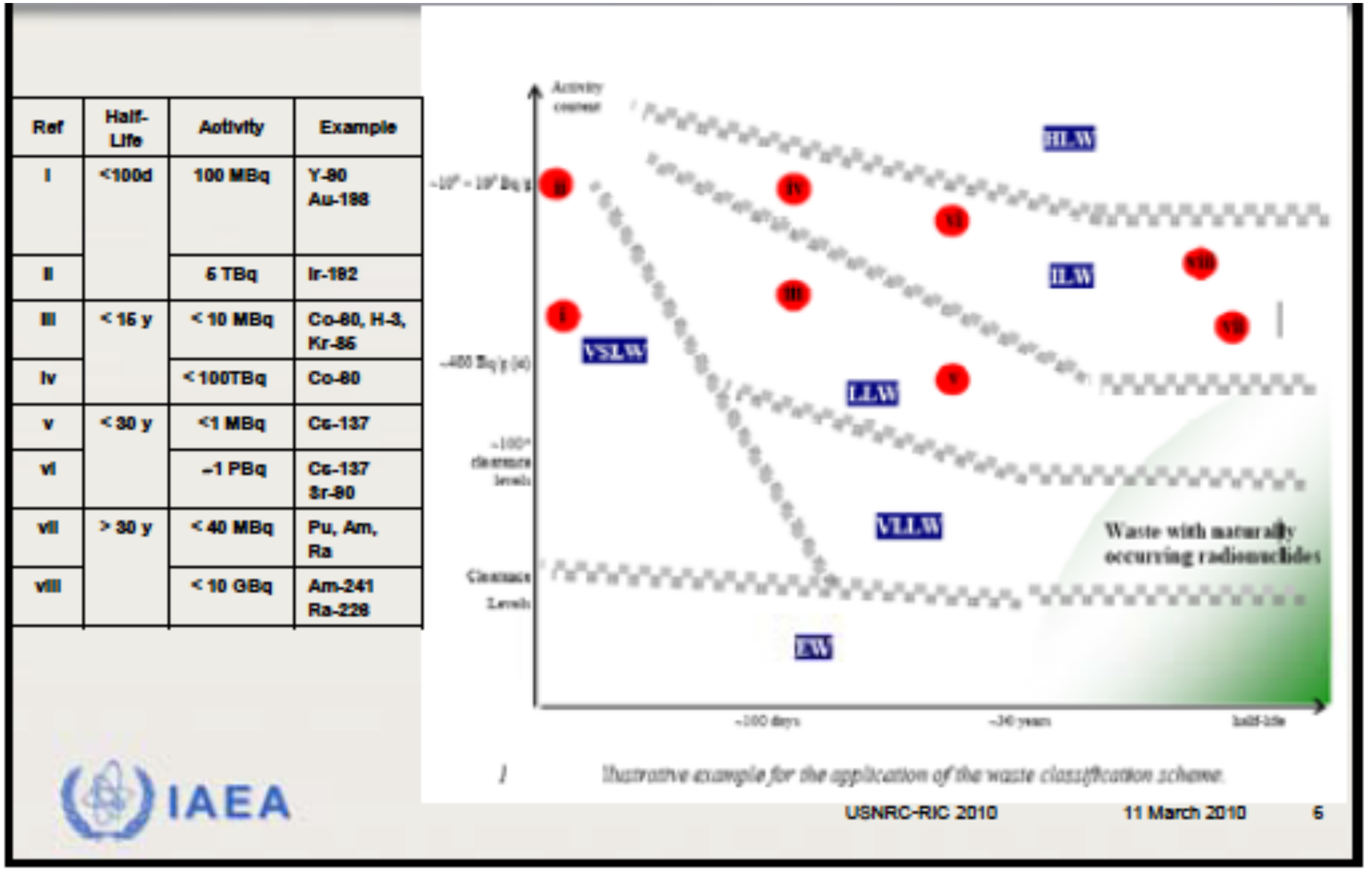
- **Safeguards**: carries out the IAEA's duties and responsibilities as the world's nuclear inspectorate, supporting global efforts to stop the spread of nuclear weapons.

- **Technical Cooperation:** aims to promote tangible socioeconomic impacts, supporting the use of nuclear science and technology to address major sustainable development priorities at the national, regional and interregional levels.

The IAEA

Definition, IAEA

Material in gaseous, liquid or solid form for which no further use is foreseen that contains or is contaminated with radionuclides at concentrations or activities greater than clearance levels as established by the regulatory body.

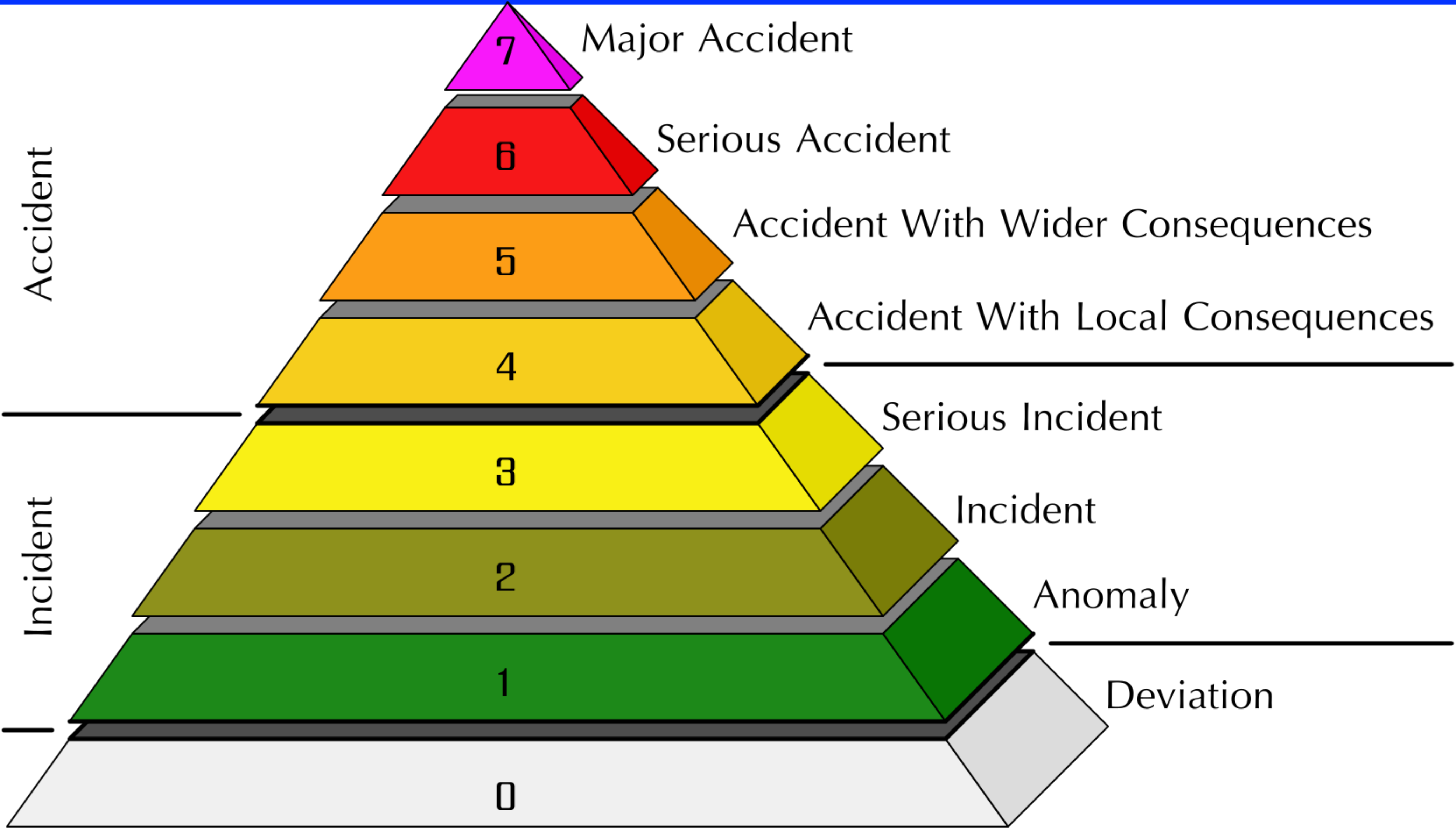


Ref	Half-Life	Activity	Example
I	<100d	100 MBq	Y-90 Au-198
II		5 TBq	Ir-192
III	< 15 y	< 10 MBq	Co-60, H-3, Kr-85
Iv		< 100TBq	Co-60
v	< 30 y	<1 MBq	Cs-137
vi		~1 PBq	Cs-137 Sr-90
vii	> 30 y	< 40 MBq	Pu, Am, Ra
viii		< 10 GBq	Am-241 Ra-226

Illustrative example for the application of the waste classification scheme.

USNRC-RIC 2010 11 March 2010 6

The IAEA



The role of IAEA in international nuclear safety has been reinforced in 1986 and 2011

In **Charge of verifying Member States declarations, which have signed the Non Proliferation Treaty (NPT).** A dedicated department: the **Safeguards Department**. In charge of providing continuing assurance to the international community that States that have entered into safeguards agreements with the IAEA are meeting their obligations.

The Department of Safeguards' three over-arching strategic objectives are to:

- **Deter the proliferation of nuclear weapons**, by detecting early the misuse of nuclear material or technology, and by providing credible assurances that States are honouring their safeguards obligations;
- **Contribute to nuclear arms control and disarmament**, by responding to requests for verification and other technical assistance associated with related agreements and arrangements;
- **Continually improve and optimize departmental operations and capabilities** to effectively carry out the IAEA's verification mission.

The Non Proliferation Treaty (NPT)

- **Opened for signature in 1968**, entered into force in **1970**, and on May 11, 1995 the NPT was extended indefinitely. A total of **191 States** have joined the Treaty, including the five nuclear-weapon States.
- **Bi-lateral agreements** between individual member states and the IAEA.

⇒ **comprehensive safeguards agreements**: regular safeguards scheme, which relies on a state's declaration of nuclear facilities and materials

⇒ put into force by all but 12 of the non-nuclear-weapons states.

⇒ **Additional Protocol** introduced in response to **the failure of the regular safeguards scheme** to provide timely indication of Saddam Hussein's nuclear weapons program before the first Gulf War in 1990.

- The **Additional Protocol** provides IAEA inspectors with **the right to collect environmental samples at locations outside of declared facilities and to obtain access to sites which have not been declared as nuclear facilities but are suspected to be.** 139 states have signed the Additional Protocol, and 117 states have put it into force.

Iran signing the additional protocole in 2003

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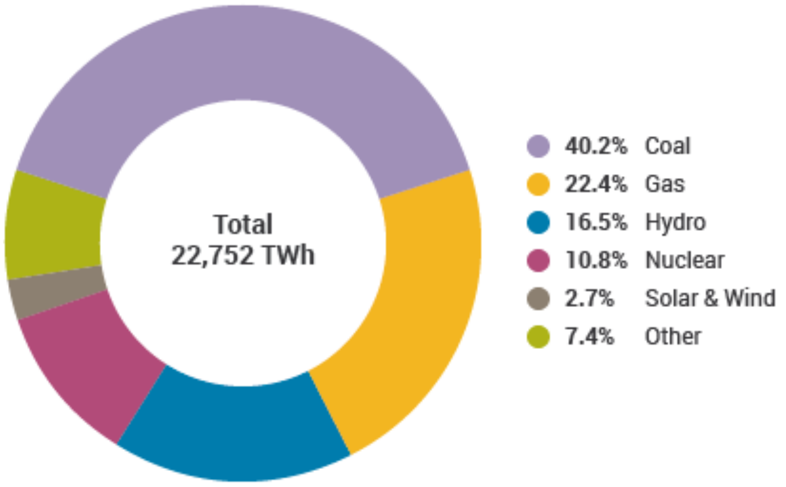
Nuclear Power in the World

The first **commercial nuclear power stations** started operation in the 1950s.

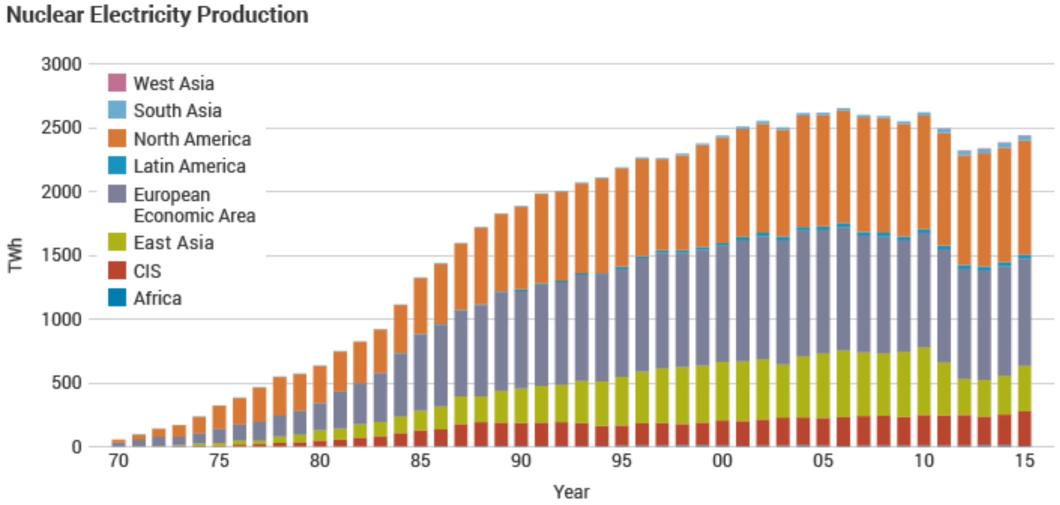
There are **over 440** commercial nuclear power reactors operable in **31 countries**, with over 390,000 MWe of total capacity. About **60 more** reactors are **under construction**.

They provide **about 11%** of the **world's electricity**

55 countries operate a total of about **250 research reactors**, and a further **180 nuclear reactors power some 140 ships and submarines.**

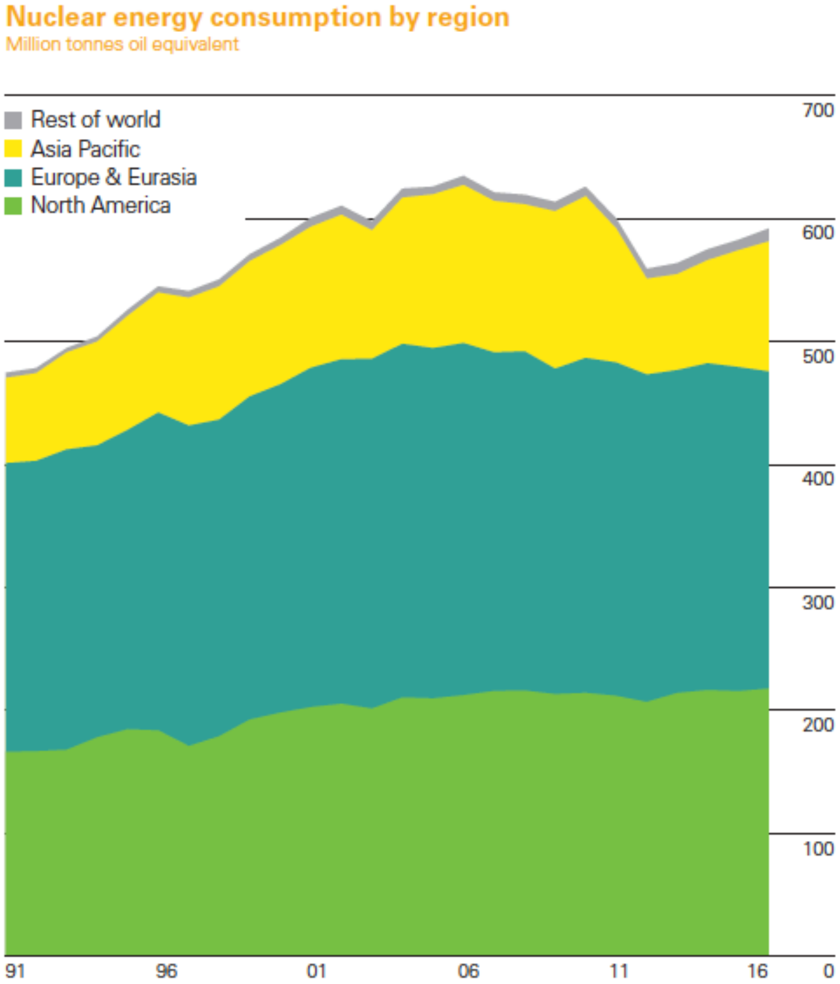


Source: IEA Electricity Information 2014


Nuclear Electricity Production

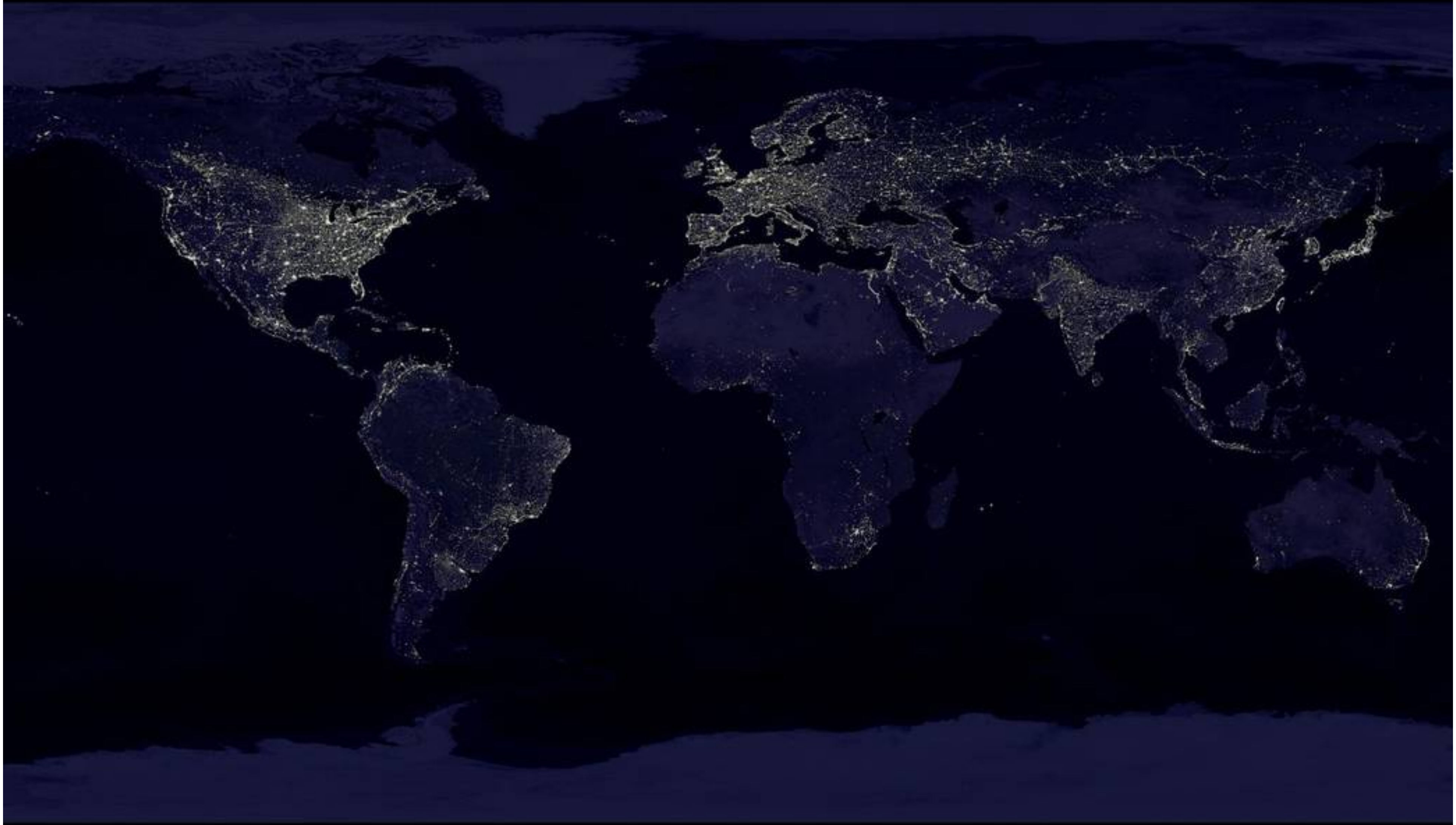
Source: IAEA PRIS

Nuclear Power in the World



Despite the accident of Fukushima, **the safeguards department forecasts a growth of the world nuclear park to monitor ranging from 90 to 350 new plants**.

The World by night…



Nuclear Power in the World

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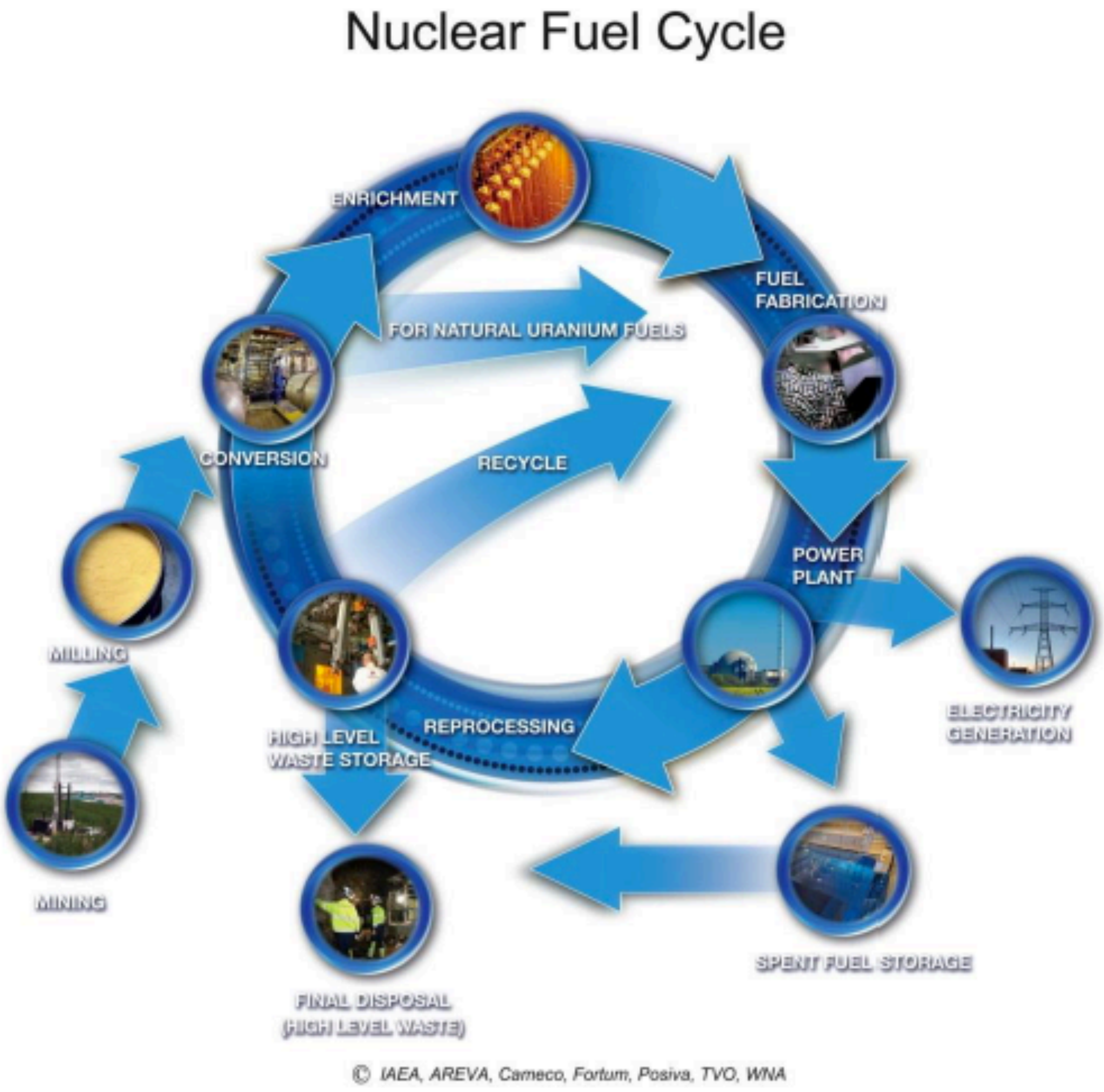
The Nuclear Fuel Cycle



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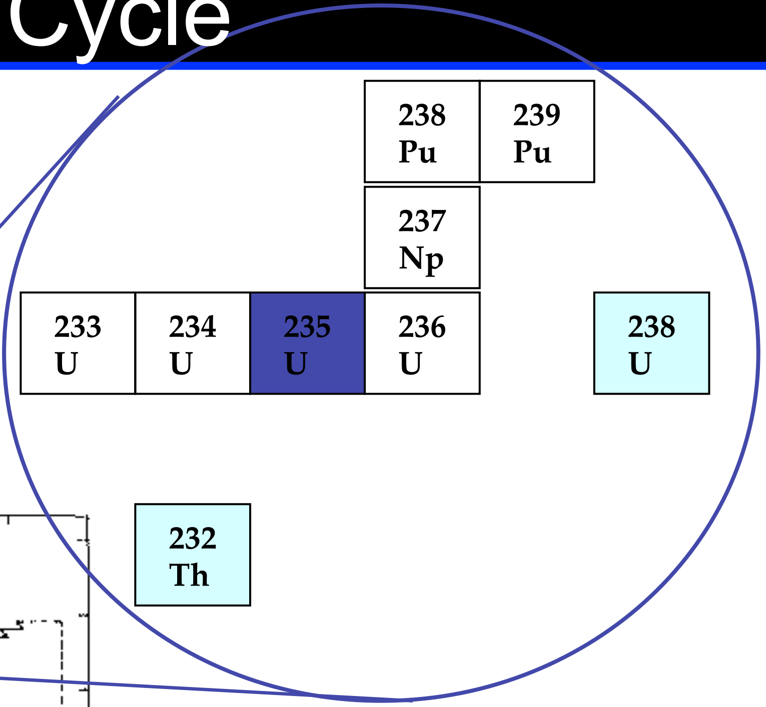
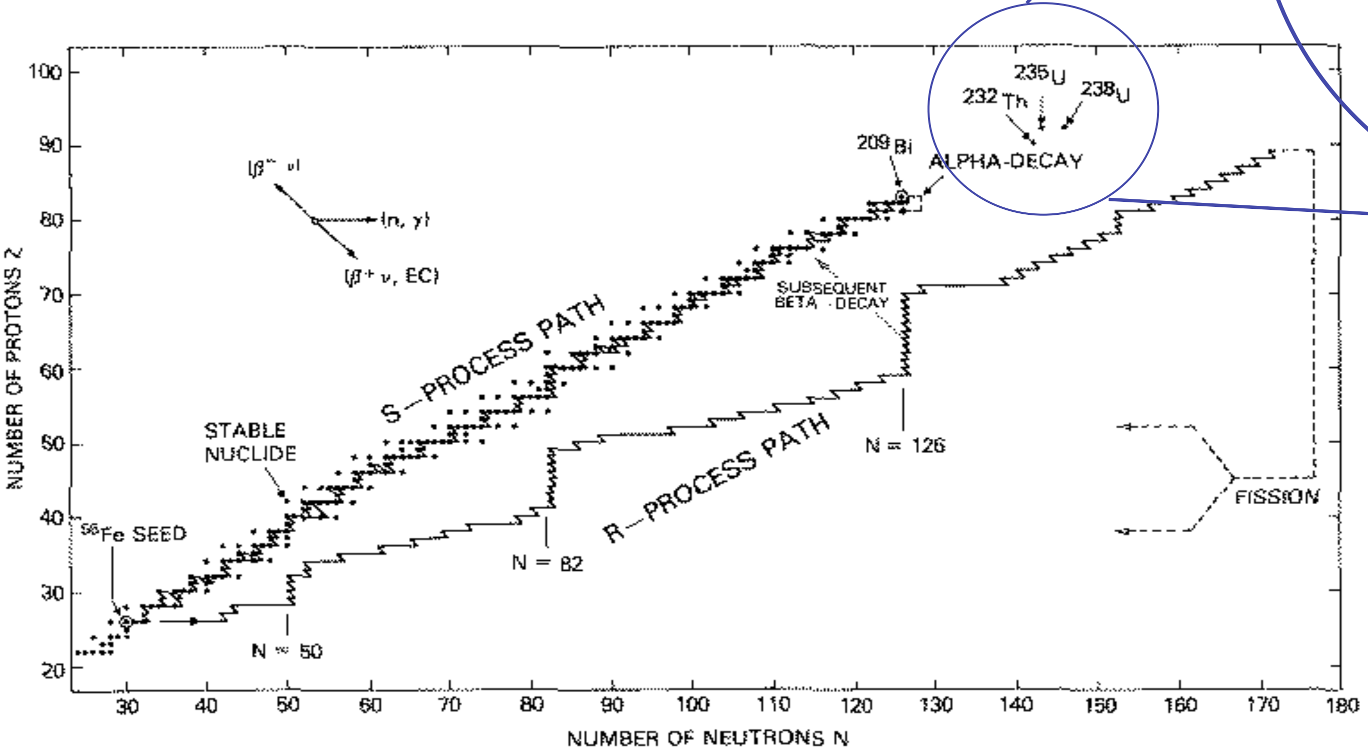
The Nuclear Fuel Cycle

235 U	Fissile
232 Th	Fertile
234 U	Semi-stable ($T_{1/2}$ > 50y)

^{235}U	0.72%	$T_{1/2}$ = 7.0 E+08
^{238}U	99.27%	$T_{1/2}$ = 4.5 E+09



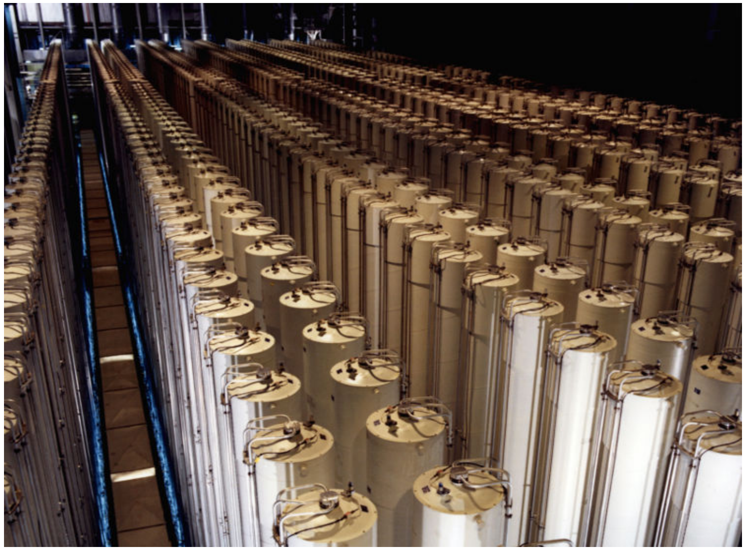


The Nuclear Fuel Cycle

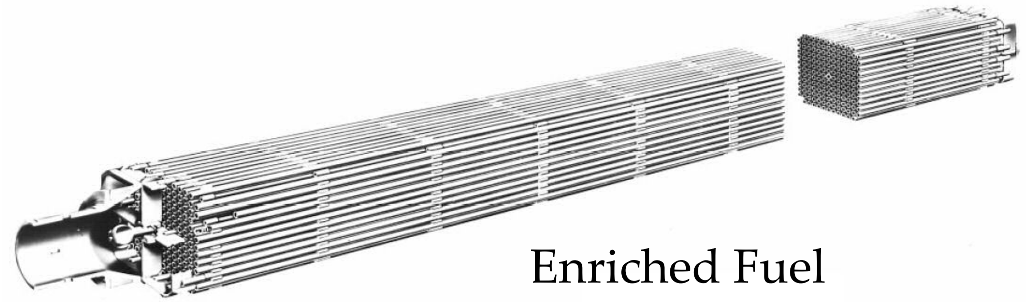
Ore

U_3O_8

Fuel U_{nat}



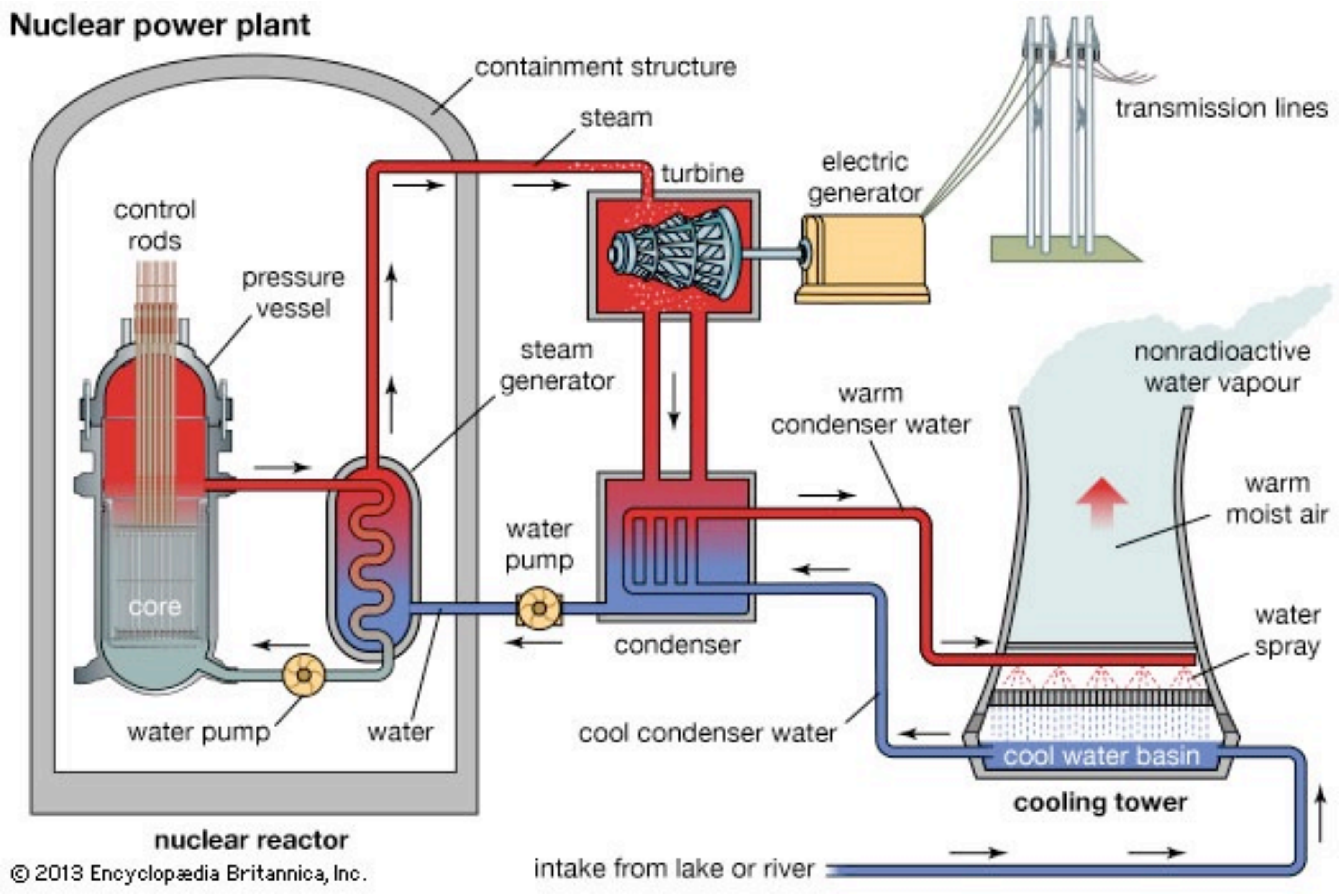
Enrichment: centrifugations



Enriched Fuel
(~3.5 % ^{235}U)

The Nuclear Fuel Cycle

- Fuel
- Moderator
- Coolant
- Control Rods



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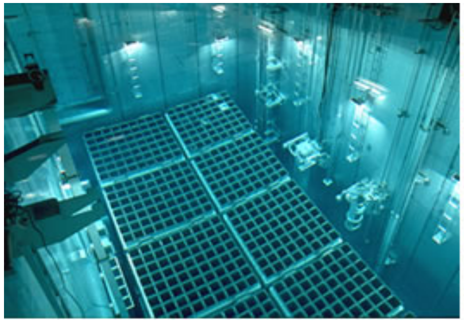
WHAT HAPPENS NEXT ?

Storage of spent fuel elements:

Is necessary because of decay heat

Under 5 m of water with a direct view…



- In pools on site:

Storage of limited duration
Stored in racks

Piscine E, entreposage des combustibles usés.
Usine de traitement des combustibles usés COGEMA
La Hague

- Storage in reprocessing plants:

A few hundreds of assemblies
Long duration storage (10y or more)
About 30 000 assemblies at La Hague, France

- Depending on the country policy:

Separation of U, Pu from Fission Products and MA
Manufacturing of Mixed U Pu Oxides (MOX) fuels
Storage sites

Usine MELOX, Marcoule

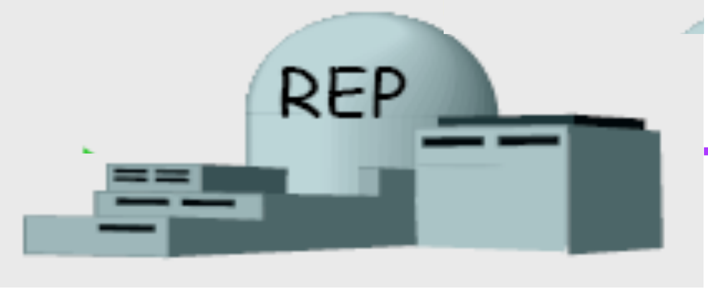
The Nuclear Fuel Cycle And Wastes

Open Cycle **Sweden, USA….**

Uranium Ore

↓

Enriched Uranium



Wastes:

- **Fission Products**
- **100% U and Pu**
- **100% Np, Am, Cu**

Closed Cycle **France, Japan….**

Uranium Ore

↓

Enriched Uranium

Wastes:

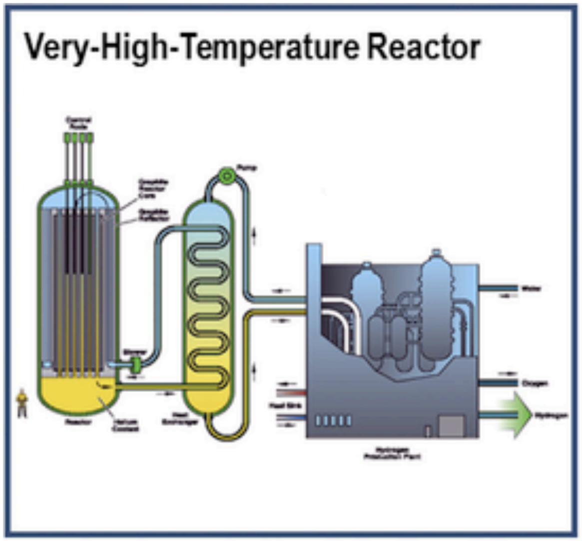
- **Fission Products**
- **0.1% U and Pu**
- **Np, Am, Cu**

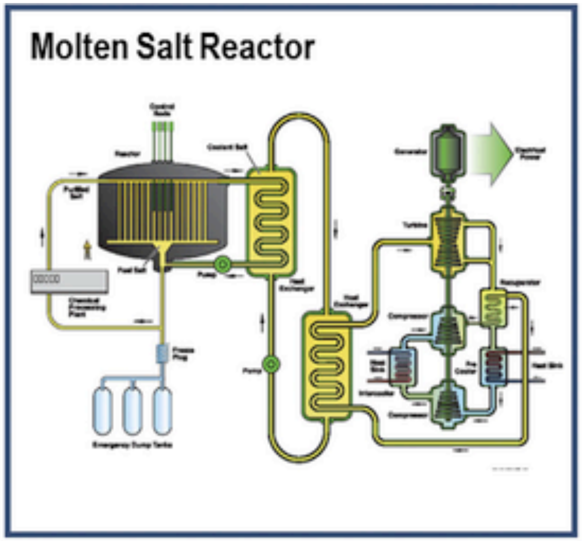
U, Pu (Mox)

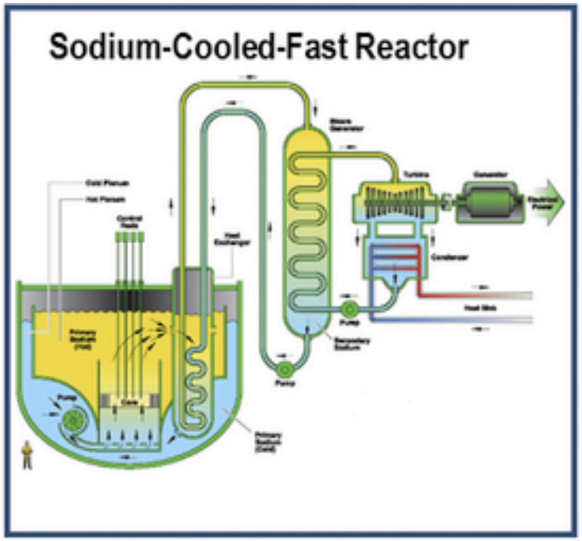
Storage U, Pu

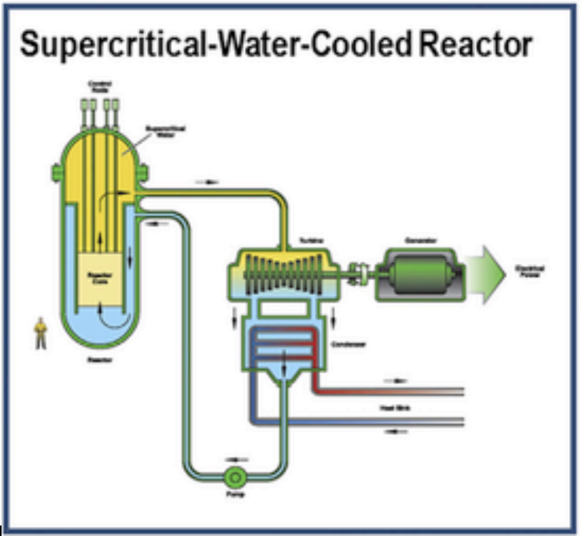
Generation IV Reactor Designs

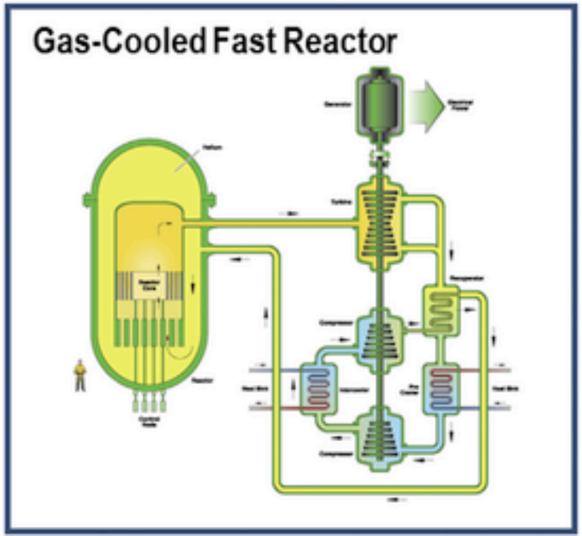
Future reactor criteria: safety, optimized waste management, sustainability, economy, non proliferation

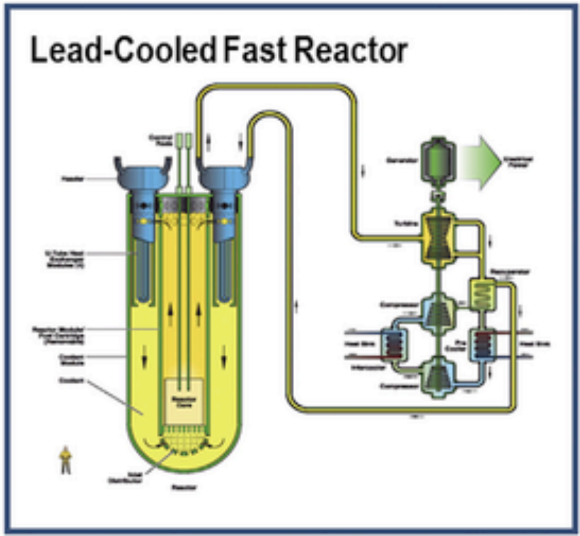

Very-High-Temperature Reactor


Molten Salt Reactor


Sodium-Cooled-Fast Reactor

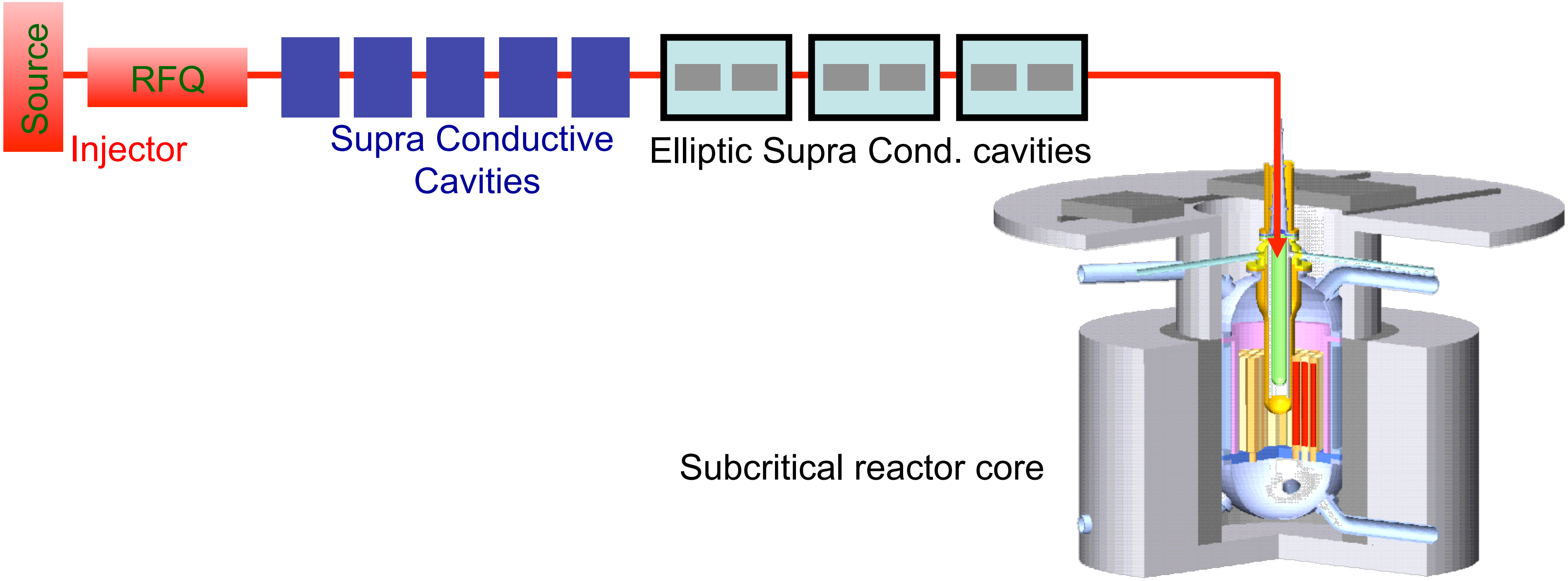

Supercritical-Water-Cooled Reactor

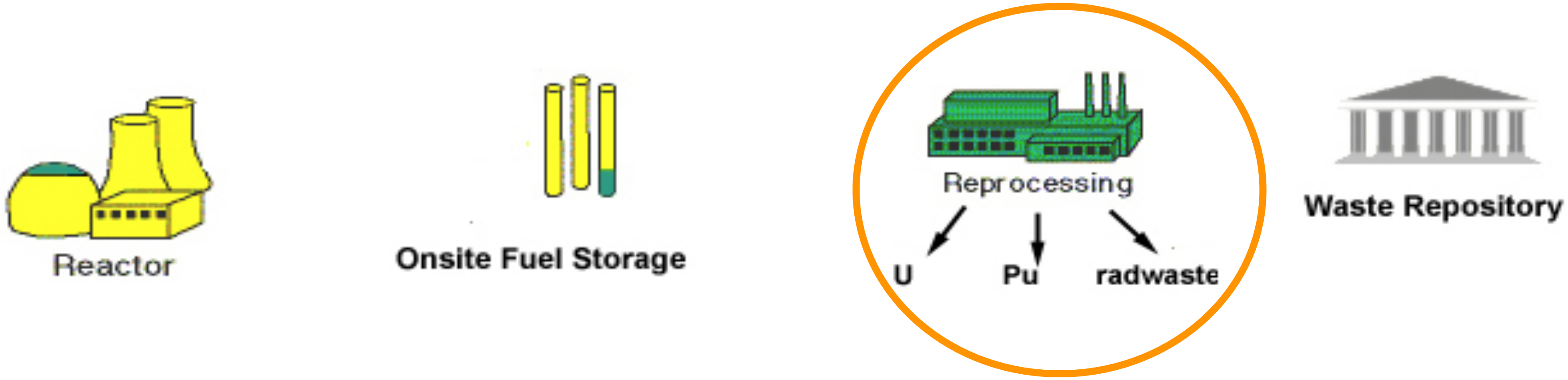

Gas-Cooled Fast Reactor


Lead-Cooled Fast Reactor

Accelerator Driven Systems

Nuclear Waste Transmutation in dedicated subcritical reactors
- fast neutrons
- Am, Cm are « bad » fuels (for safety considerations)
- critical reactors hard to operate (Temp. Effect, delayed neutrons…)





Fourth Generation Reactors will require **new surveillance methods**, especially for fast reactors (fast breeders) which would **close the fuel cycle**. Indeed the **number of reprocessing plants would increase significantly**, propice to nuclear material diversion.

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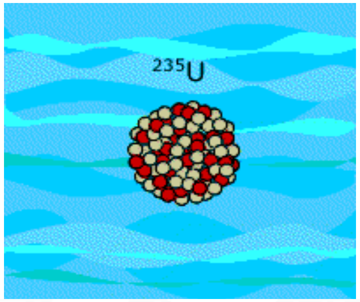
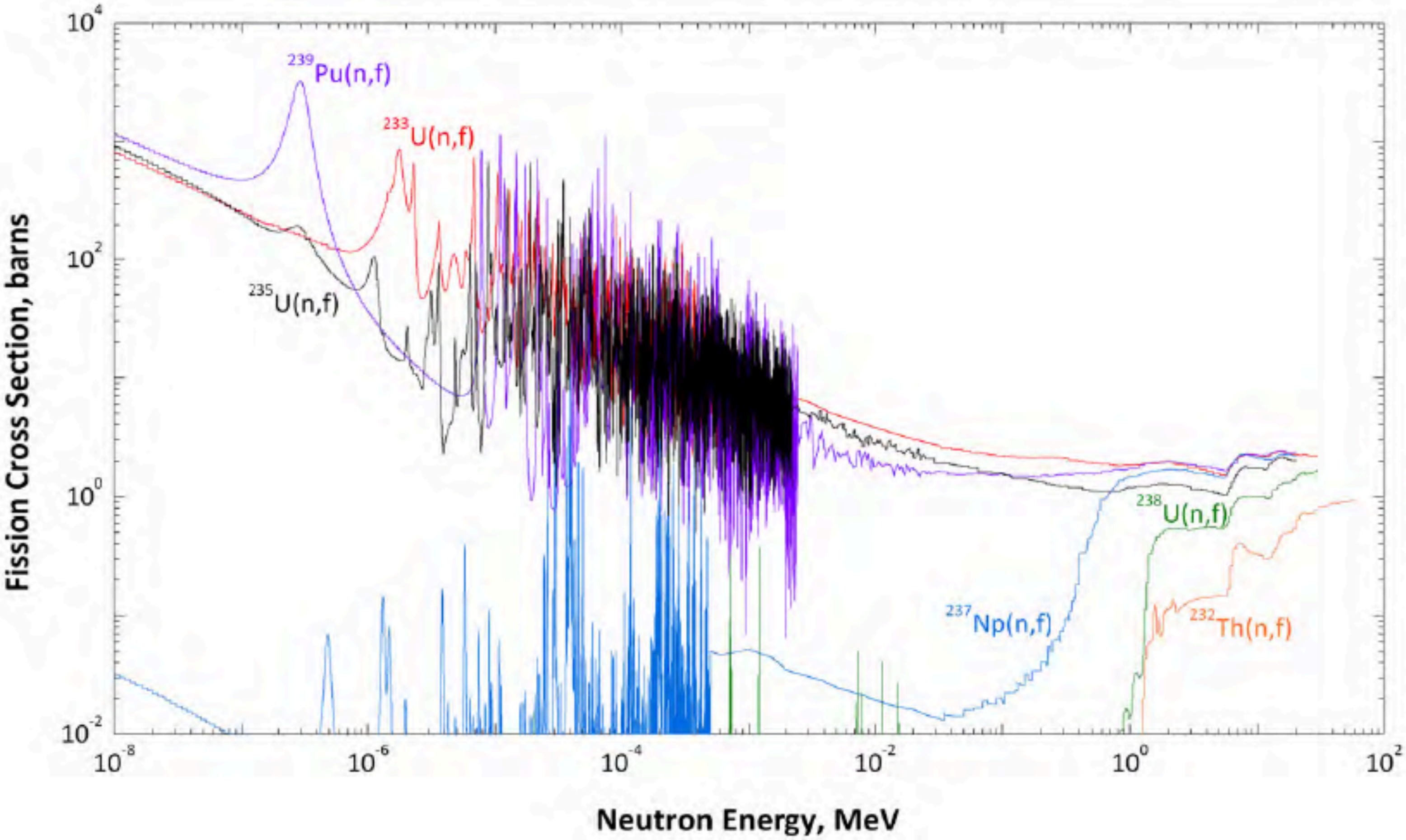
The Fission Process



The fission process provides thermal energy:

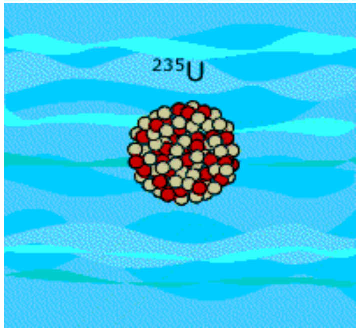
$n + {}^{235}U \rightarrow {}^{236}U^* \rightarrow PF_1 + PF_2$ + 2-3 neutrons (200 MeV)

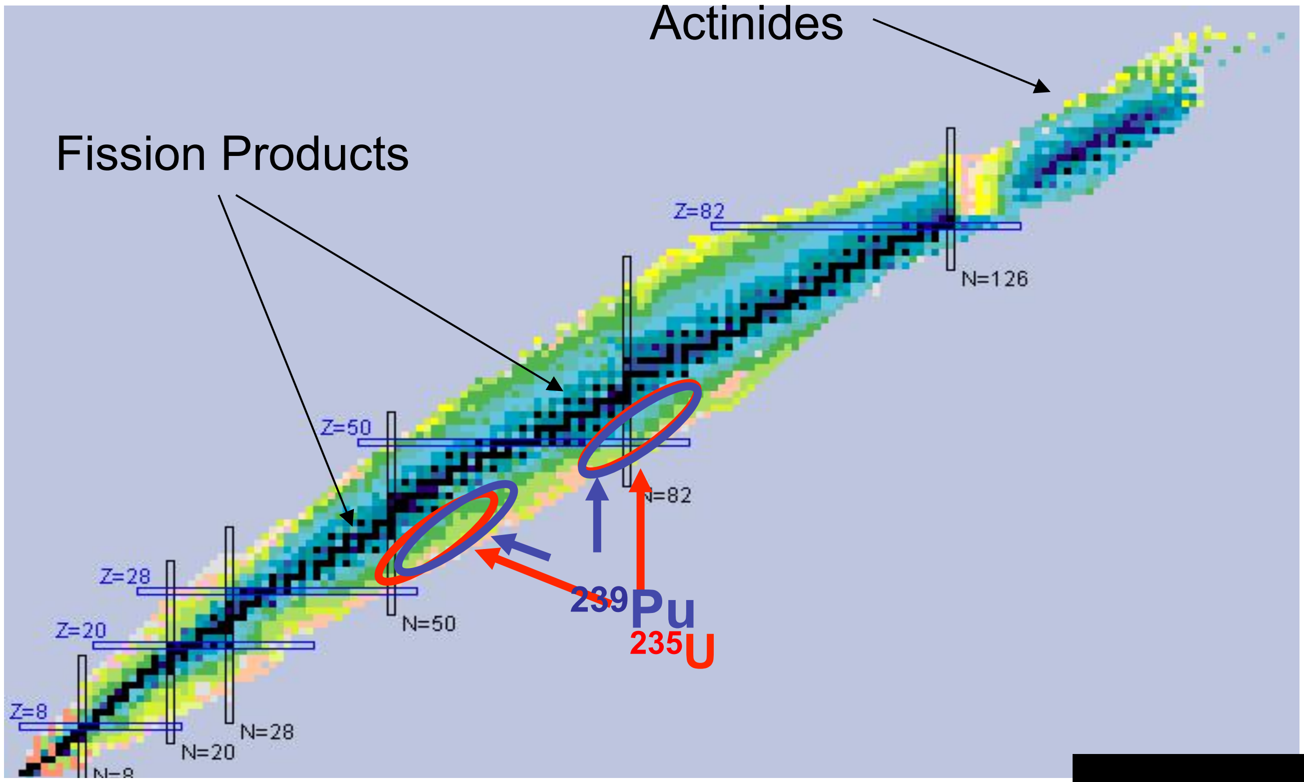


Fuel Content

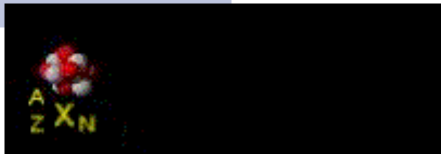
The fission process provides thermal energy:

$n + {}^{235}U \rightarrow {}^{236}U^* \rightarrow PF_1 + PF_2 + \text{2-3 neutrons (200 MeV)}$





Fission Products are mostly neutron-rich nuclei which can undergo β^- decay: $${}^{A}_{Z}X \longrightarrow {}^{A}_{Z+1}Y + e^- + \boxed{\bar{\nu}_e}$$



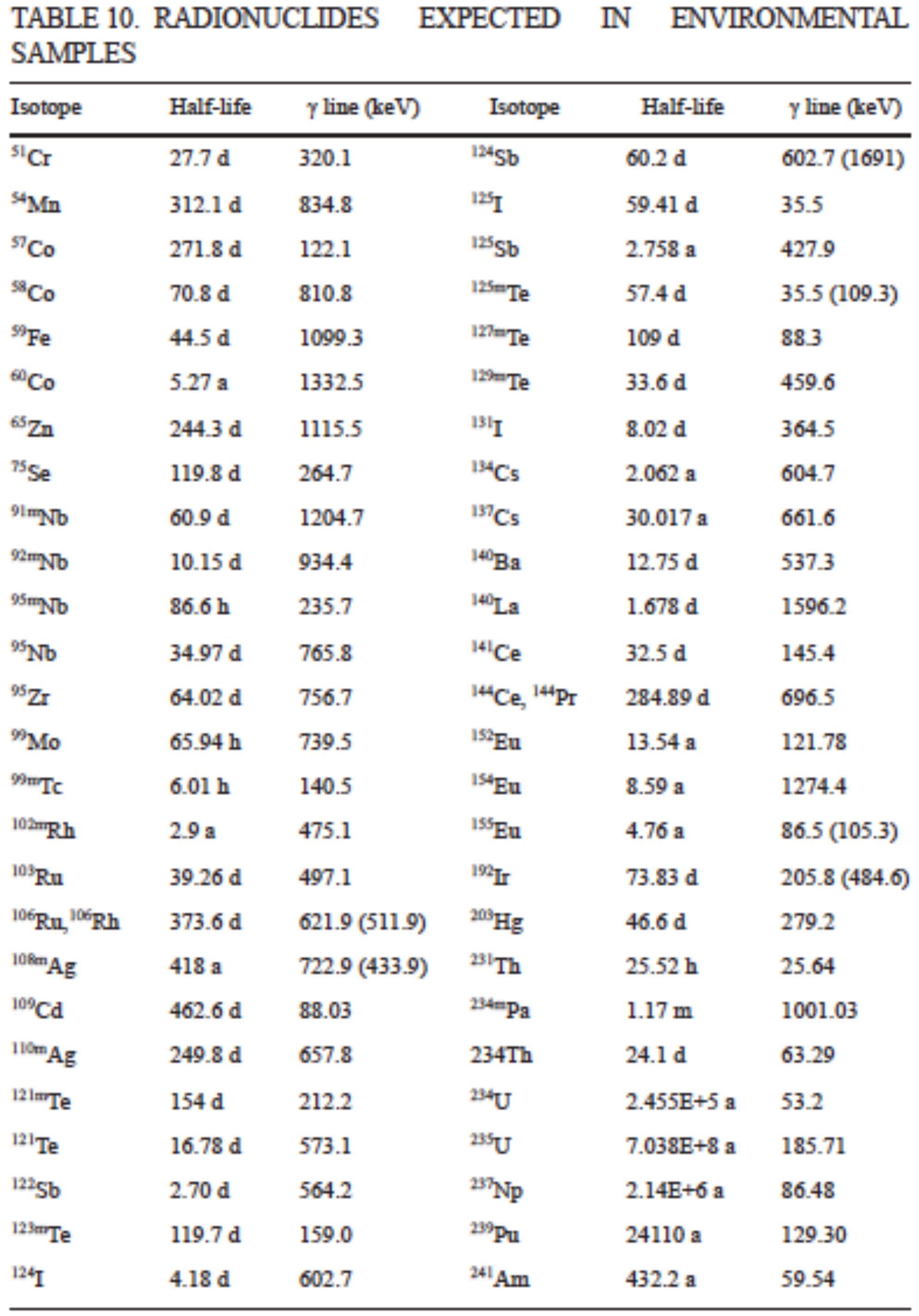
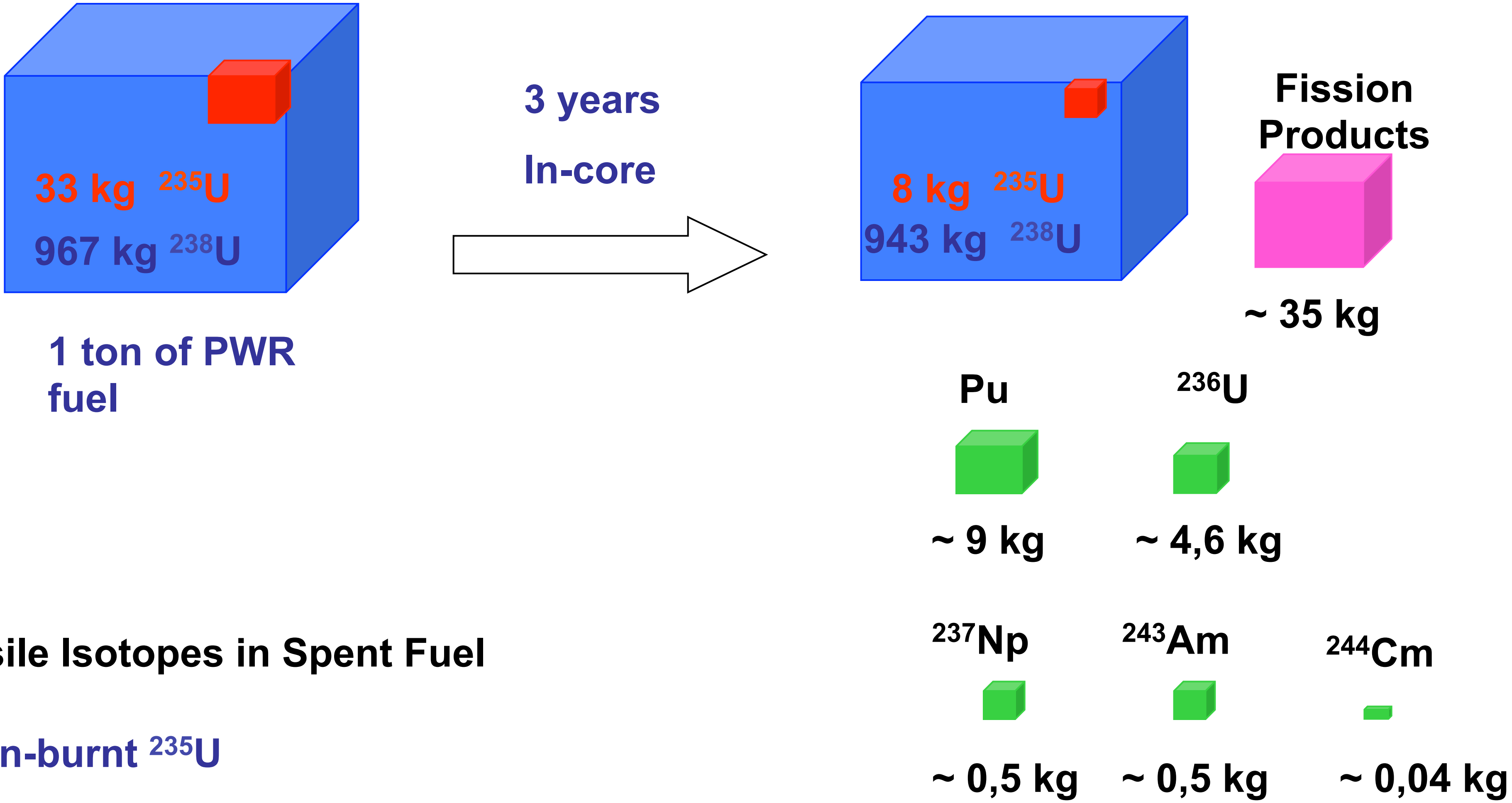


TABLE 10. RADIONUCLIDES EXPECTED IN ENVIRONMENTAL SAMPLES

Isotope	Half-life	γ line (keV)	Isotope	Half-life	γ line (keV)
^{51}Cr	27.7 d	320.1	^{124}Sb	60.2 d	602.7 (1691)
^{54}Mn	312.1 d	834.8	^{125}I	59.41 d	35.5
^{57}Co	271.8 d	122.1	^{125}Sb	2.758 a	427.9
^{58}Co	70.8 d	810.8	^{125m}Te	57.4 d	35.5 (109.3)
^{59}Fe	44.5 d	1099.3	^{127m}Te	109 d	88.3
^{60}Co	5.27 a	1332.5	^{129m}Te	33.6 d	459.6
^{65}Zn	244.3 d	1115.5	^{131}I	8.02 d	364.5
^{75}Se	119.8 d	264.7	^{134}Cs	2.062 a	604.7
^{91m}Nb	60.9 d	1204.7	^{137}Cs	30.017 a	661.6
^{92m}Nb	10.15 d	934.4	^{140}Ba	12.75 d	537.3
^{95m}Nb	86.6 h	235.7	^{140}La	1.678 d	1596.2
^{95}Nb	34.97 d	765.8	^{141}Ce	32.5 d	145.4
^{95}Zr	64.02 d	756.7	^{144}Ce, ^{144}Pr	284.89 d	696.5
^{99}Mo	65.94 h	739.5	^{152}Eu	13.54 a	121.78
^{99m}Tc	6.01 h	140.5	^{154}Eu	8.59 a	1274.4
^{102m}Rh	2.9 a	475.1	^{155}Eu	4.76 a	86.5 (105.3)
^{103}Ru	39.26 d	497.1	^{192}Ir	73.83 d	205.8 (484.6)
^{106}Ru, ^{106}Rh	373.6 d	621.9 (511.9)	^{203}Hg	46.6 d	279.2
^{108m}Ag	418 a	722.9 (433.9)	^{231}Th	25.52 h	25.64
^{109}Cd	462.6 d	88.03	^{234m}Pa	1.17 m	1001.03
^{110m}Ag	249.8 d	657.8	234Th	24.1 d	63.29
^{121m}Te	154 d	212.2	^{234}U	2.455E+5 a	53.2
^{121}Te	16.78 d	573.1	^{235}U	7.038E+8 a	185.71
^{122}Sb	2.70 d	564.2	^{237}Np	2.14E+6 a	86.48
^{123m}Te	119.7 d	159.0	^{239}Pu	24110 a	129.30
^{124}I	4.18 d	602.7	^{241}Am	432.2 a	59.54

Evolution of the fuel content



33 kg ^{235}U

967 kg ^{238}U

1 ton of PWR fuel

3 years

In-core

8 kg ^{235}U

943 kg ^{238}U

Fission Products

~ 35 kg

Pu	**^{236}U**	
~ 9 kg	**~ 4,6 kg**	
^{237}Np	**^{243}Am**	**^{244}Cm**
~ 0,5 kg	**~ 0,5 kg**	**~ 0,04 kg**

Fissile Isotopes in Spent Fuel

- non-burnt ^{235}U

- Most of the Pu isotopes

Isotopes in spent fuel

- Transuranian nuclei
  - **Heavy Nuclei undergoing successive neutron captures**
  - Mostly Neptunium, plutonium, Americium, Curium, Californium, Berkelium and above in small quantities
  - **Minor Actinides: ^{237}Np (Half-life: 2,4 10^{6} y), ^{241}Am (433 y), ^{243}Am (7400 y) ^{244}Cm (18 y), the most active components of long life nuclear wastes**
- **Long Life Fission Products**
  - **β, γ Emitters:** ^{59}Ni (7.5 10^{4} y), ^{107}Pd (6.5 10^{6} y) , **^{99}Tc (2.1 10^{5} y),** ^{129}I (1.6 10^{7} y), **^{135}Cs (2 10^{6} y)**
- **Activation Products**
  - **β, γ Emitters:** ^{108}Ag (127 y), ^{93}Mo (3.5 10^{3} y), ^{94}Nb (2 10^{4} y), ^{93}Zr (1.5 10^{6} y)

For PWR fuel, after 3 years in-core

OUTLINE

- Introduction about IAEA and Non Proliferation
- Nuclear Power Worldwide and Nuclear Fuel Cycle
- The Fission Process in a Nutshell
- Non Proliferation
- Safeguarding Techniques: NDA, C&S, Remote Monitoring, Environmental Sampling and Nuclear Forensics
- Safeguards Inspections
- New and Novel Technologies: antineutrino detection, reactor simulations and nuclear data

Non Proliferation

What does IAEA look for ?

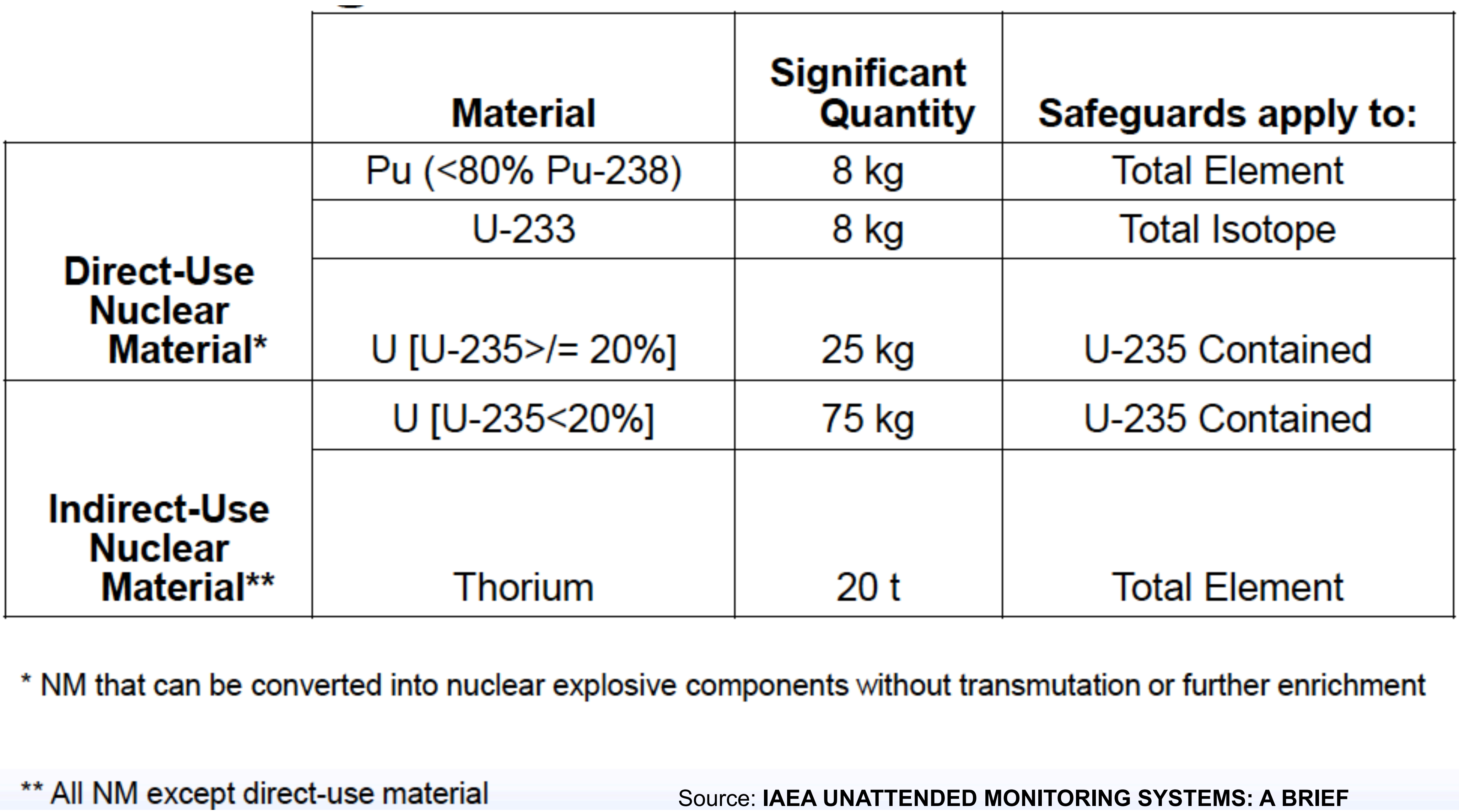
- **Significant Quantity** = quantity of nuclear material above which you can't acertain that the manufacturing of a weapon is impossible. It depends on:
  - ❑ type of nuclear material (nucleus /enrichment…)
- « **Timeliness** » is linked to the **conversion time** in order to make the material usable for a weapon.
  - ❑ depends mainly whether the material has been irradiated or not

25 kg of HEU (about the size of a grapefruit)

or 8 kg of plutonium (about the size of a soda can)

Significant Quantities of fissile material and timeliness detection (all materials irradiated in-core – source IAEA safeguards glossary 2001))

Non Proliferation



	Material	Significant Quantity	Safeguards apply to:
Direct-Use Nuclear Material*	Pu (<80% Pu-238)	8 kg	Total Element
	U-233	8 kg	Total Isotope
	U [U-235>/= 20%]	25 kg	U-235 Contained
Indirect-Use Nuclear Material**	U [U-235<20%]	75 kg	U-235 Contained
	Thorium	20 t	Total Element

* NM that can be converted into nuclear explosive components without transmutation or further enrichment

** All NM except direct-use material

Source: **IAEA UNATTENDED MONITORING SYSTEMS: A BRIEF OVERVIEW - Futures Toolkit by Mark SchanfeinIdaho National Laboratory - NGSI Student VTC Series**

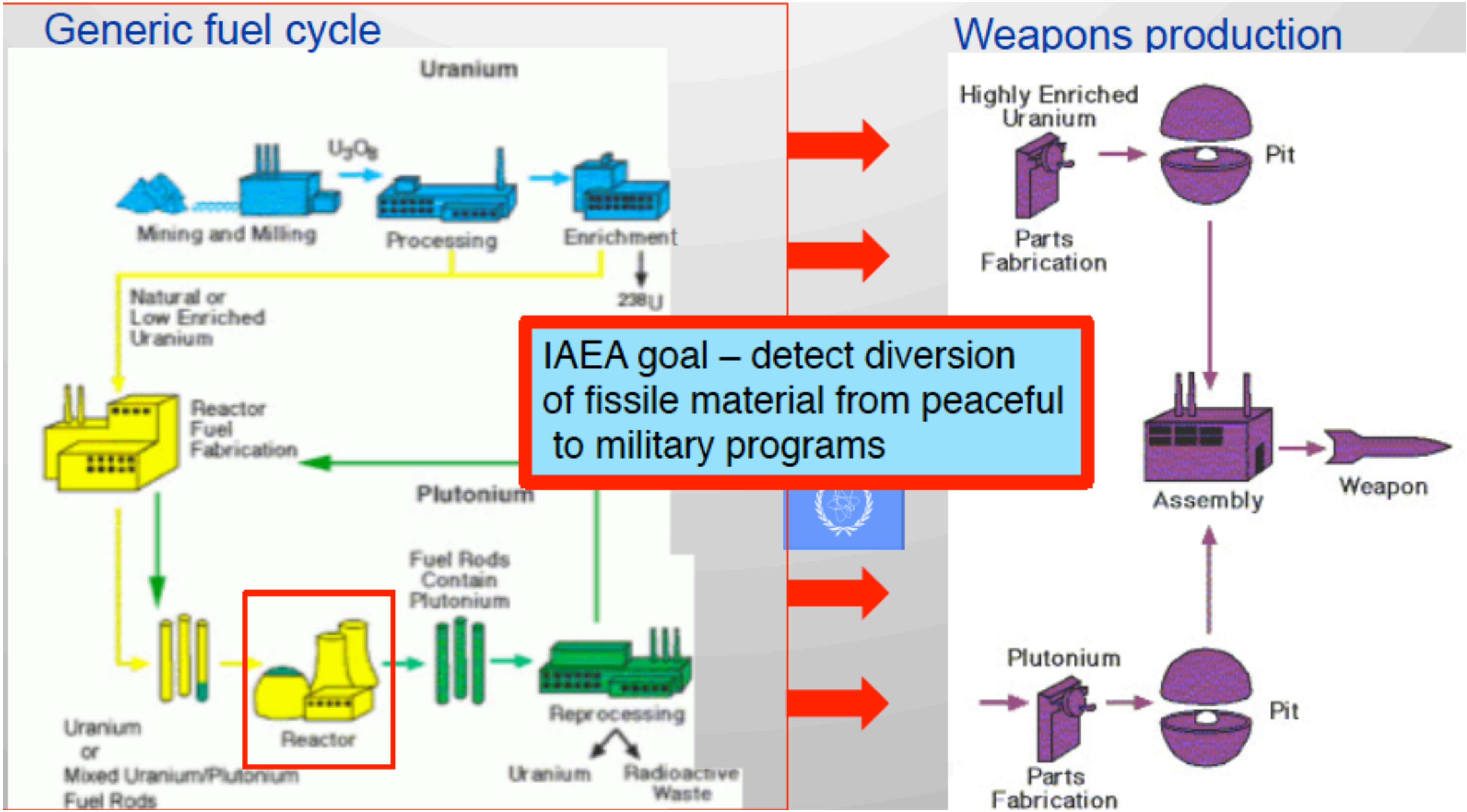
Non Proliferation

Beginning Material Form	Conversion Time
Pu, HEU or U-233 Metal	Order of Days (7-10)
PuO2, Pu(NO3)4, or other pure Pu compounds; HEU or U-233 oxide or other pure compounds; MOX or other non-irradiated pure mixtures containing Pu, U [(U-233+U-235)>/=20%; Pu, HEU and/or U-233 in scrap or other miscellaneous impure compounds	Order of Weeks (1-3)
Pu, HEU or U-233 in irradiated fuels	Order of Months (1-3)
U containing < 20% U-235 and U-233; Th	Order of one year

Source: **IAEA UNATTENDED MONITORING SYSTEMS: A BRIEF OVERVIEW - Futures Toolkit by Mark SchanfeinIdaho National Laboratory - NGSI Student VTC Series**

Non-Proliferation

The IAEA safeguards department monitors the flow of fissile material through the nuclear fuel cycle in 170 countries



IAEA goal – detect diversion of fissile material from peaceful to military programs

OUTLINE

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- Safeguards Inspections
- New and Novel Technologies: antineutrino detection, reactor simulations and nuclear data

Method of Safeguarding

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

$\left.\begin{array}{l}\text{3. Nondestructive Assay (NDA)}\\ \text{4. Destructive Assay (DA)}\end{array}\right\}$ material accountancy as a safeguards measure of fundamental importance

Balancing the books … **M**aterial **U**naccounted **F**or (MUF)

$$\mathbf{MUF \equiv (BI + I - R - EI)}$$

Where:

BI = beginning inventory

I = new inputs into a system

R = removals from a system

EI = ending inventory

Safeguards Techniques and Equipments

- Basic verification measure: **nuclear material accountancy**. Inspectors count items, measure attributes of these items during their inspections using non-destructive analysis (**NDA**) techniques, and compare their findings with the declared figures and the operator’s records => **gross defect**.

- **Partial defect**: weighing of items, measurements using **NDA techniques** such as **neutron counting or γ ray spectrometry** => accuracy of the order of a few per cent

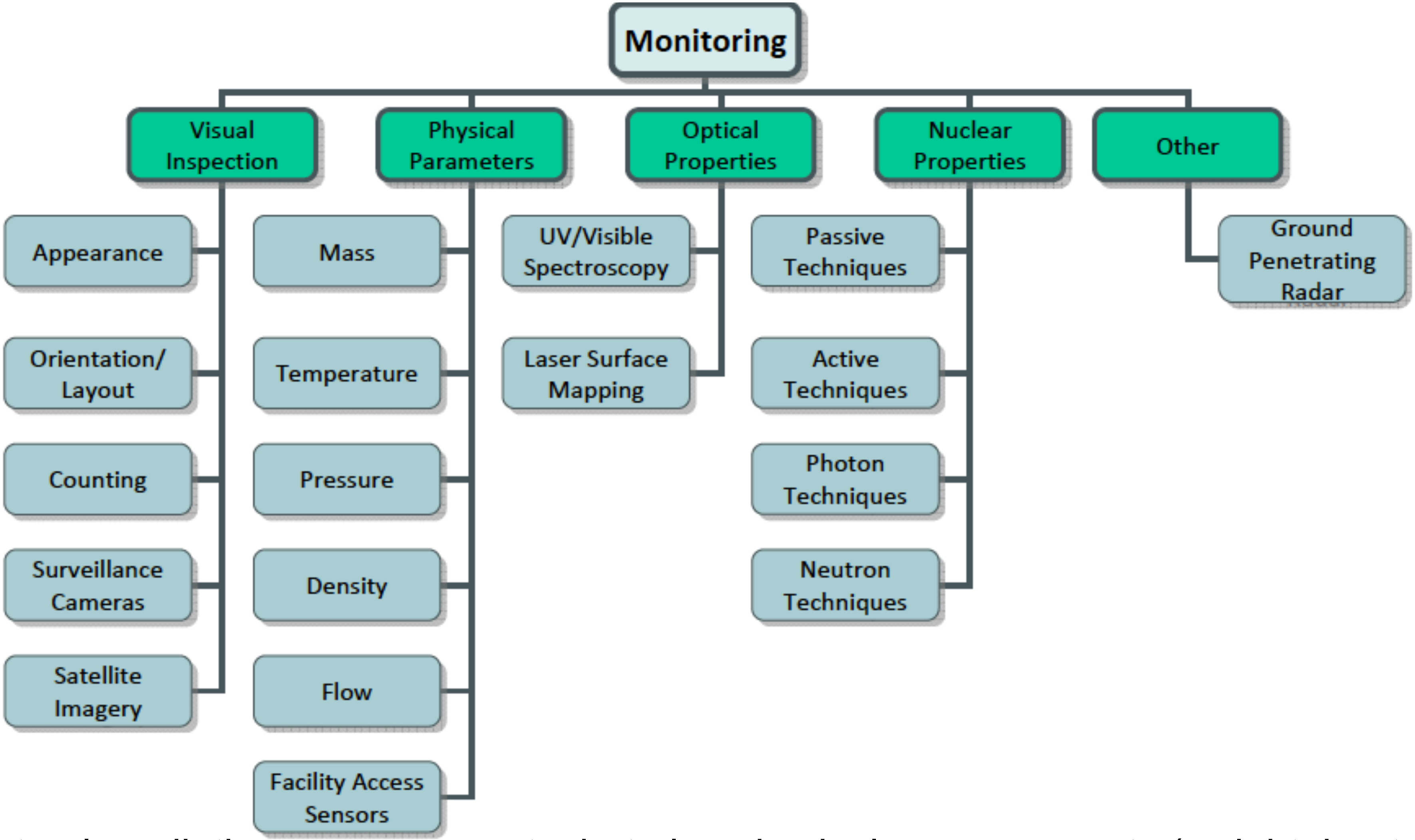
- **Bias defect**: **sample** some of the items and **apply physical and chemical analysis** techniques (Destructive Analysis, **DA**) of the highest possible accuracy, typically <1%

NDA Techniques

More than 100 NDA systems!

FIG 1. Overview of NDA instruments.

NDA BROAD DEFINITION



- Monitoring
  - Visual Inspection
    - Appearance
    - Orientation/ Layout
    - Counting
    - Surveillance Cameras
    - Satellite Imagery
  - Physical Parameters
    - Mass
    - Temperature
    - Pressure
    - Density
    - Flow
    - Facility Access Sensors
  - Optical Properties
    - UV/Visible Spectroscopy
    - Laser Surface Mapping
  - Nuclear Properties
    - Passive Techniques
    - Active Techniques
    - Photon Techniques
    - Neutron Techniques
  - Other
    - Ground Penetrating Radar

Not only radiation measurements, but also physical measurements (weight, heat, volume, thickness, light emission/absorption…)

VISUAL INSPECTION

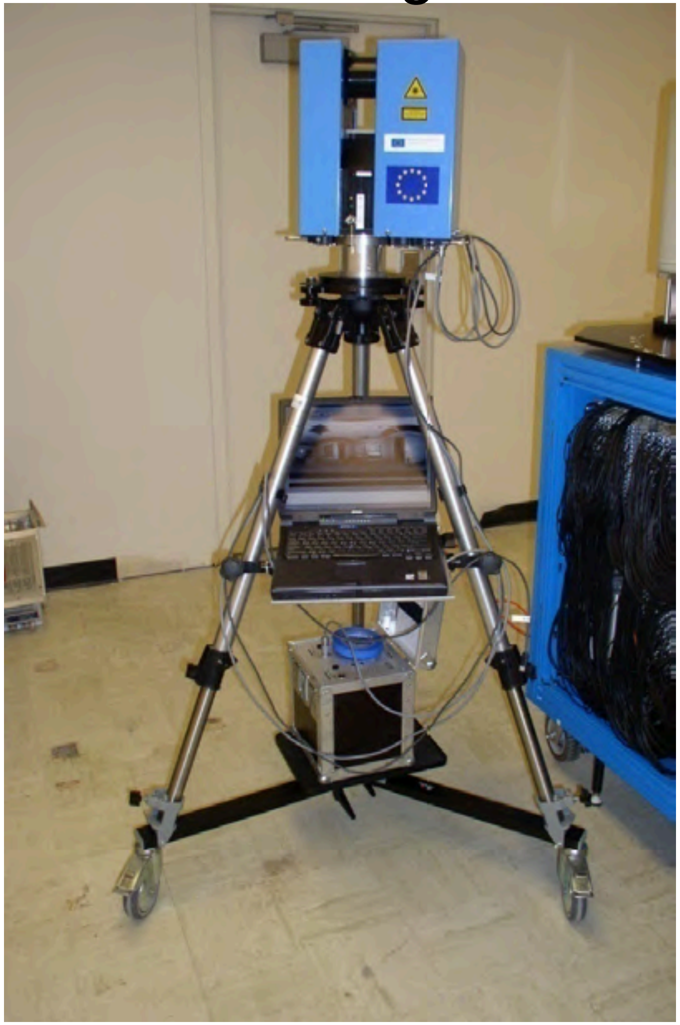
- Visual inspections are the easiest, cheapest, most commonly performed type of safeguard assessments and visual observation by skilled and knowledgeable inspectors is a key part of safeguards

Things that are counted …

- Fuel pins, rods, assemblies, canisters
- UF6 containers
- Waste storage containers
- Pipes, valves, …

Design Information Verification

3D Laser Range Finder



Nuclear processing facilities can be very complex; DIV confirms a facility is laid out to achieve the declared task(s)

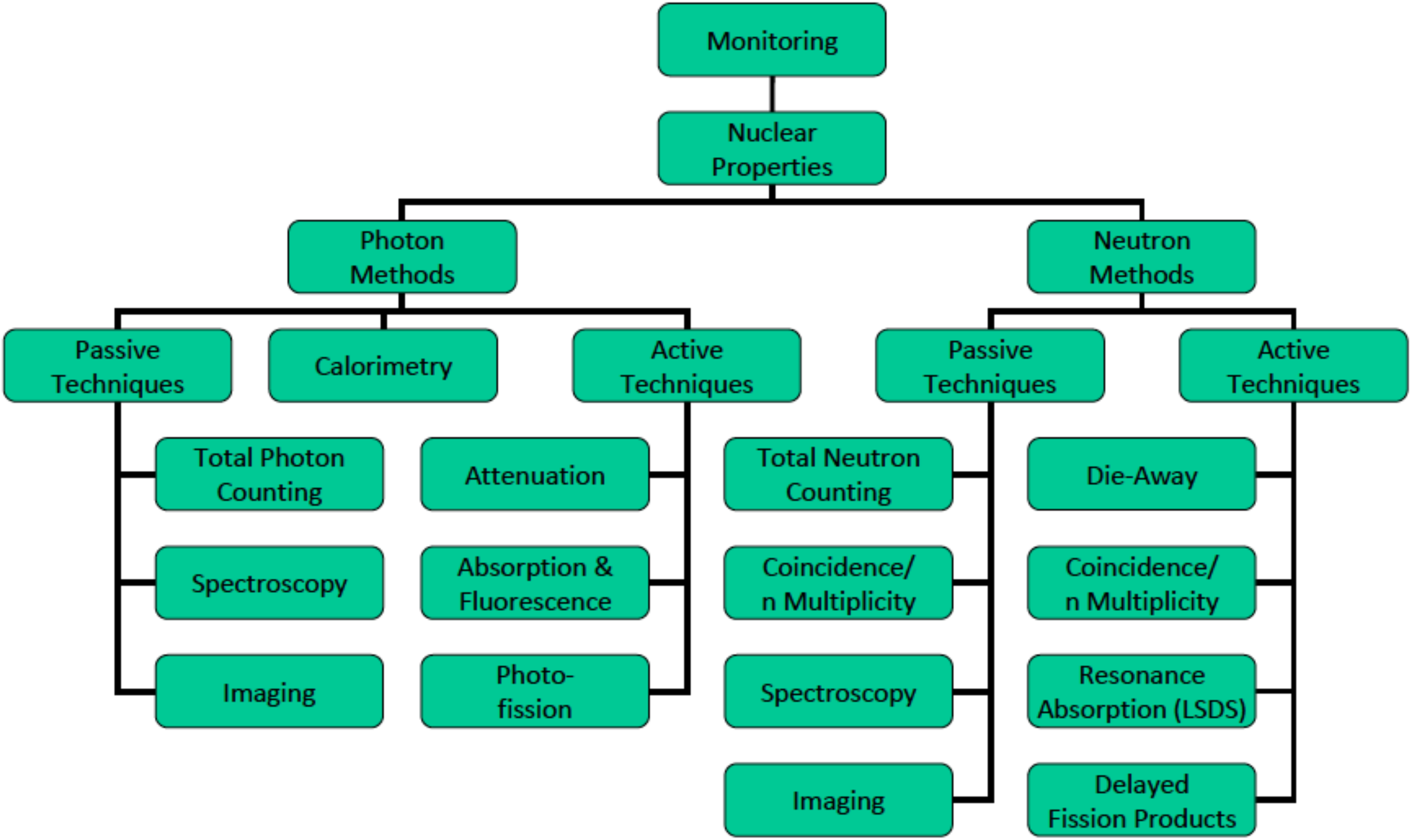
Design Information Verification

Reference Image

New Image

Differences Highlighted

Nuclear NDA



- Monitoring
  - Nuclear Properties
    - Photon Methods
      - Passive Techniques
        - Total Photon Counting
        - Spectroscopy
        - Imaging
      - Calorimetry
      - Active Techniques
        - Attenuation
        - Absorption & Fluorescence
        - Photo-fission
    - Neutron Methods
      - Passive Techniques
        - Total Neutron Counting
        - Coincidence/ n Multiplicity
        - Spectroscopy
        - Imaging
      - Active Techniques
        - Die-Away
        - Coincidence/ n Multiplicity
        - Resonance Absorption (LSDS)
        - Delayed Fission Products

Gamma Emission and Detection of Nuclear Materials

- Most nuclear materials under IAEA safeguards emit γ **rays usable for NDA**
- Well defined energies **characteristic of the isotopes** emitting them
- **Energies & relative intensities** = **identification of the isotopic composition** of the materials
- **Absolute intensities** = **quantitative info** on amount of material that is present

A few examples

- Enriched U fuel: **strong 186keV γ-ray** associated with the α **decay of ^{235}U**

⇒ Verify the **^{235}U enrichment**

- Plutonium samples generally content ^{238}Pu, ^{239}Pu and ^{240}Pu & decay products

⇒ **Complex mix of γ-rays**

- Relative intensities of γ-rays from **fission and activation products**

⇒ **Date of irradiated fuel discharge** from a reactor. Especially 662keV γ ray from ^{137}Cs.

Gamma-Ray Spectrometry Techniques

- **NaI:** large volumes, γ ray efficiency+++, energy resolution--
- **Ge:** energy resolution+++, resolve complex γ ray spectra, efficiency—range in size from small planar types to large (80–90 cm^3) coaxial detectors, needs cooling with liquid N_2
- **CdZnTe**: energy resolution+, intrinsic efficiency++, limited size
- **LaBr$_3$:** energy resolution+, efficiency+++
- **Gas filled detectors**: long term stability++

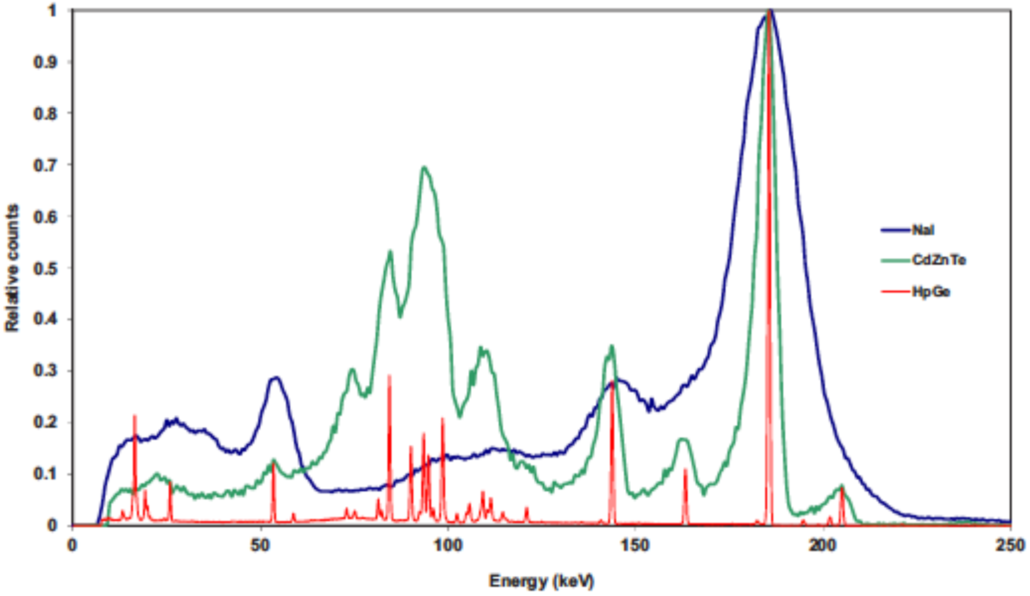


FIG 2. Comparison of γ ray spectrometric performance of various types of detector (low, medium and high resolution).

Examples of instruments

Mini MultiChannel Analyser

MMCA paired with a NaI detector: **verification of enrichment of uranium in pure, homogeneous powders and pellets. Enrichment derived from intensity of γ-rays attributed to ^{235}U (186keV).**

MMCA paired with a CdZnTe detector: mainly applied for **fresh fuel verification.**
Equiped with a probe of less than one centimetre in diameter
⇒ Can be **inserted into the water tube or control rod guide tube** of fuel assemblies

HM-5

- **The HM-5 field spectrometer**: battery powered, hand-held, digital, low resolution γ spectrometer.

⇒ **Regularly used by safeguards inspectors** for dose rate measurement, source search, isotope identification, active length determination for fuel rods and assemblies, determination of the enrichment of non-irradiated uranium materials, and plutonium/uranium attribute verification

FIG 5. HM-5 field spectrometer.

Examples of instruments

- **High Resolution Gamma-ray Spectrometry:**

⇒ often **used to determine the ^{235}U enrichment of uranium hexafluoride (UF6) in shipping cylinders**. Automated UF6 measurement procedure in the applications firmware = series of predetermined steps to measure and calculate the enrichment.

- **Electrically Cooled Germanium System (ECGS)**

⇒ Verification of U enrichment and Pu isotopic composition **in non-laboratory environments**

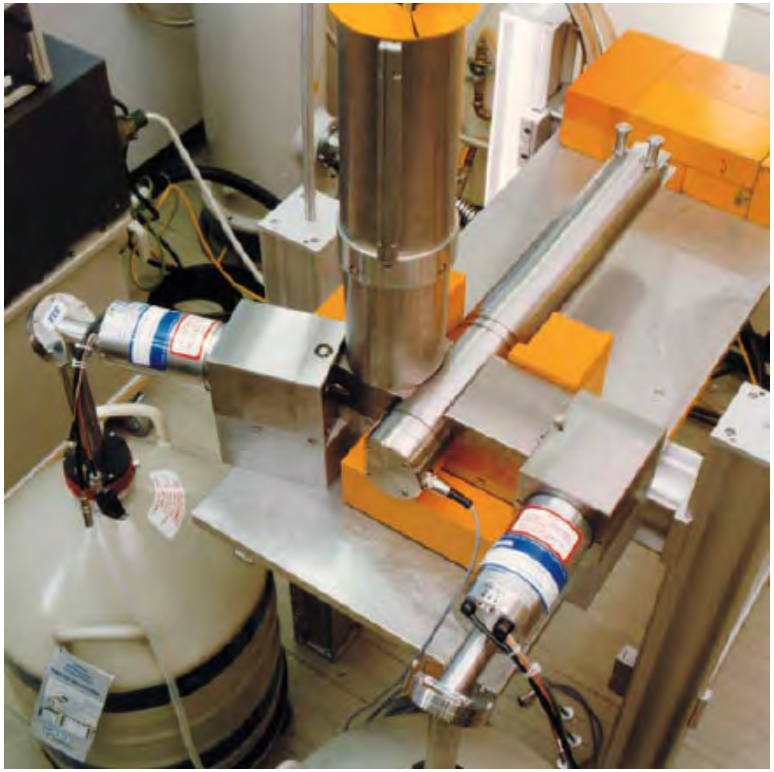
HKED

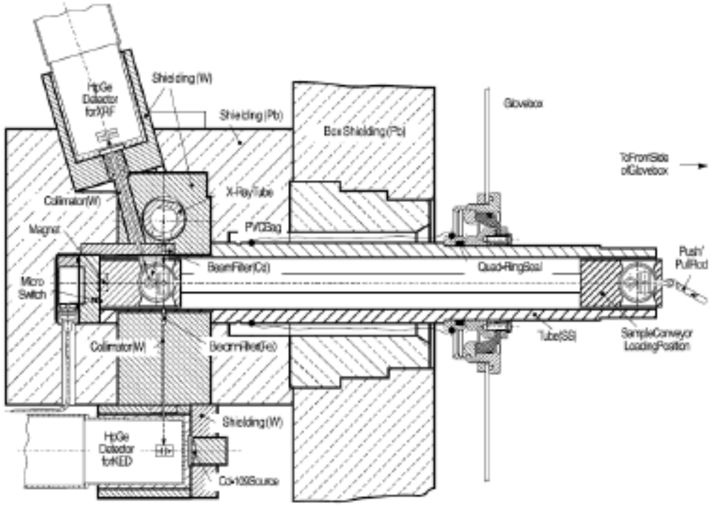
- Hybrid K-Edge/XRF Densitometry

⇒ for **assaying uranium and plutonium concentrations in liquid process streams**

⇒ X rays 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**





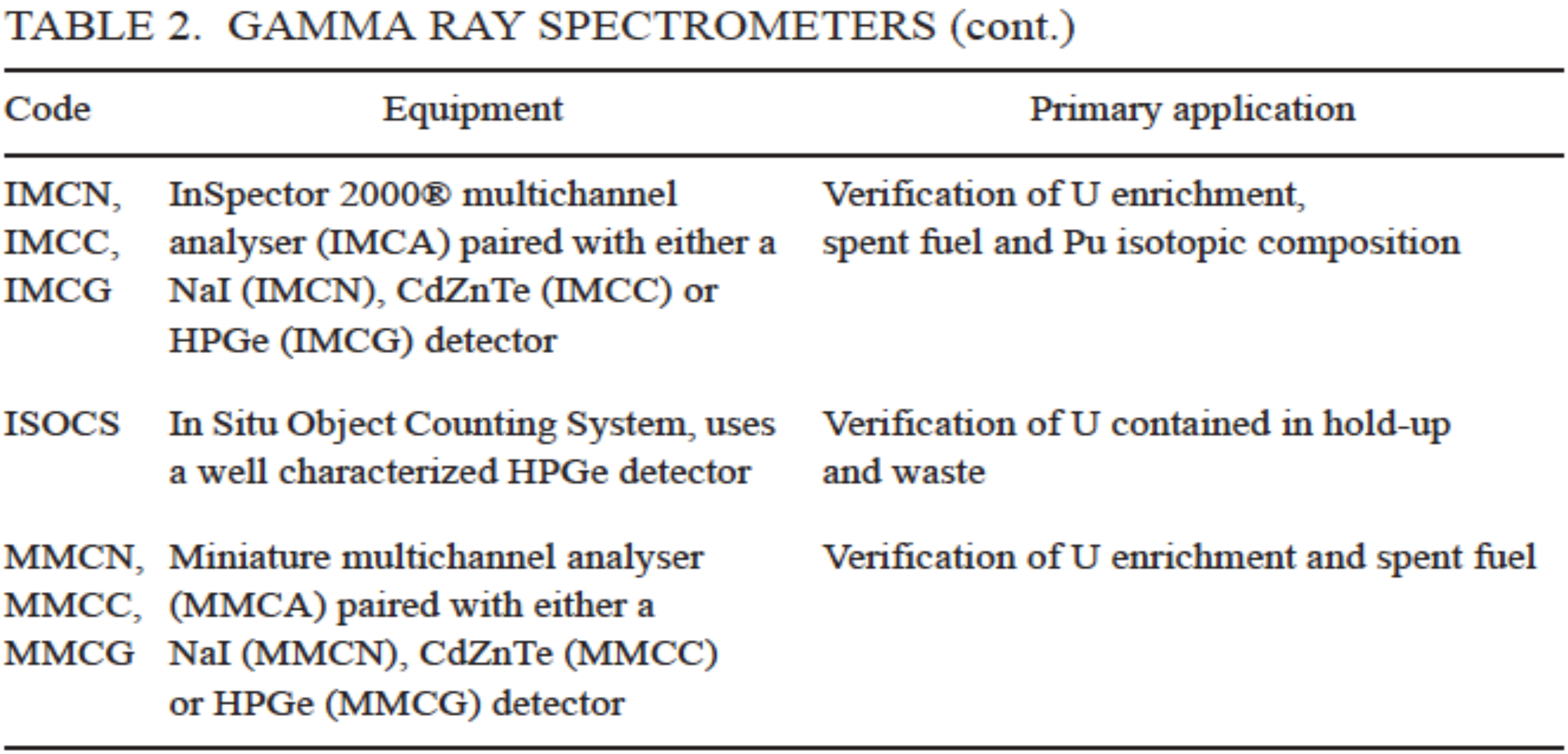
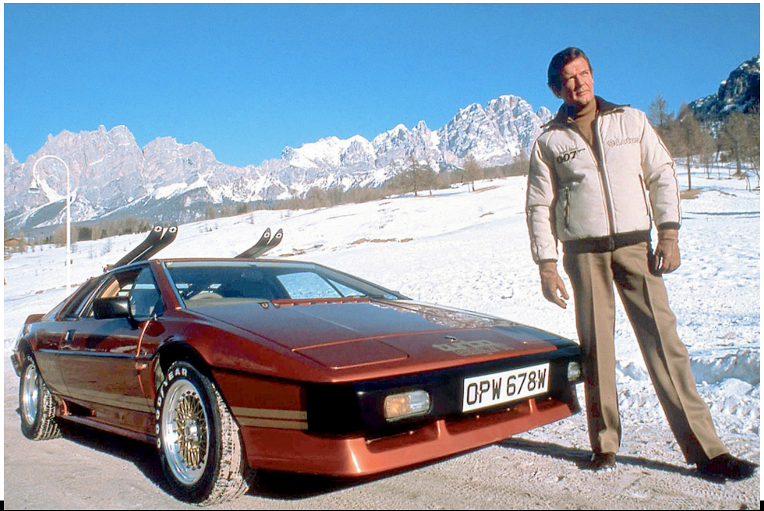


TABLE 2. GAMMA RAY SPECTROMETERS (cont.)

Code	Equipment	Primary application
IMCN, IMCC, IMCG	InSpector 2000® multichannel analyser (IMCA) paired with either a NaI (IMCN), CdZnTe (IMCC) or HPGe (IMCG) detector	Verification of U enrichment, spent fuel and Pu isotopic composition
ISOCS	In Situ Object Counting System, uses a well characterized HPGe detector	Verification of U contained in hold-up and waste
MMCN, MMCC, MMCG	Miniature multichannel analyser (MMCA) paired with either a NaI (MMCN), CdZnTe (MMCC) or HPGe (MMCG) detector	Verification of U enrichment and spent fuel

« Some of these gadgets cost more than a sportscar… »

« Some of these gadgets cost more than a sportscar… »
Head of the IAEA Non Destructive Assay Section that provides monitoring tools for inspector use



In Inspector’s luggage…

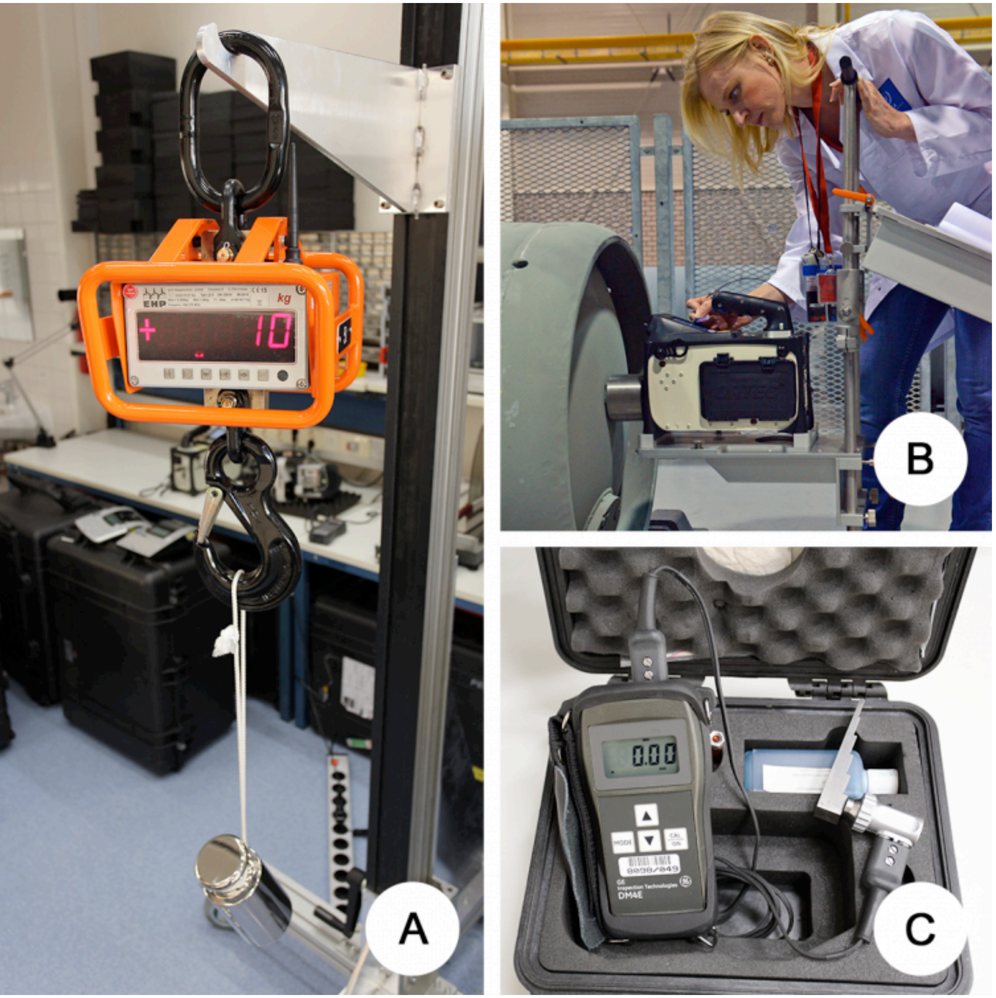


FIG 17. X ray fluorescence analyser (XRFA).

Neutron Counting

Neutron emission and detection in non-irradiated fissile fuel

- Neutrons are emitted in 3 ways:
  - ☐ **Spontaneous fission of U and Pu** isotopes (mainly even isotopes of Pu): gives **from 0 to 10 neutrons per fission event**
  - ☐ **Induced fission from fissile isotopes of U and Pu** by neutrons from other sources: **gives from 0 to 10 neutrons** per fission event
  - ☐ **Alpha particle induced reactions (alpha,n)** involving light elements such as O and F: alpha particles are emitted by nearly all U, Pu and transuranic elements which can interact with light elements (O or F, or B, Be and Li) **to form a uniform neutron background.**

⇒ **Neutron coincidence counting discriminates against this (alpha, n) background**.

Neutron Counting

- **Passive coincidence detector systems:**

⇒ Mass of plutonium based on **spontaneous fission**, primarily in the even numbered isotopes (^{238}Pu, ^{240}Pu and ^{242}Pu, with ^{240}Pu being the dominant contributor). ^{239}Pu makes an insignificant contribution to the spontaneous fission neutron signal.

⇒ **Isotopic abundance** must be known or verified (high resolution γ ray measurement)

⇒ Using the isotopic abundance, the $^{240}Pu_{eff}$ mass determined from coincident neutron count rates can be converted into the total plutonium mass of the sample.

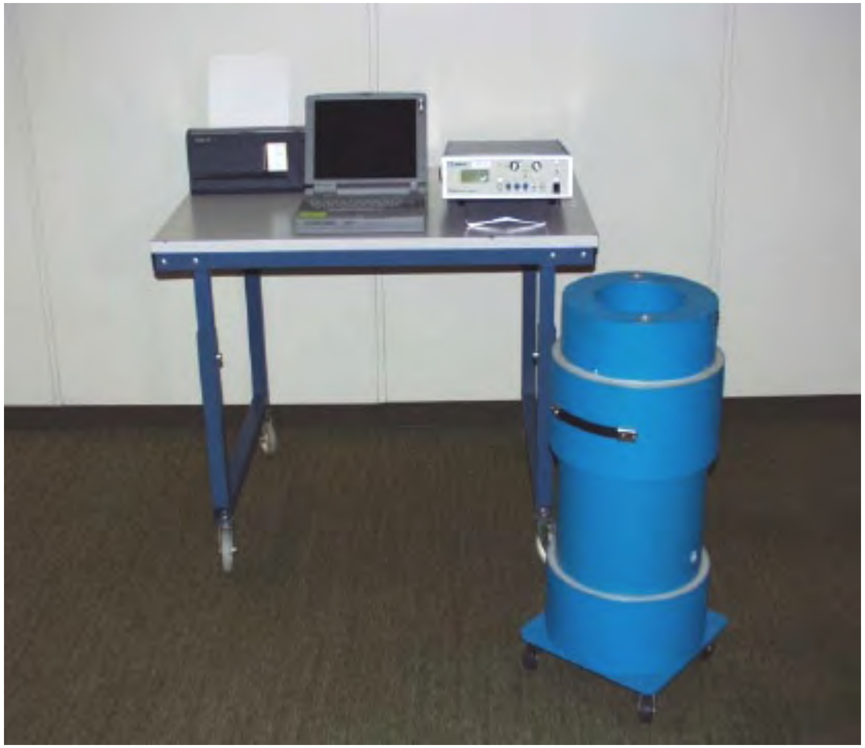
- **Active detector system:** ^{235}U does not undergo sufficient spontaneous fission for practical passive detection.

⇒ system **incorporates americium–lithium (AmLi) neutron sources**

⇒ ‘interrogates’ (induce fission in) the ^{235}U content.

Neutron Counting

High Efficiency Passive Counter (HEPC)

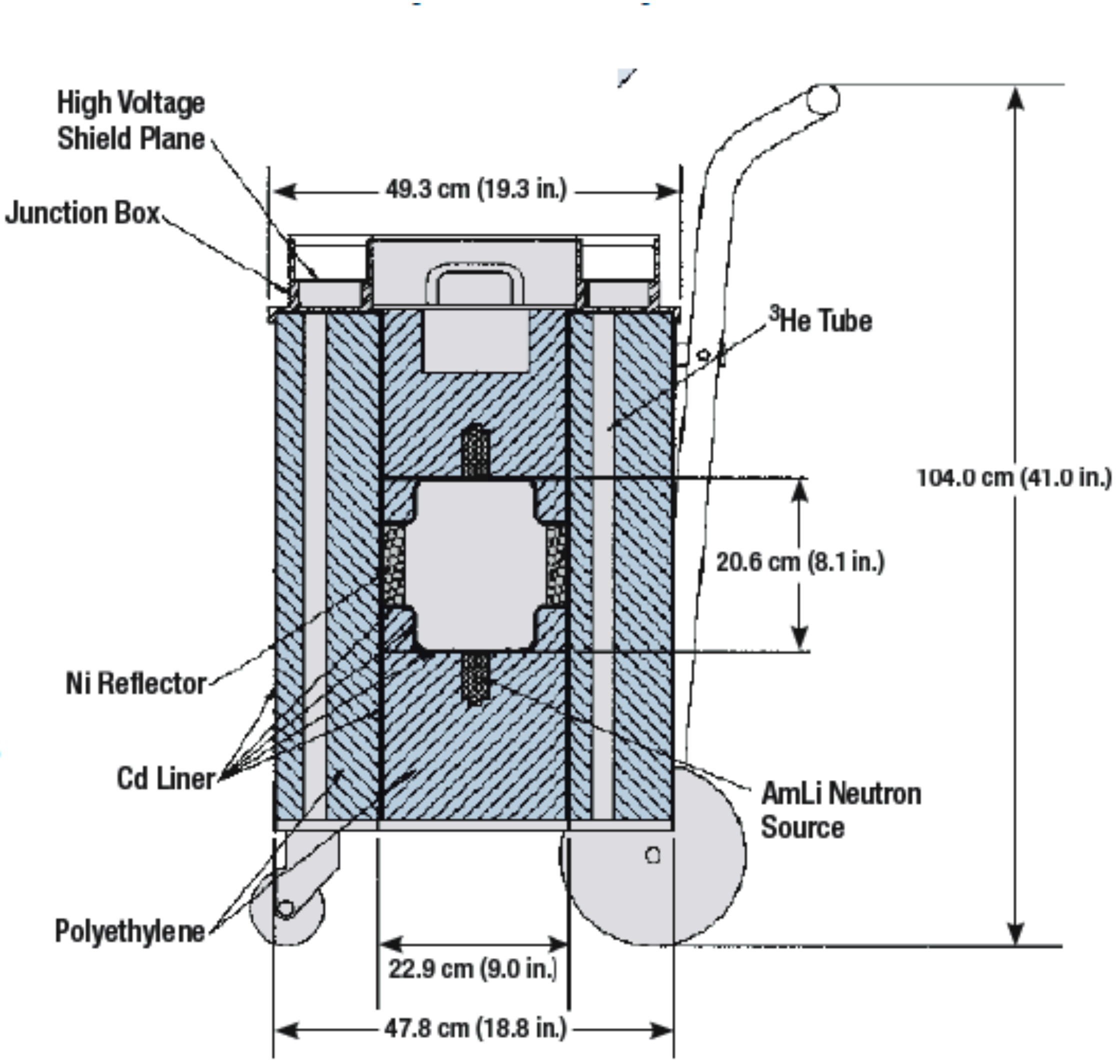


High Level Neutron Coincidence (HLNC) counter, with He-3 detectors and coincidence counter electronics for verification of Pu bearing materials

Active Well Coincidence Counter

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"

Neutron Counting

Neutron emission and detection in spent fuel.

- **Spontaneous fission in the ^{242}Cm and ^{244}Cm isotopes** is the major source of neutrons emanating from spent fuel. Fission products in the irradiated fuel produce an extremely high radiation background in which the neutrons must be detected.

⇒ choose a detector which is basically insensitive to γ rays.

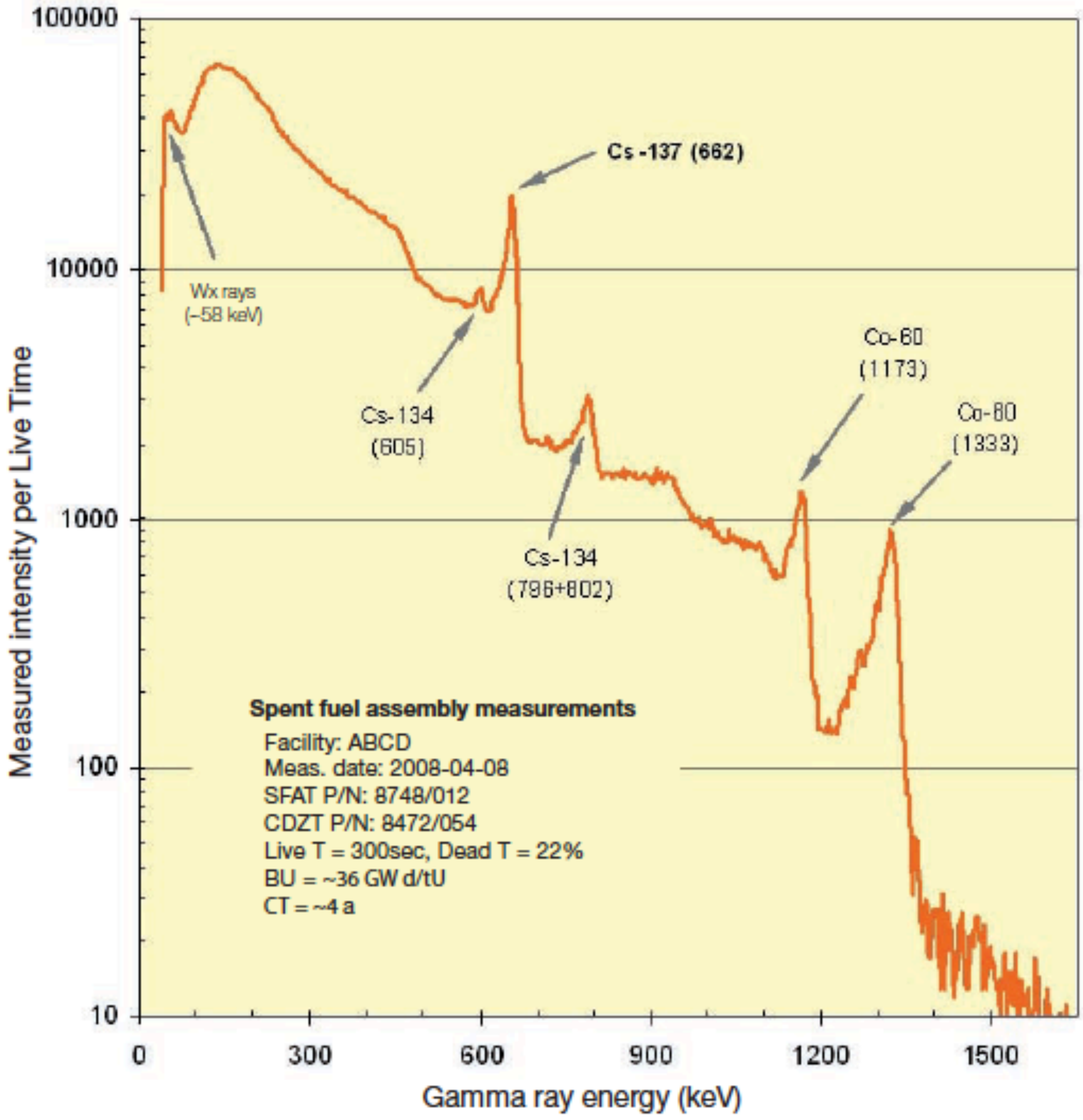
⇒ shield against the γ rays while allowing neutrons to pass through the shield into the neutron detector.

- **The 662 keV γ ray line from ^{137}Cs**

⇒ dominates a spectrum for spent fuel that has cooled longer than two years

⇒ provides a useful signature for verifying the spent fuel.

⇒ For shorter cooling times, the 757/766 keV line from ^{95}Nb/^{95}Zr is used to verify the presence of spent fuel.



Spent fuel assembly measurements

Facility: ABCD
Meas. date: 2008-04-08
SFAT P/N: 8748/012
CDZT P/N: 8472/054
Live T = 300sec, Dead T = 22%
BU = ~36 GW d/tU
CT = ~4 a

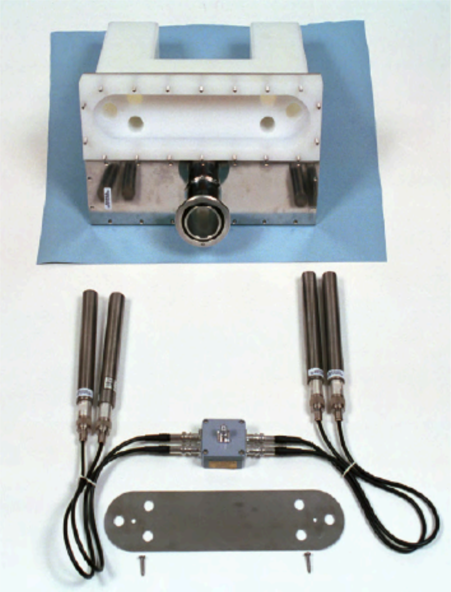
FIG. 13. Typical γ ray spectrum acquired with SFAT.

FDET

Fork detector irradiated fuel measuring system (FDET)

- The FDET detector heads are used to measure boiling water reactor (BWR) and pressurized water reactor (PWR) type fuels.

⇒ incorporates γ ray insensitive neutron detectors (four gas filled fission chamber proportional counters) and γ ray detectors suitable for measuring extremely high γ ray intensities (two gas filled ionization chambers).



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.

⇒ used to verify the highly radioactive spent fuel assemblies stored under water in spent fuel ponds.

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

FDET

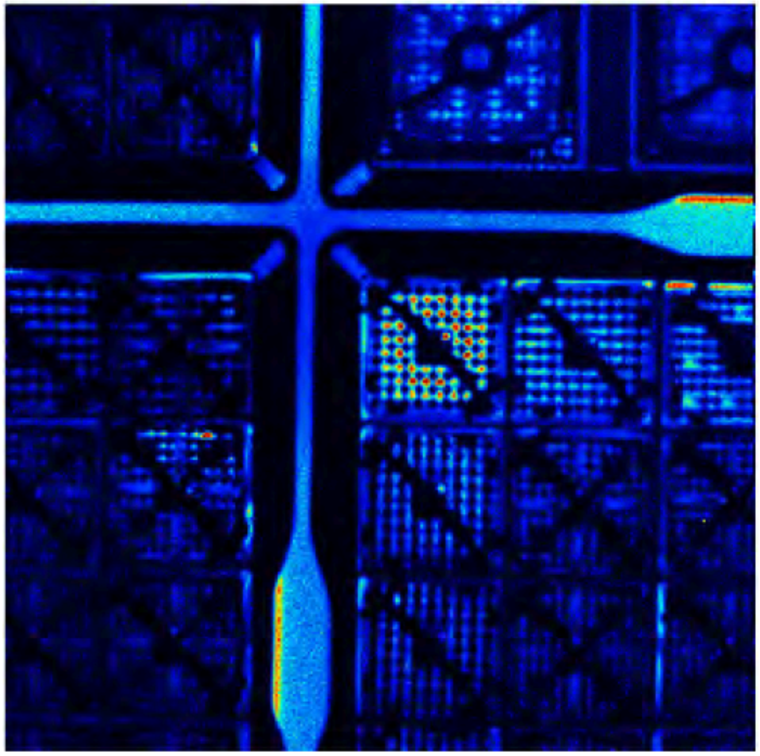
Ratio of the neutron to γ ray data, combined with other complementary information:

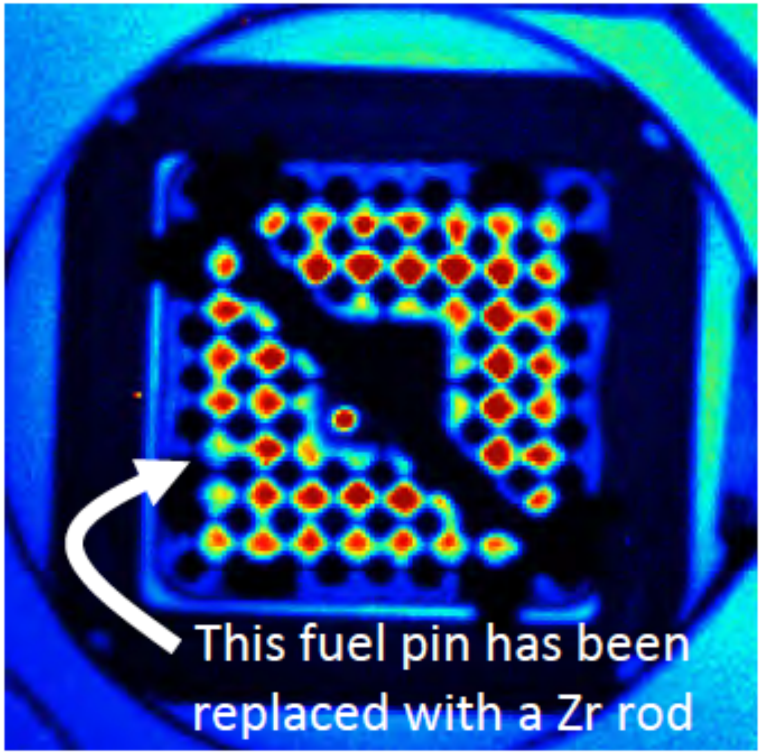
⇒ used to characterize a particular type of fuel assembly, giving information related to its neutron exposure in the reactor, its initial fissile fuel content and its irradiation history (e.g. the number of cycles for which the assembly was in the reactor).

Spent Fuel Measurement

- Spent Fuel emits **intense γ radiation** which produces **high energy recoil electrons** exceeding in many cases the speed of light in water and therefore must lose energy by emitting radiation (**Cerenkov radiation**). Spent fuel also emits **β particles**, adding to the Cerenkov radiation

⇒ ICVD, DCVD: Improved/Digital Cerenkov Viewing Device are image intensifier viewing devices that are sensitive to ultraviolet radiation in the water surrounding spent fuel assemblies;





C/S

Containment and surveillance (C/S) techniques are applied in order to **maintain continuity of the knowledge** gained through IAEA verification, by giving assurance that nuclear material follows predetermined routes, that the integrity of its containment remains unimpaired and that the material is accounted for at the correct measurement points.

They also lead to **savings in the safeguards inspection effort** (e.g. by reducing the required frequency of accountancy verification).

A variety of C/S techniques are applied, primarily **optical surveillance and sealing.**

These measures serve as a **backup to nuclear material accountancy** through monitoring access to nuclear material and detecting any undeclared movement of material.

Unattended & Remote Monitoring

- **Unattended and remote monitoring:** application of **NDA or C/S techniques**, or a combination of these techniques, that operate for extended periods without the presence of inspectors.
- Implies a high reliability and authentification of the data source
- Data security is an important feature of unattended and remote monitoring systems. These data need to be verified to guarantee their authenticity and may need to be **encrypted** to avoid disclosure of specific information and/or to provide assurance of confidentiality to States.

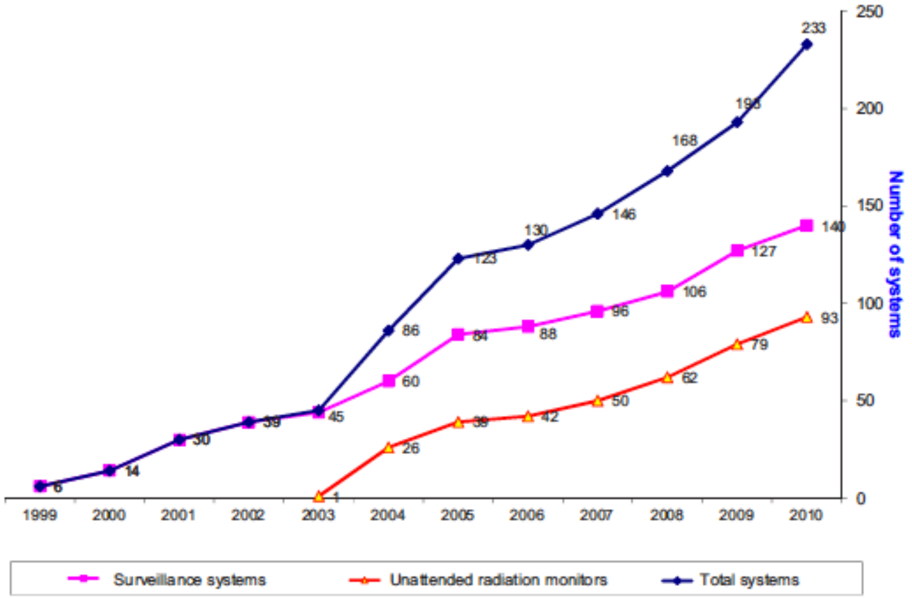
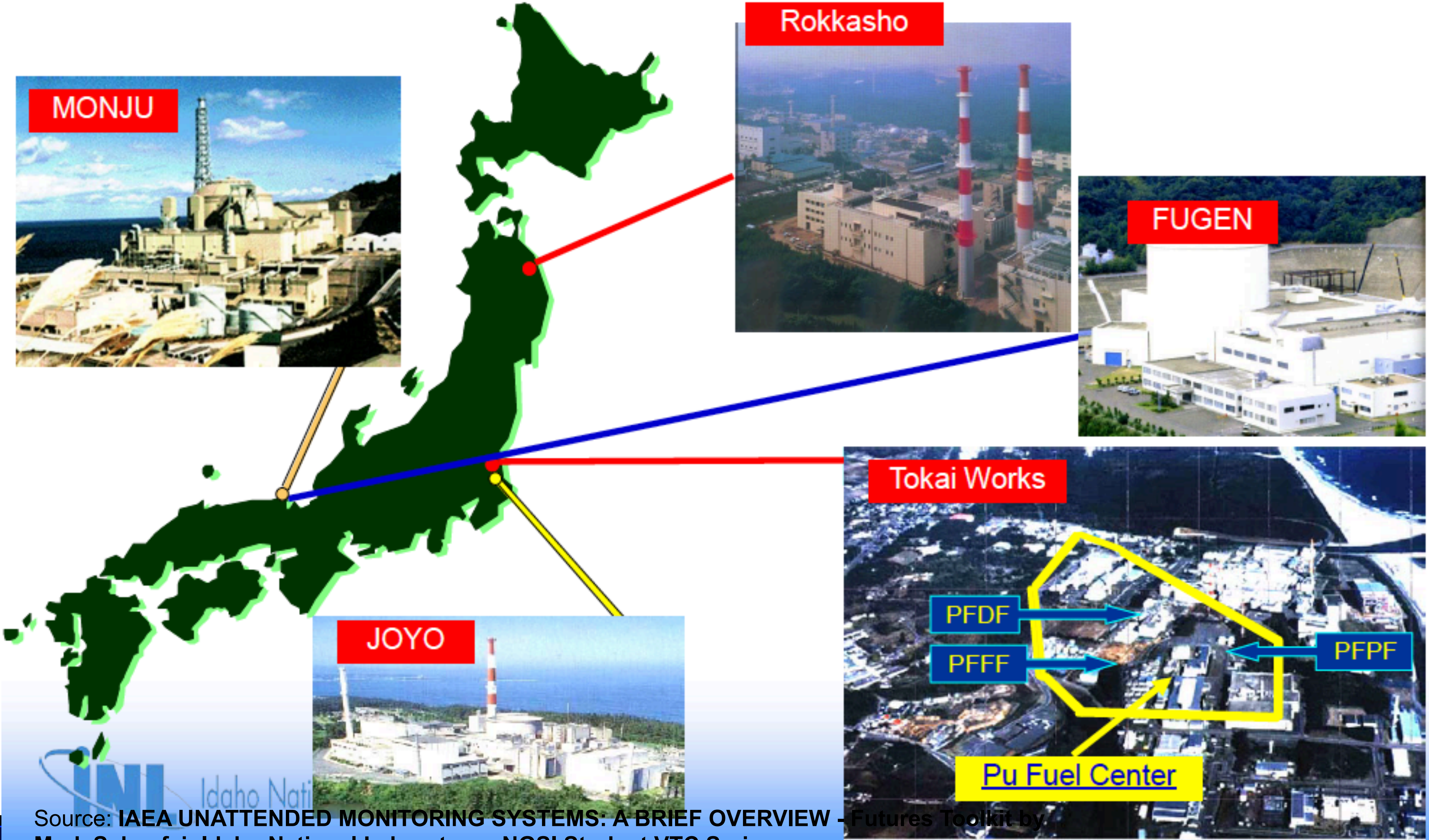


FIG 40. Expansion of remote monitoring, 1999–2010.

Unattended & Remote Monitoring

- It is a system that **automatically monitors** the flow of nuclear materials 24 hours a day / 365 days a year **without the need for human interaction**
- It is **permanently installed in a nuclear facility**
- It is **computer based for data retrieval** either on-site or remotely
- It may use a **variety of sensors** such as radiation, pressure, temperature, flow, vibration, & electromagnetic fields to collect qualitative or quantitative data
- All external components are **in tamper indicating enclosures**

Japan: Largest non-weapons state with complete fuel cycle under IAEA safeguards



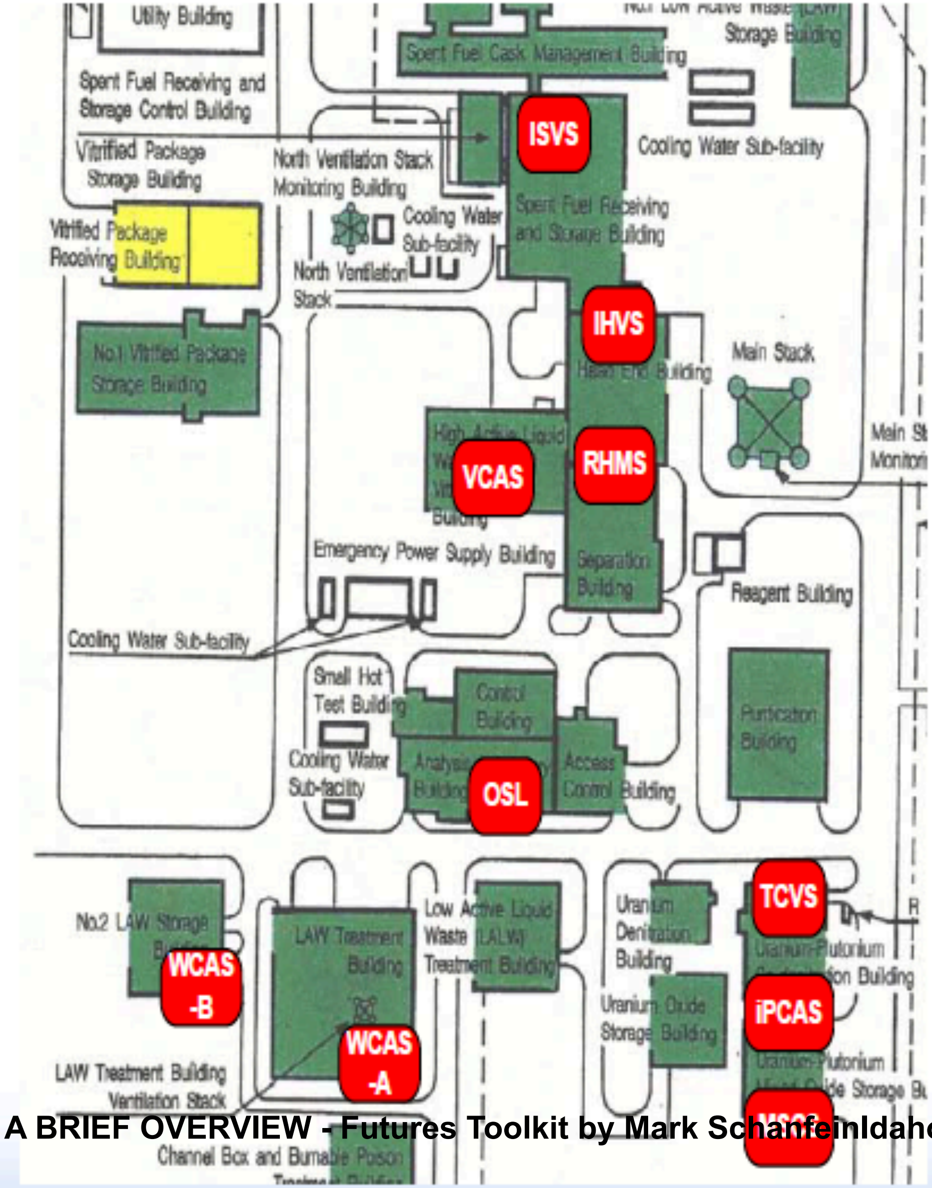
Source: **IAEA UNATTENDED MONITORING SYSTEMS: A BRIEF OVERVIEW - Futures Toolkit by Mark SchanfeinIdaho National Laboratory - NGSI Student VTC Series**

Rokkasho Reprocessing Plant Characteristics

- Only large scale reprocessing plant **outside a Nuclear Weapons State** (full scope IAEA safeguards)
- Safeguards on bulk handling facilities (vs. item) **800 tons heavy metal** ~ 8 tons Pu/yr
- Analytical error (~0.3% including sampling error) gives a 1σ error on throughput of Pu of **~24 kg per year**
- 2σ is 48 kg = ~4 kg/month (considering abrupt diversion, compare to IAEA significant goal quantity 8kg, with 95% C.L. that reduces to ~2.5kg)

NDA systems at Rokkasho Reprocessing Facility are the State of the Art.

- ISVS – Integrated Spent fuel Verification System
- IHVS – Integrated Head end Verification System
- RHMS – Rokkasho Hulls Measurement System
- VCAS – Vitrified waste Canister Assay System
- HKED – Hybrid K-Edge Densitometer
- TCVS - Temporary Canister Verification System
- iPCAS - improved Plutonium Canister Assay System
- WCAS A/B - Waste Crate Assay System



Source: **IAEA UNATTENDED MONITORING SYSTEMS: A BRIEF OVERVIEW - Futures Toolkit by Mark SchanfeinIdah National Laboratory - NGSI Student VTC Series**

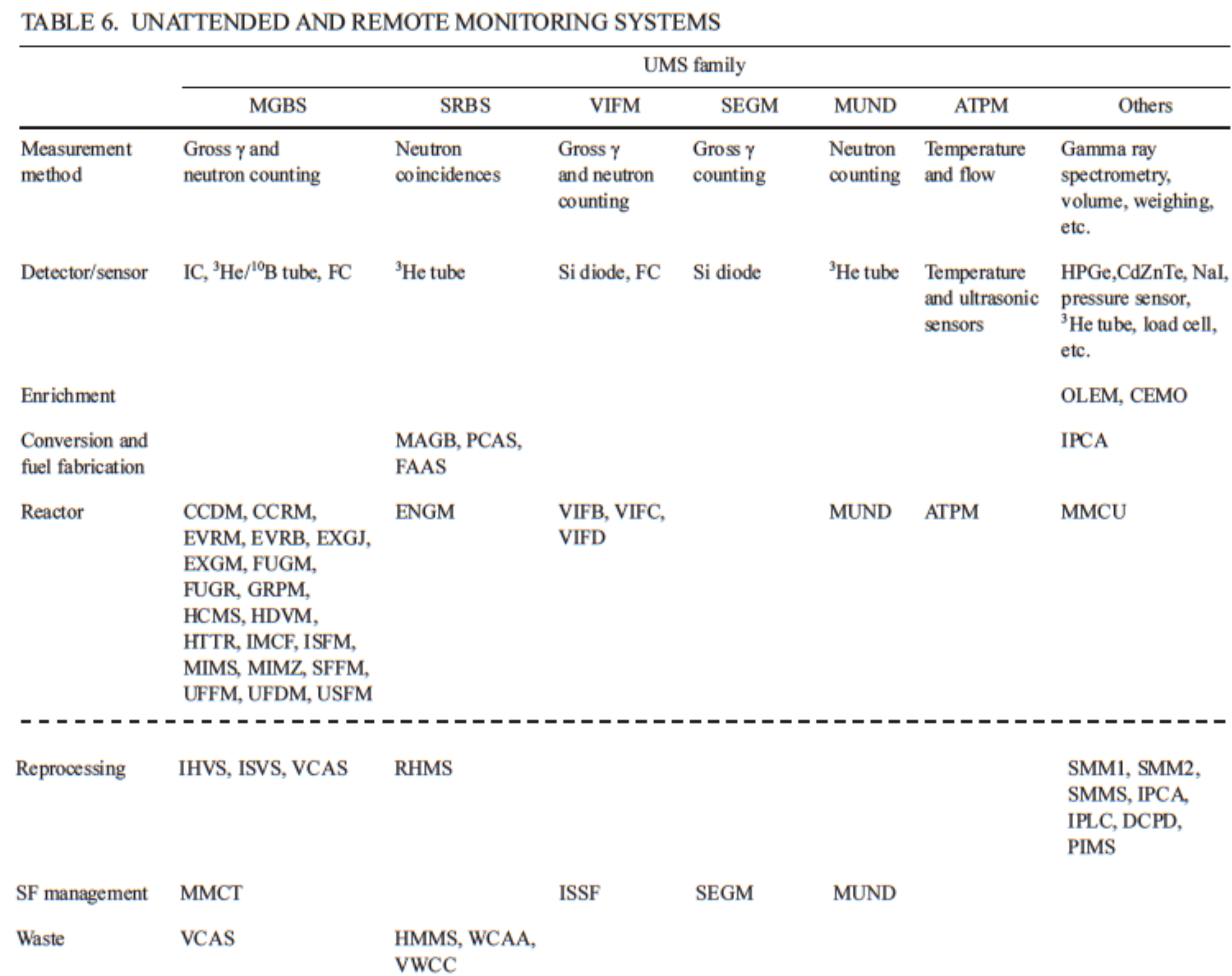
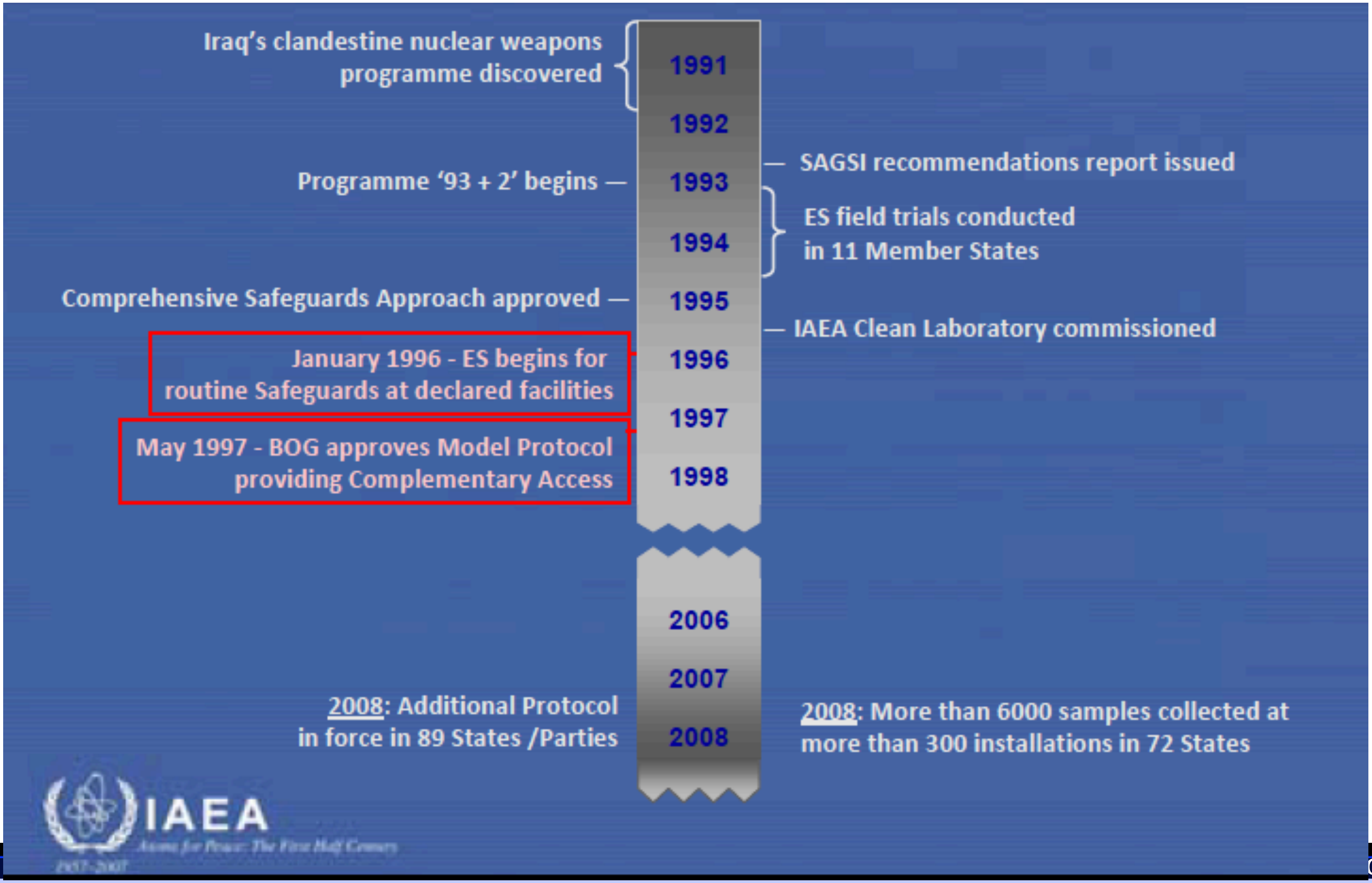


TABLE 6. UNATTENDED AND REMOTE MONITORING SYSTEMS

	UMS family						
	MGBS	SRBS	VIFM	SEGM	MUND	ATPM	Others
Measurement method	Gross γ and neutron counting	Neutron coincidences	Gross γ and neutron counting	Gross γ counting	Neutron counting	Temperature and flow	Gamma ray spectrometry, volume, weighing, etc.
Detector/sensor	IC, ^{3}He/^{10}B tube, FC	^{3}He tube	Si diode, FC	Si diode	^{3}He tube	Temperature and ultrasonic sensors	HPGe,CdZnTe, NaI, pressure sensor, ^{3}He tube, load cell, etc.
Enrichment							OLEM, CEMO
Conversion and fuel fabrication		MAGB, PCAS, FAAS					IPCA
Reactor	CCDM, CCRM, EVRM, EVRB, EXGJ, EXGM, FUGM, FUGR, GRPM, HCMS, HDVM, HTTR, IMCF, ISFM, MIMS, MIMZ, SFFM, UFFM, UFDM, USFM	ENGM	VIFB, VIFC, VIFD		MUND	ATPM	MMCU
Reprocessing	IHVS, ISVS, VCAS	RHMS					SMM1, SMM2, SMMS, IPCA, IPLC, DCPD, PIMS
SF management	MMCT		ISSF	SEGM	MUND		
Waste	VCAS	HMMS, WCAA, VWCC					

Environmental Sampling

- Based on the premise that every nuclear process, no matter how leak tight, emits small amounts of process material to the environment.
- The released process material can settle on equipment and surfaces within buildings, and can be transported outside to deposit there.



1991

Iraq's clandestine nuclear weapons programme discovered

1992

1993

Programme '93 + 2' begins

SAGSI recommendations report issued

1994

ES field trials conducted in 11 Member States

1995

Comprehensive Safeguards Approach approved

IAEA Clean Laboratory commissioned

1996

January 1996 - ES begins for routine Safeguards at declared facilities

1997

May 1997 - BOG approves Model Protocol providing Complementary Access

1998

2006

2007

2008

2008: Additional Protocol in force in 89 States /Parties

2008: More than 6000 samples collected at more than 300 installations in 72 States

Environmental Sampling

Sampling of Surface Soil

Sampling of Aerosols

Swipes from Vegetation

High Volume Water Sampling

Environmental Sampling

Sampling kit for hot cells

Standard swipe kit

Environmental Sampling

▨ KAERI South Korea

🟩 PNNL USA

🟩 LLNL USA

🟩 LANL USA

🟩 ORNL USA

🟨 AFTAC USA

🟨 AWE UK

🟨 QinetiQ UK

▨ IRD Brazil

🟩 ANSTO Australia

🟨🟩 JAEA Japan

🟨 LMA Russia

🟩 KRI Russia

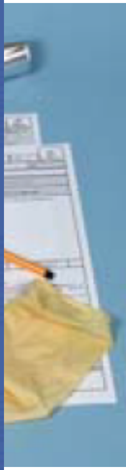
▨ STUK Finland

▨ NRI Rez Czech Rep.

🟨🟩 SAL IAEA

🟨 ITU EC, Germany

🟨🟩 CEA France



🟩 Bulk analysis

🟨 Particle analysis

▨ Laboratory under qualification

IAEA

Atoms for Peace: The First Half Century

1957-2007

Network of Analytical Laboratories for analysis of environmental samples for Safeguards