IAEA safeguards

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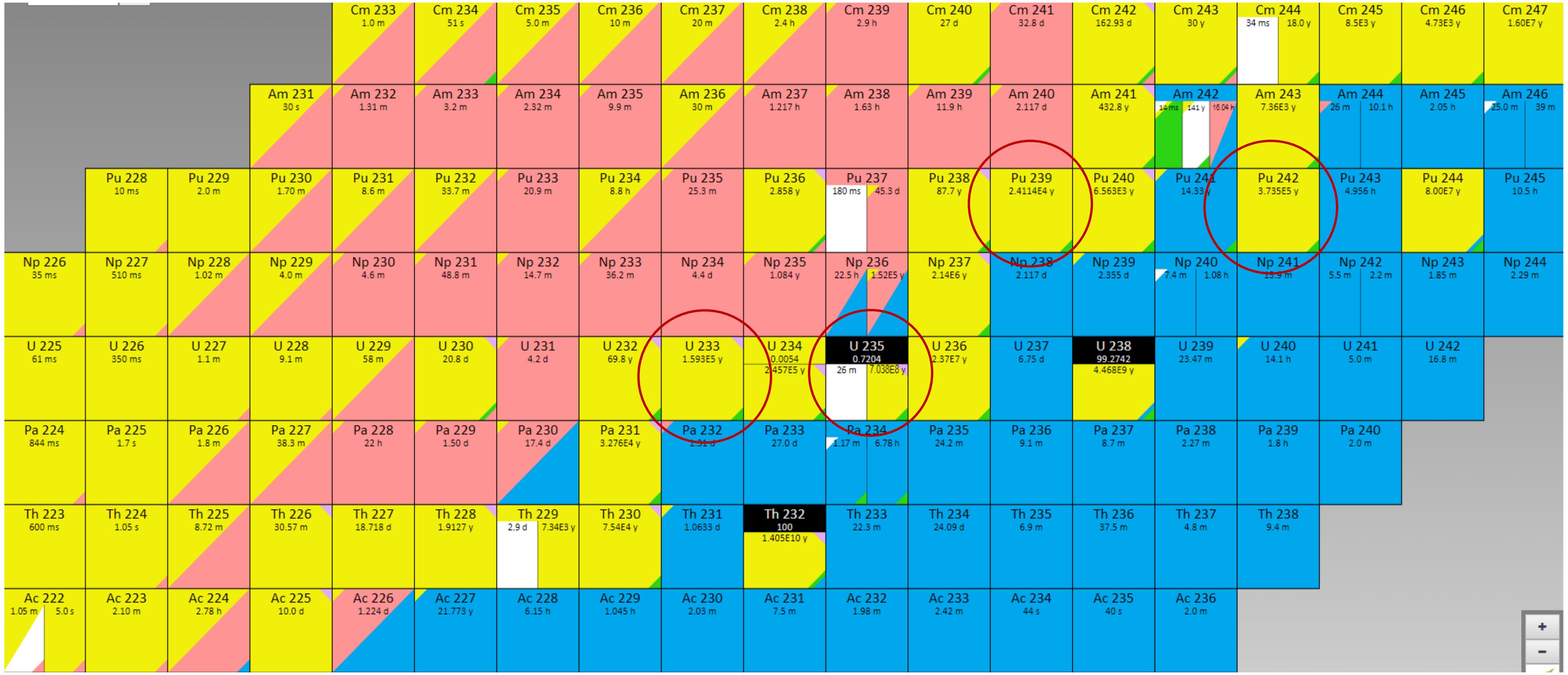
Overview

- U and Pu fissile isotopes
- History of safeguards
- Key legal elements of IAEA safeguards
- How the IAEA implements safeguards
- Examples of non-destructive measurements
- U enrichment
- Pu assay

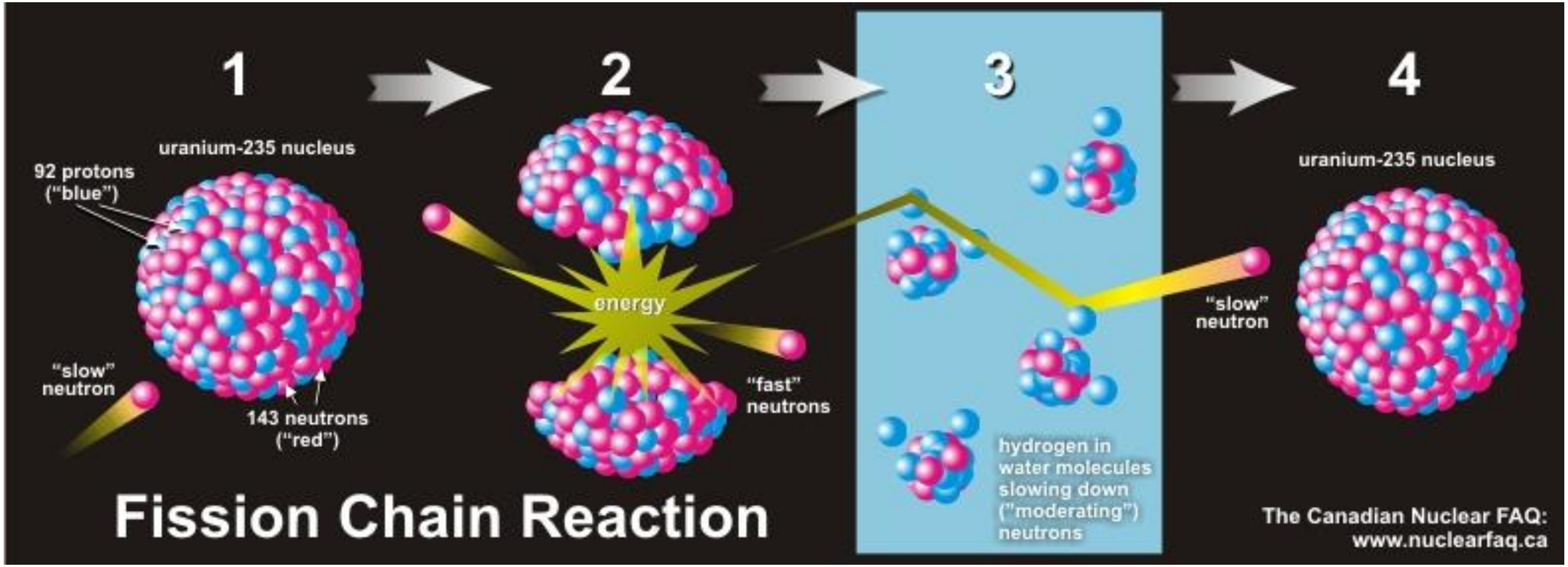
Actinides Pu and U



				Cm 233 1.0 m	Cm 234 51 s	Cm 235 5.0 m	Cm 236 10 m	Cm 237 20 m	Cm 238 2.4 h	Cm 239 2.9 h	Cm 240 27 d	Cm 241 32.8 d	Cm 242 162.93 d	Cm 243 30 y	Cm 244 34 ms 18.0 y	Cm 245 8.5E3 y	Cm 246 4.73E3 y	Cm 247 1.60E7 y
			Am 231 30 s	Am 232 1.31 m	Am 233 3.2 m	Am 234 2.32 m	Am 235 9.9 m	Am 236 30 m	Am 237 1.217 h	Am 238 1.63 h	Am 239 11.9 h	Am 240 2.117 d	Am 241 432.8 y	Am 242 14 ms 141 y 16.04 h	Am 243 7.36E3 y	Am 244 26 m 10.1 h	Am 245 2.05 h	Am 246 25.0 m 39 m
	Pu 228 10 ms	Pu 229 2.0 m	Pu 230 1.70 m	Pu 231 8.6 m	Pu 232 33.7 m	Pu 233 20.9 m	Pu 234 8.8 h	Pu 235 25.3 m	Pu 236 2.858 y	Pu 237 180 ms 45.3 d	Pu 238 87.7 y	Pu 239 2.4114E4 y	Pu 240 6.563E3 y	Pu 241 14.33 y	Pu 242 3.735E5 y	Pu 243 4.956 h	Pu 244 8.00E7 y	Pu 245 10.5 h
Np 226 35 ms	Np 227 510 ms	Np 228 1.02 m	Np 229 4.0 m	Np 230 4.6 m	Np 231 48.8 m	Np 232 14.7 m	Np 233 36.2 m	Np 234 4.4 d	Np 235 1.084 y	Np 236 22.5 h 1.52E5 y	Np 237 2.14E6 y	Np 238 2.117 d	Np 239 2.355 d	Np 240 7.4 m 1.08 h	Np 241 13.9 m	Np 242 5.5 m 2.2 m	Np 243 1.85 m	Np 244 2.29 m
U 225 61 ms	U 226 350 ms	U 227 1.1 m	U 228 9.1 m	U 229 58 m	U 230 20.8 d	U 231 4.2 d	U 232 69.8 y	U 233 1.593E5 y	U 234 0.0054 2.457E5 y	U 235 0.7204 26 m 7.038E8 y	U 236 2.37E7 y	U 237 6.75 d	U 238 99.2742 4.468E9 y	U 239 23.47 m	U 240 14.1 h	U 241 5.0 m	U 242 16.8 m	
Pa 224 844 ms	Pa 225 1.7 s	Pa 226 1.8 m	Pa 227 38.3 m	Pa 228 22 h	Pa 229 1.50 d	Pa 230 17.4 d	Pa 231 3.276E4 y	Pa 232 1.31 d	Pa 233 27.0 d	Pa 234 1.17 m 6.78 h	Pa 235 24.2 m	Pa 236 9.1 m	Pa 237 8.7 m	Pa 238 2.27 m	Pa 239 1.8 h	Pa 240 2.0 m		
Th 223 600 ms	Th 224 1.05 s	Th 225 8.72 m	Th 226 30.57 m	Th 227 18.718 d	Th 228 1.9127 y	Th 229 2.9 d 7.34E3 y	Th 230 7.54E4 y	Th 231 1.0633 d	Th 232 100 1.405E10 y	Th 233 22.3 m	Th 234 24.09 d	Th 235 6.9 m	Th 236 37.5 m	Th 237 4.8 m	Th 238 9.4 m			
Ac 222 1.05 m 5.0 s	Ac 223 2.10 m	Ac 224 2.78 h	Ac 225 10.0 d	Ac 226 1.224 d	Ac 227 21.773 y	Ac 228 6.15 h	Ac 229 1.045 h	Ac 230 2.03 m	Ac 231 7.5 m	Ac 232 1.98 m	Ac 233 2.42 m	Ac 234 44 s	Ac 235 40 s	Ac 236 2.0 m				

- Fissile isotopes ^{233}U, ^{235}U, ^{239}Pu and ^{241}Pu can sustain a nuclear chain reaction→ applications in nuclear weapons and nuclear reactors
- Uranium is naturally occurring: ^{234}U (0.0055 %), ^{235}U (0.72 %), ^{238}U (99.275 %)
- Plutonium is synthetically produced by uranium neutron capture.

Chain reaction



The Canadian Nuclear FAQ: www.nuclearfaq.ca

Chain reaction

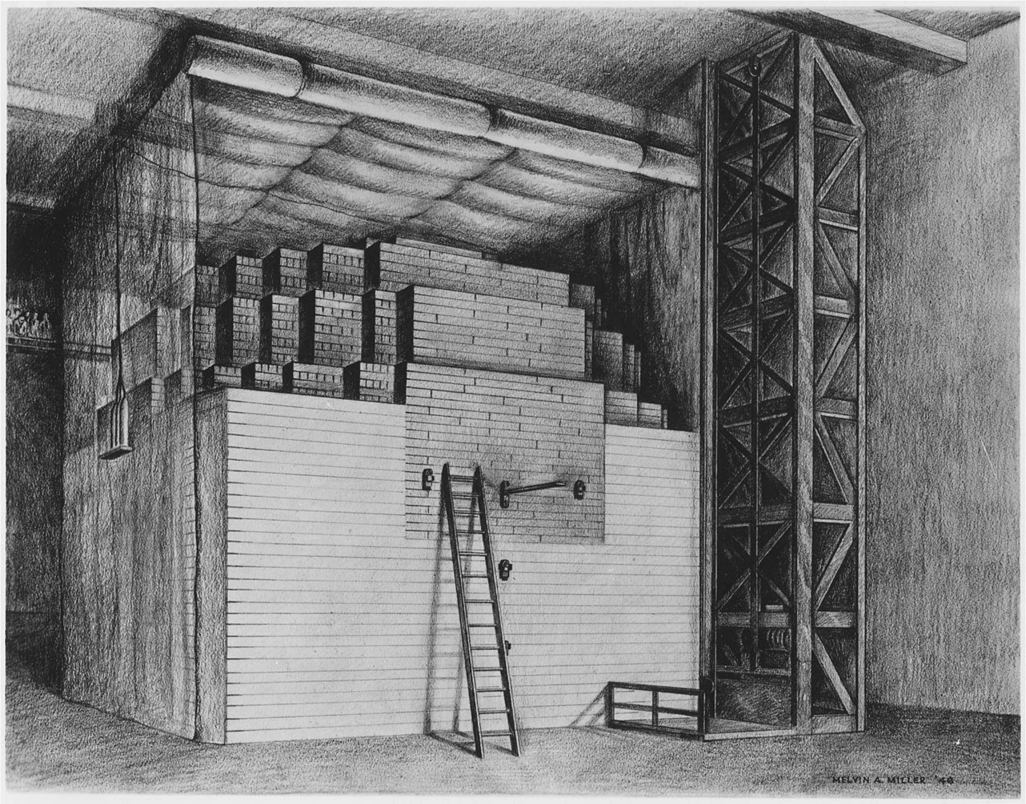
- Neutrons → induce next generation fissions
- Multiplication factor k-infinity = $\nu\, \Sigma_f / \Sigma_a$

  ν = number of neutrons per fission
  Σ_f = Fission cross-section
  Σ_a = Total absorption cross-section (including fission)
- Chain reaction: k-infinity > 1.0

History

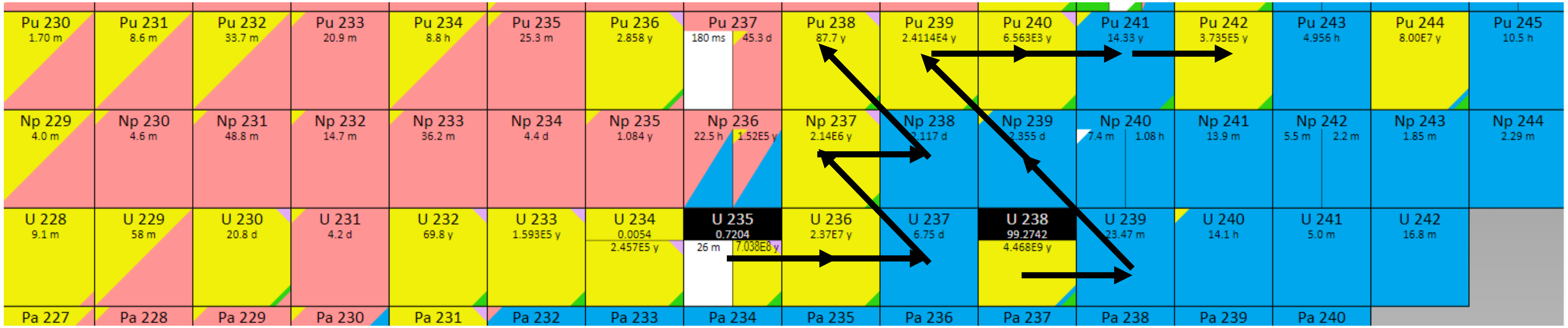
Chicago Pile (USA)

- 1942
- First controlled chain reaction
- No comprehensive nuclear data
- Poor calculational capability
- Graphite and uranium impurities
- Absorption in air
- >30 piles before success



Pu production

- In nuclear reactors from uranium via neutron capture.
- Several isotopes are bred.
- Extracted via chemical separation from fission products.



Pu 230 1.70 m	Pu 231 8.6 m	Pu 232 33.7 m	Pu 233 20.9 m	Pu 234 8.8 h	Pu 235 25.3 m	Pu 236 2.858 y	Pu 237 180 ms 45.3 d	Pu 238 87.7 y	Pu 239 2.4114E4 y	Pu 240 6.563E3 y	Pu 241 14.33 y	Pu 242 3.735E5 y	Pu 243 4.956 h	Pu 244 8.00E7 y	Pu 245 10.5 h
Np 229 4.0 m	Np 230 4.6 m	Np 231 48.8 m	Np 232 14.7 m	Np 233 36.2 m	Np 234 4.4 d	Np 235 1.084 y	Np 236 22.5 h 1.52E5 y	Np 237 2.14E6 y	Np 238 2.117 d	Np 239 2.355 d	Np 240 7.4 m 1.08 h	Np 241 13.9 m	Np 242 5.5 m 2.2 m	Np 243 1.85 m	Np 244 2.29 m
U 228 9.1 m	U 229 58 m	U 230 20.8 d	U 231 4.2 d	U 232 69.8 y	U 233 1.593E5 y	U 234 0.0054 2.457E5 y	U 235 0.7204 26 m 7.038E8 y	U 236 2.37E7 y	U 237 6.75 d	U 238 99.2742 4.468E9 y	U 239 23.47 m	U 240 14.1 h	U 241 5.0 m	U 242 16.8 m	
Pa 227	Pa 228	Pa 229	Pa 230	Pa 231	Pa 232	Pa 233	Pa 234	Pa 235	Pa 236	Pa 237	Pa 238	Pa 239	Pa 240		

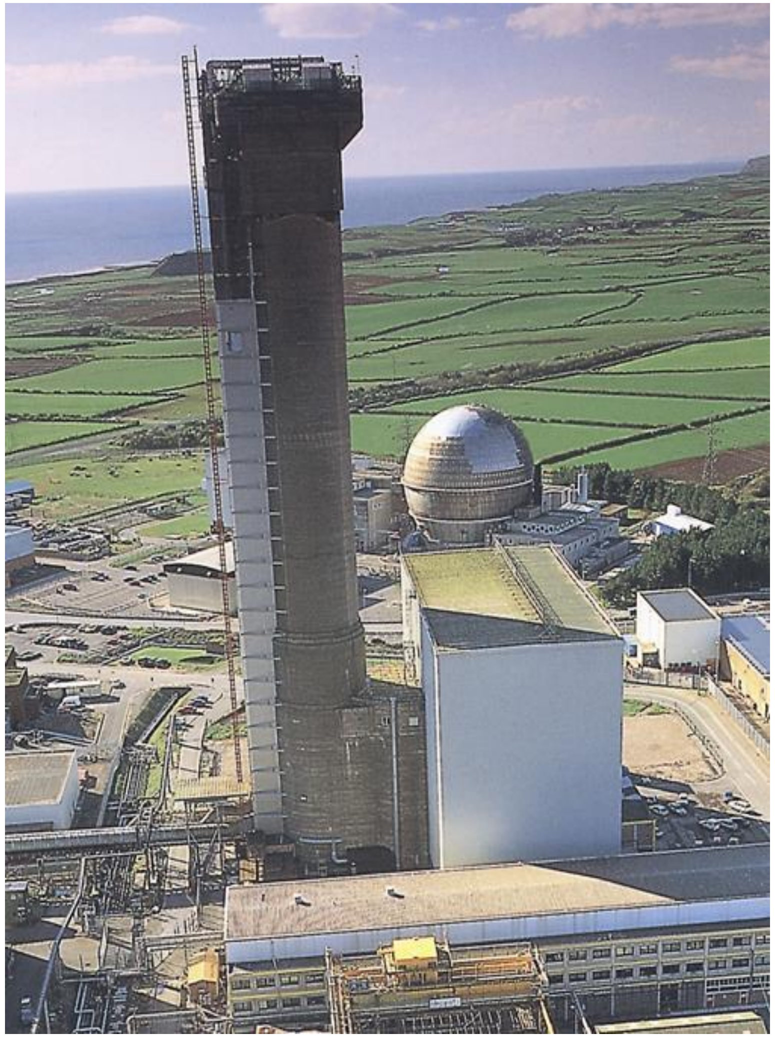
First reactors for Pu production

- Hanford reactor (USA)
  - Learnt from Chicago piles
  - Water-cooled, ~ 250 MW(th)
  - Xe-135 absorption – first seen after increasing power
  - Required additional fuelling

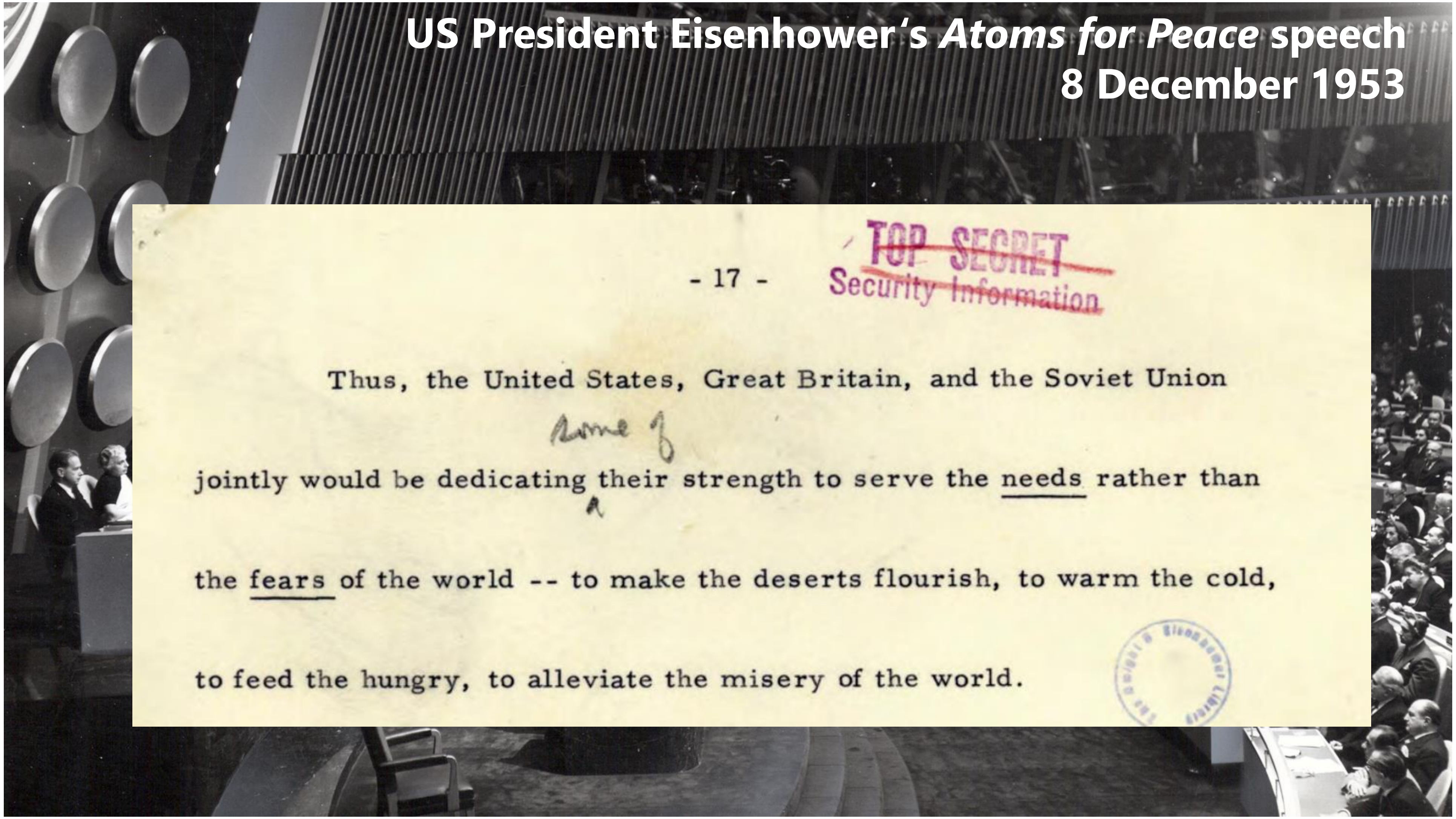
- Mayak reactor (USSR)
  - Produced components for the RSD-1 nuclear device, exploded in August 1949
  - Part of a complex that included: five Pu and five ^3H production reactors, several reprocessing plants, Pu metallurgy plant, radiochemical plant to separate weapons-grade plutonium

First reactors for Pu production

- Windscale piles (UK)
  - Fuelled with natural uranium metal
  - Graphite moderator
  - Air-cooled, ~180 MW(th)
  - Cooling air discharged through stack via filters
  - Uranium fire, extinguished by flooding core



History of safeguards



US President Eisenhower's *Atoms for Peace* speech
8 December 1953

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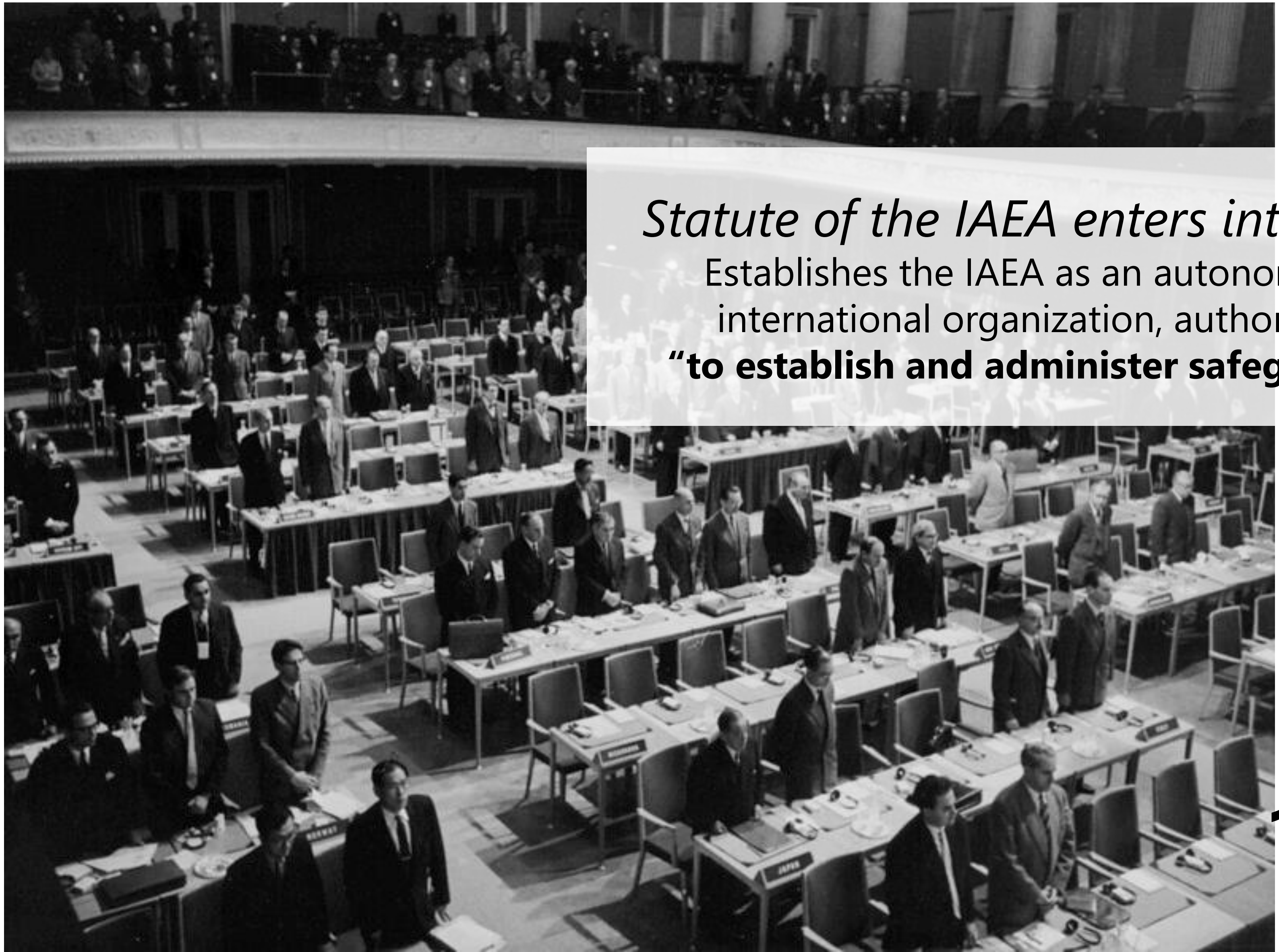
~~TOP SECRET~~
~~Security Information~~

Thus, the United States, Great Britain, and the Soviet Union jointly would be dedicating some of their strength to serve the needs rather than the fears of the world -- to make the deserts flourish, to warm the cold, to feed the hungry, to alleviate the misery of the world.

History of safeguards



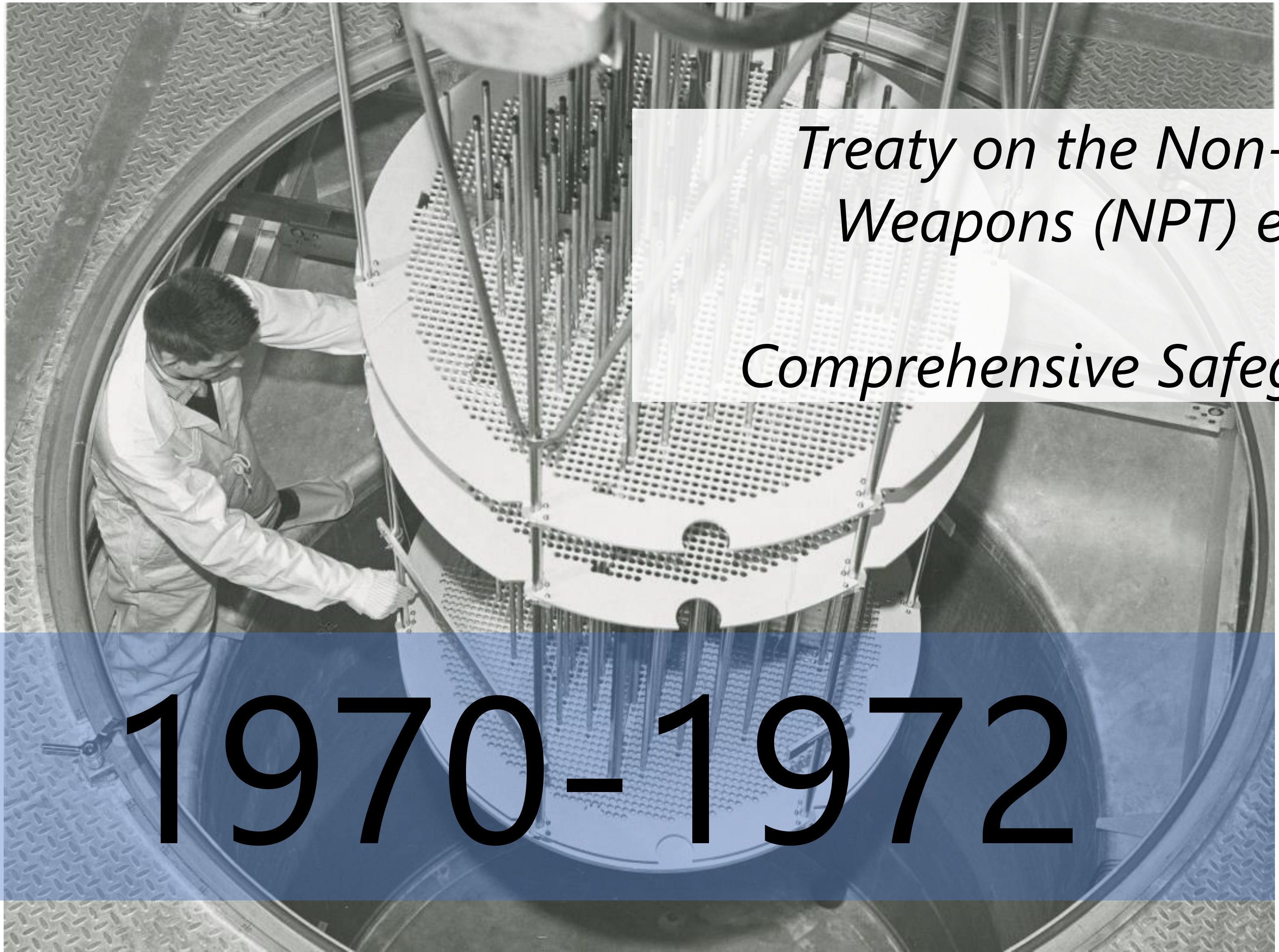
Statute of the IAEA enters into force

Establishes the IAEA as an autonomous international organization, authorized **“to establish and administer safeguards”**

1957

History of safeguards

Safeguards



Treaty on the Non-Proliferation of Nuclear Weapons (NPT) enters into force (1970)

Comprehensive Safeguards Agreements (1972)

1970-1972

Key legal elements of IAEA safeguards

Three types of safeguards agreements

Comprehensive Safeguards Agreement (CSA)

Voluntary offer agreement (VOA)

Item-specific agreement (INFCIRC/66)

+ADDITIONAL PROTOCOL: improve the Agency's capability to detect undeclared nuclear material and activities

Nuclear fuel cycle

Manufacturers

R&D

Without NM

R&D

With NM

Mines

UOC

Conversion

Enrichment

Fuel

Reactors

Wet

Storage

Reprocessing

Geological disposal

Comprehensive Safeguards Agreement

Additional Protocol

How the IAEA implements safeguards

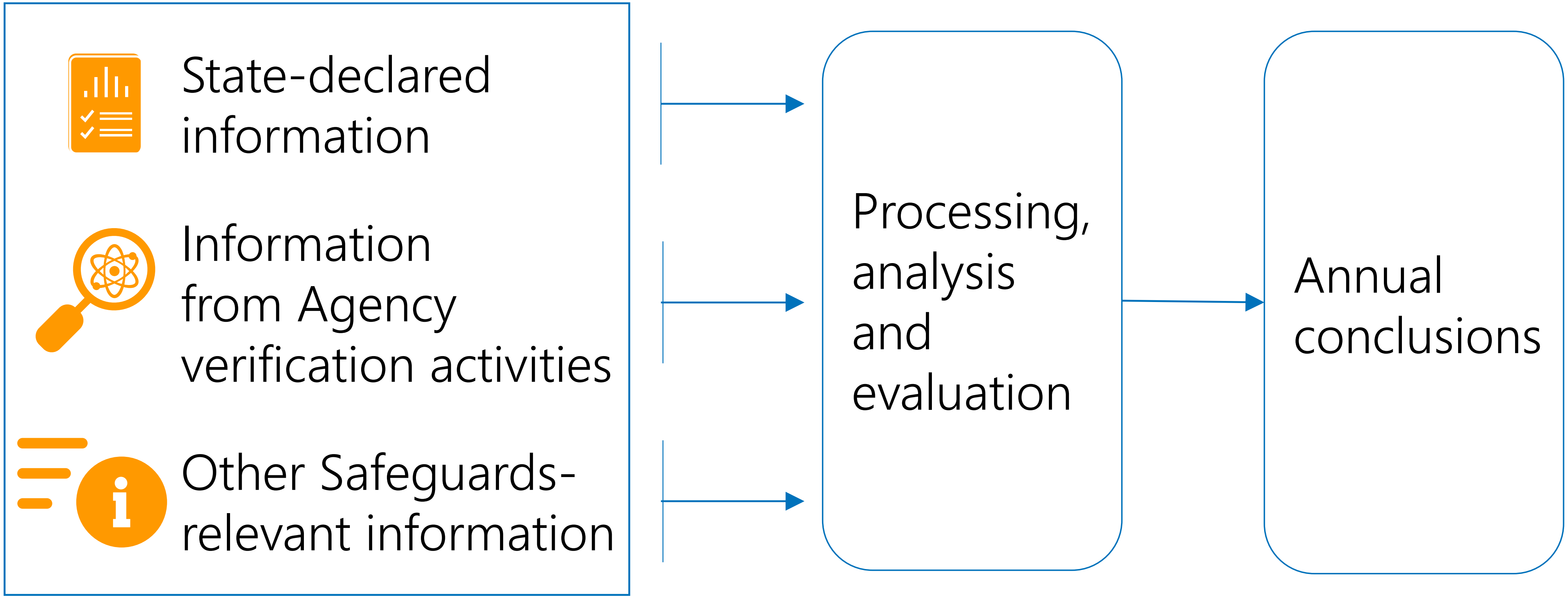
Safeguards technical objectives

- Correctness of state-declared material and activities

- Completeness of state-declared material and activities

- Assurances as to the absence of undeclared nuclear material and activities in a State.

Collecting and evaluating information



State-declared information

Information from Agency verification activities

Other Safeguards-relevant information

Processing, analysis and evaluation

Annual conclusions

Verification measures

- Nuclear material accountancy
  - Counting
  - Weighing
  - Volume determination

- Containment and surveillance
  - Tamper-proof seals
  - Cameras installed in facilities

- Material flow monitoring/verification
- Destructive assay
- non-destructive assay
  - Gross defect: all or most of the nuclear material is missing
  - Partial defect: a fraction of the nuclear material is still present
  - Small bias defect: a small fraction of the declared amount is missing

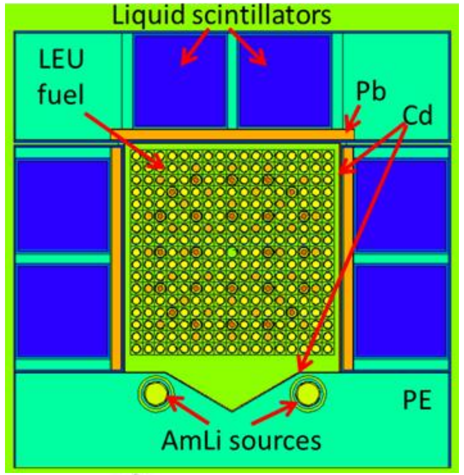
Fresh fuel verification

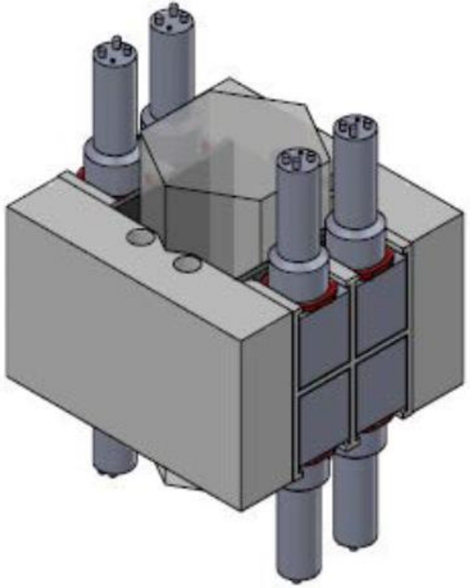
- Enrichment and active length verification:
  - Portable spectrometer HM-5

- Comparison of verified vs. declared fuel IDs
- Core/containment sealing

Fresh fuel verification

- Spontaneous fission yield of U isotopes is quite low→ passive measurements are impractical
- Induced-fission neutrons from ^{235}U using active interrogation
    - AmLi source
    - Neutron below ^{238}U fission threshold
- Neutron detection system heavily impacted by the presence of unverifiable burnable poison in fresh fuel
- Organic liquid scintillators for fast neutron detection
- Pulse shape discrimination of neutron/gamma
- Determination of ^{235}U linear mass





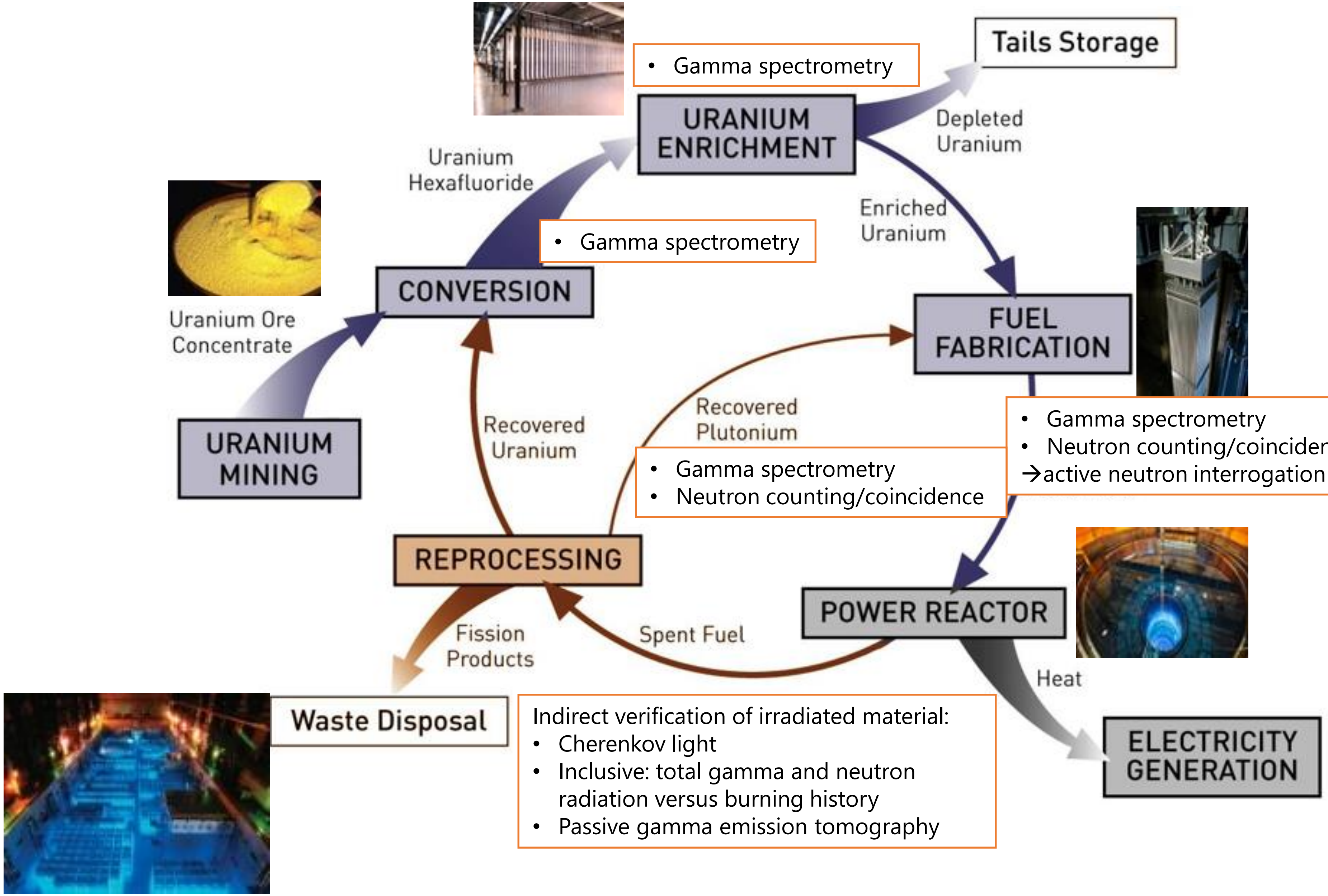
Probability of detection of diversion

- PWR 17x17, ca. 3% init. enrich., ca. 55-60 GWd/tU of BU,
  - ca. 4 kg of U-235
  - ca. 3 kg of Pu-239

- 1 SQ of U-235 == 25 kg → 12-13 assemblies (large scale diversion, 50%)
  → ca. 60 assemblies (small scale diversion, 10%)

- 1 SQ of Pu-239 == 8 kg → ca. 5 assemblies (large scale diversion, 50%)
  → 30 assemblies (small scale diversion, 10%)

Non-destructive assay verification



- Gamma spectrometry

- Gamma spectrometry

- Gamma spectrometry
- Neutron counting/coincidence

→active neutron interrogation

- Gamma spectrometry
- Neutron counting/coincidence

Indirect verification of irradiated material:

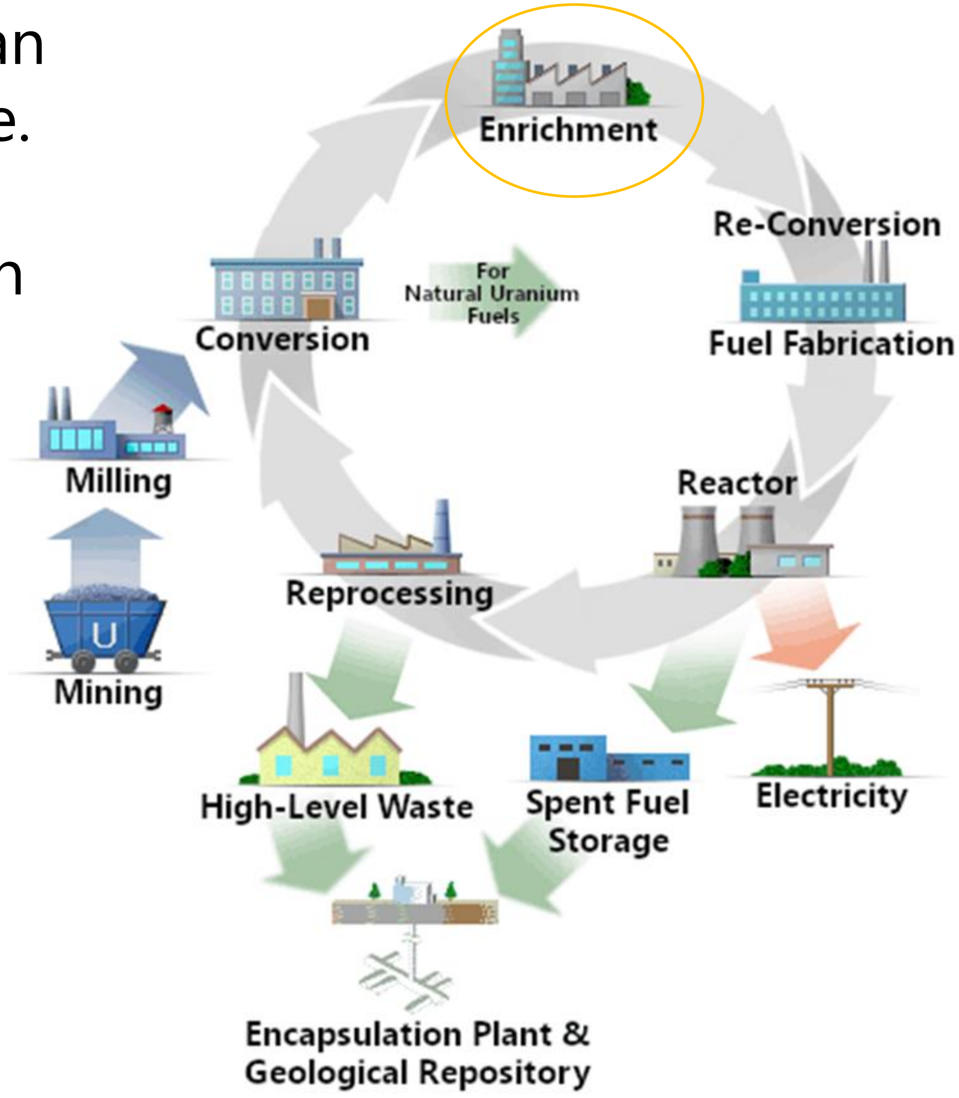
- Cherenkov light
- Inclusive: total gamma and neutron radiation versus burning history
- Passive gamma emission tomography

Example of non-destructive assay verification:

U enrichment

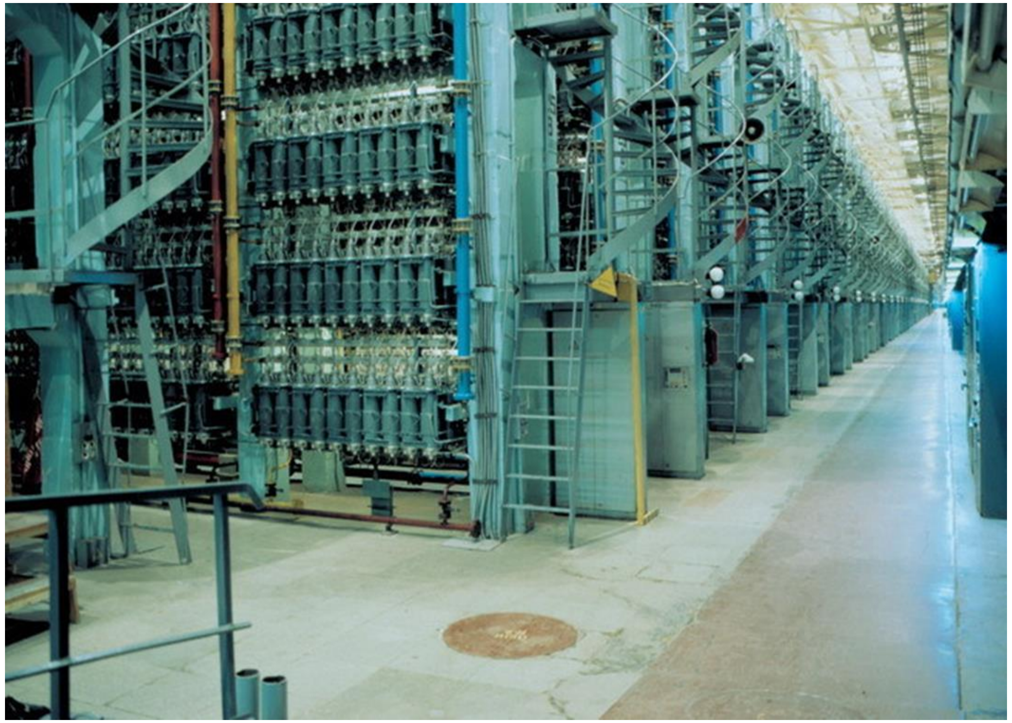
Uranium enrichment

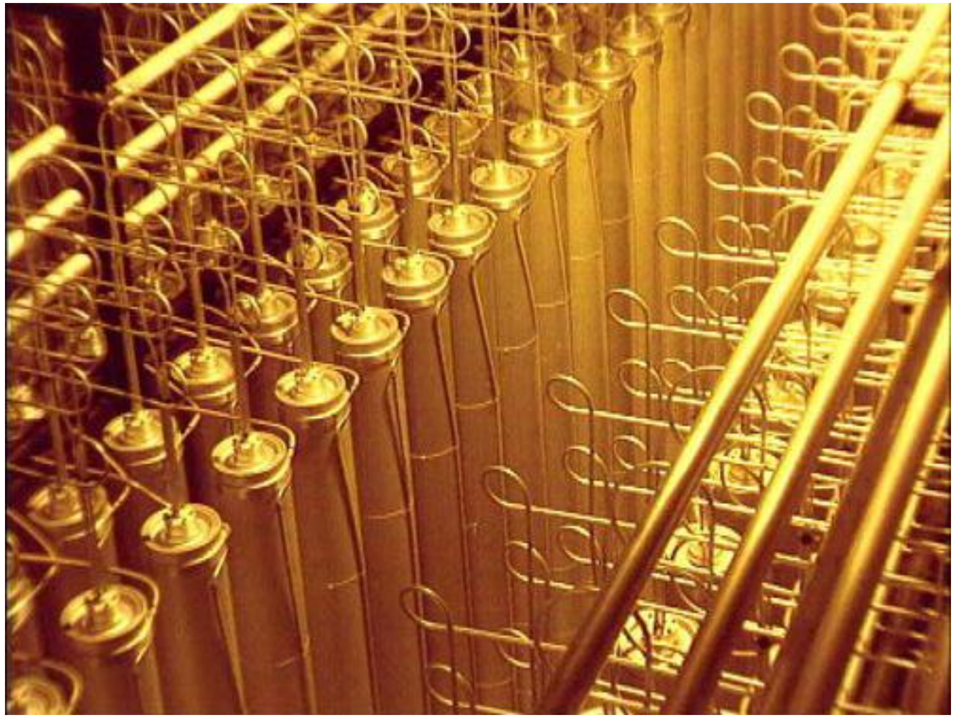
- Most nuclear reactors use uranium fuel with an increased concentration of the U-235 isotope.
- The proportion of the U-235 isotope has been raised from the natural level of 0.711% to around 3.5–5%.
- The gas centrifuge is the most common enrichment technology. It uses UF_6 as the process material because of its unique properties.
- The same process can be used to produce higher enrichment (≥20% U-235).



UF$_6$ centrifuges

IAEA Safeguards





Gaseous UF_6 enrichment monitor

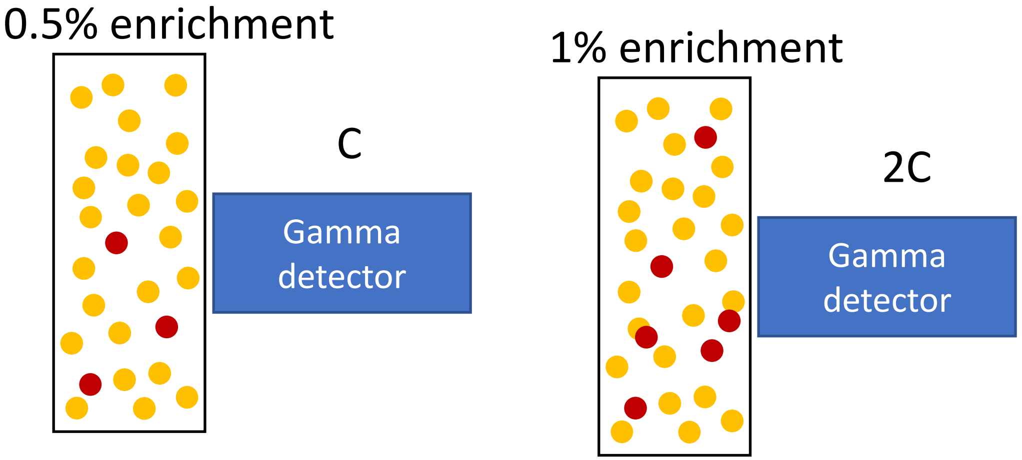
- To address the potential “misuse” of an enrichment facility

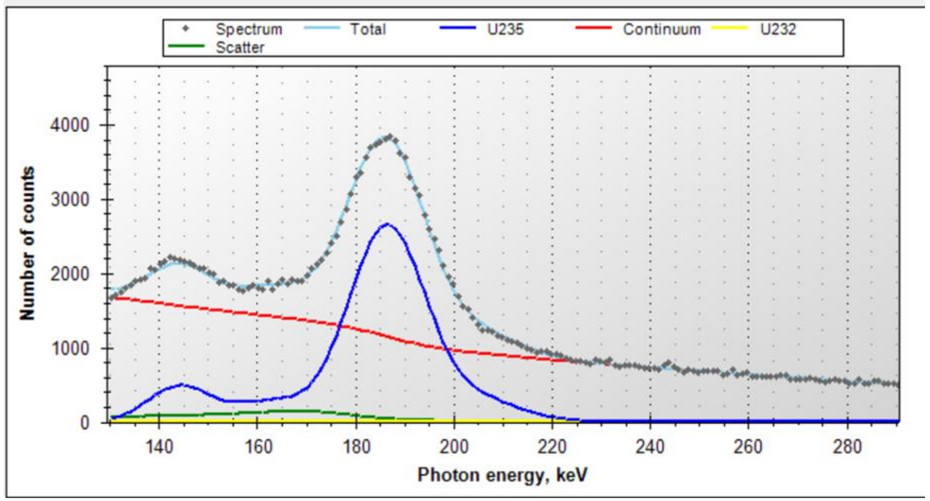
$$\text{Enrichment} = \frac{Density\ of\ U{-}235}{Density\ of\ U}$$

- Measurement of:
  - – U-235 Gamma spectrum
  - – Temperature
  - – Pressure
- Unattended mode of operation
  - permanently operating systems
  - No inspector presence

Gaseous UF_6 enrichment monitor

- The density of U-235 is calculated from the U-235 gamma spectrum:



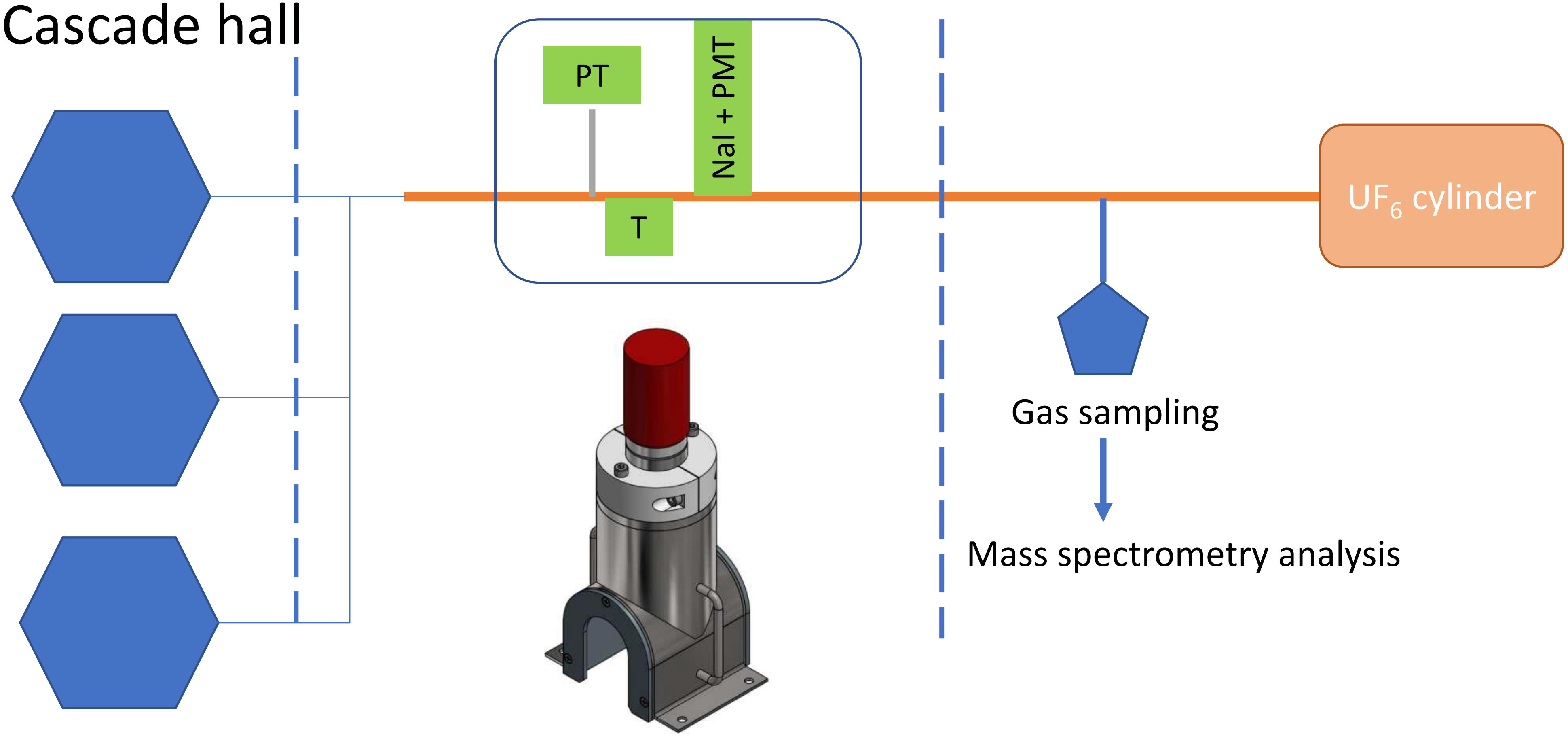


$$\rho_{U-235} = const \ * \ {}^{235}U_{gas} count\, rate$$

- Uranium density is calculated from the ideal gas law:

$$\rho_{U\ gas} \propto \frac{P}{T}$$

Online enrichment monitor



Cascade hall

PT

NaI + PMT

T

UF$_6$ cylinder

Gas sampling

Mass spectrometry analysis

Example of non-destructive assay verification:

Pu quantification

Reprocessing

Civil reactor

Spent fuel
reprocessing

Separated Pu

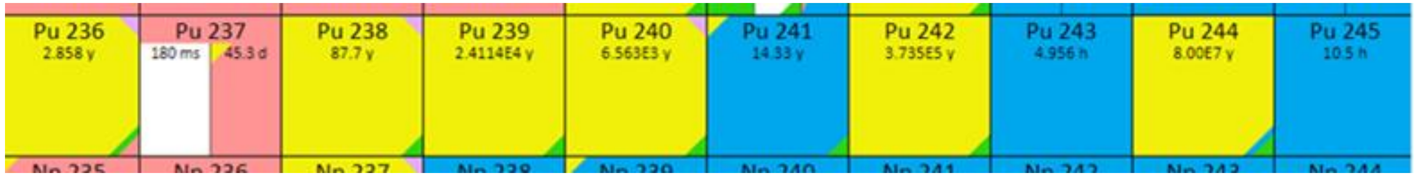
- Items can be bulky, e.g., cans of several kg of PuO_2
- For the human body it is chemically toxic as some other heavy metals like lead and mercury.
- Old separated Pu contains Am-241

Plutonium non-destructive assay

- Non destructive assay of Pu is only possible on reprocessed material (not irradiated)
  - Metal Pu
  - Oxide
  - Mixed oxide

- Gamma spectrometry of ^{239}Pu ($^{239}Pu \rightarrow {}^{235}U^* + \alpha$) is very challenging:
  - Major γ emission at 129.3 keV and 413.7 keV
  - Complex decay scheme
  - γ self absorption by Pu

Spontaneous fission neutrons



Pu 236	Pu 237	Pu 238	Pu 239	Pu 240	Pu 241	Pu 242	Pu 243	Pu 244	Pu 245
2.858 y	180 ms 45.3 d	87.7 y	2.4114E4 y	6.563E3 y	14.33 y	3.735E5 y	4.956 h	8.00E7 y	10.5 h

- Pu isotopes: Characterized by large SF branching ratio → strong neutron emission → correlated
- Neutrons: penetrating radiation compared to gamma
  - Can probe the entire volume of the item
  - Not easily shielded
- Neutron production rates around 10^5 n/s per kg of Pu (spontaneous fission)
  - Pu-239 neutron emission is very small compared to other even-even isotopes.

Other sources of neutrons: (α,n)

- Pu isotopes: Characterized by large α-decay ratio
- α particles can produce neutrons through (α,n) reactions:

$$\alpha + {}^{18}O \rightarrow {}^{21}Ne + n$$

$$\alpha + {}^{19}F \rightarrow {}^{22}Na + n$$

- Uncorrelated neutrons
- Makes quantification of Pu mass via total neutron counting quite complex

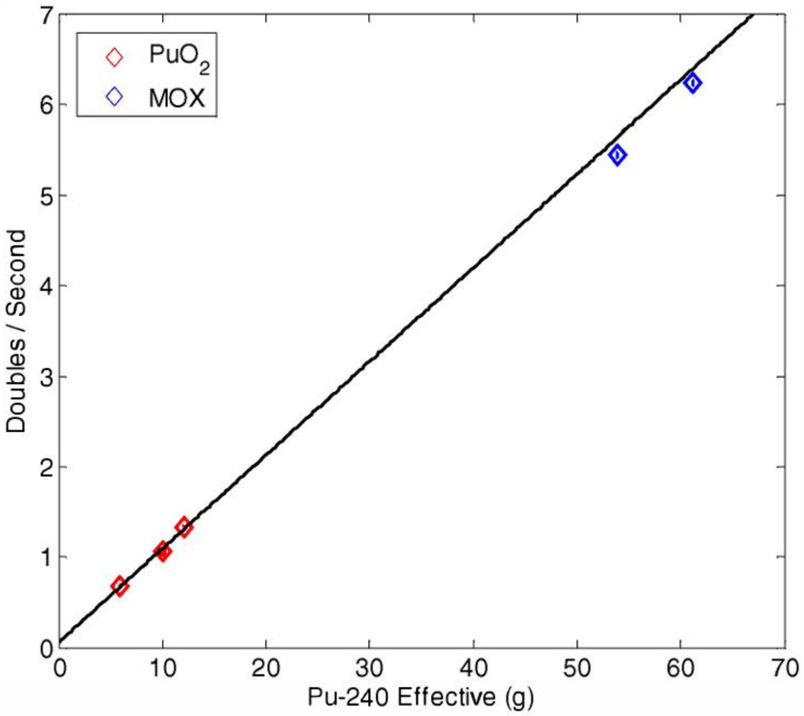
Neutron coincidence measurements

- Coincidence measurements are cleaner compared to total neutron counting
- Unaffected by the chemical composition of the material that yields to single neutrons from (α,n) reactions
- Sensitive only to ^{238}Pu, ^{240}Pu and ^{242}Pu

Pu mass determination

- Coincidence rates: can be expressed as ^{240}Pu effective mass

$$^{240}Pu_{eff} = 2.52\,^{238}Pu + \,^{240}Pu + 1.68\,^{242}Pu$$



$$^{Total}Pu = \,^{240}Pu_{eff}/(2.52f_{238} + f_{240} + 1.68f_{242})$$

- Using isotopic composition, the total quantity of fissile ^{239}Pu can be determined

Other sources of neutrons: multiplication

- Neutron production rates can be enhanced due to induced fission rates.
- Multiplication of a sample depends on its:
  - Chemical form
  - Mass
  - Shape
- 10 g of Pu metal shows 5% enhancement of double coincidences.

- Corrections to the coincidence rate need to be applied

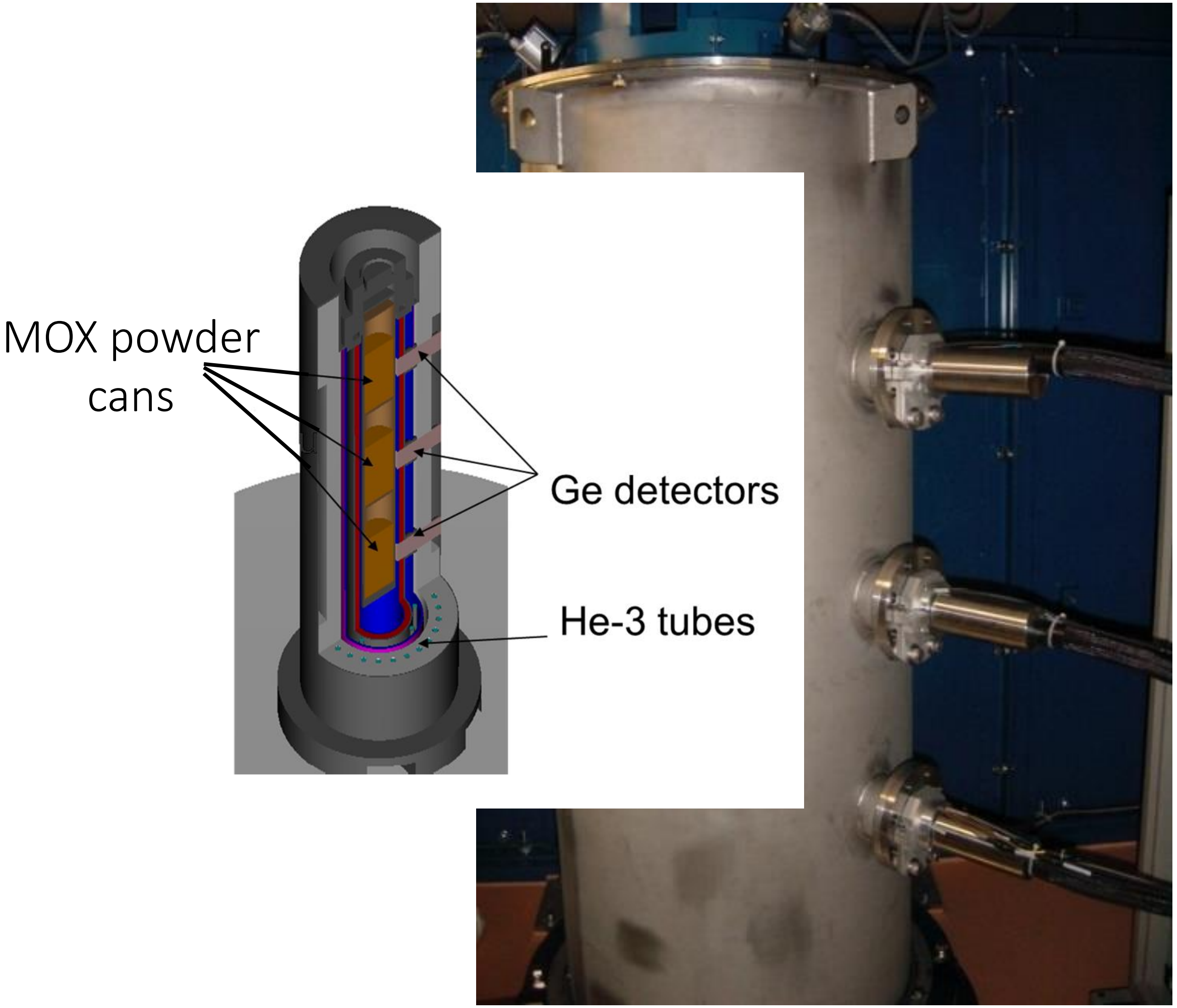
Pu mass determination

- If single, double and triples rate are measured, the three sources of neutrons can be precisely accounted for.

- Otherwise modeling of the source term is required for multiplication correction

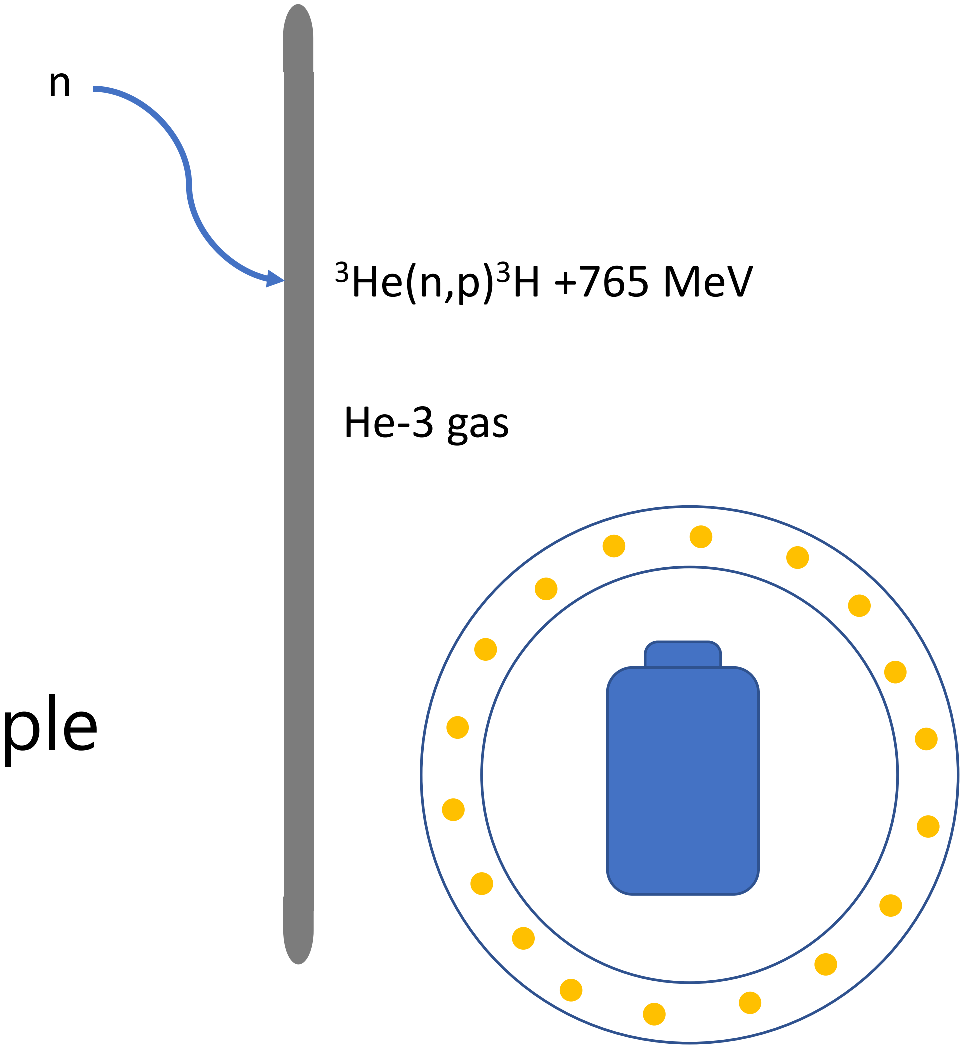
Plutonium powder assay

- 30 He-3 tubes
  - 24 outer ring
  - 6 inner ring
- 3 HPGe detectors
  - Positioned in front of each can of MOX
- 1 digital camera
  - To provide canister IDs
- 1 load cell



Passive neutron coincidence counter

- Detection in He-3 gas-filled proportional counters
- Thermalize neutrons in polyethylene
- Coincidence time on the order of 50–60 μs: delayed neutron coincidences
- Maximize detection efficiency to increase triple coincidence count rate (40–60%)



Summary

- Safeguards ensures that nuclear material and activities are conducted for peaceful purpose only
- IAEA has the right and obligation to perform safeguards
- In order to apply safeguards measures, inspectors need to be able to verify the operator's declaration for correctness and completeness.
- A number of non-destructive-assay techniques may be used to verify operator declarations and confirm the absence of undeclared activities.
- The anticipated rapid growth of nuclear activities in the years to come will require new methods of maintaining optimum cost/ effectiveness in safeguards work.

Thank you!

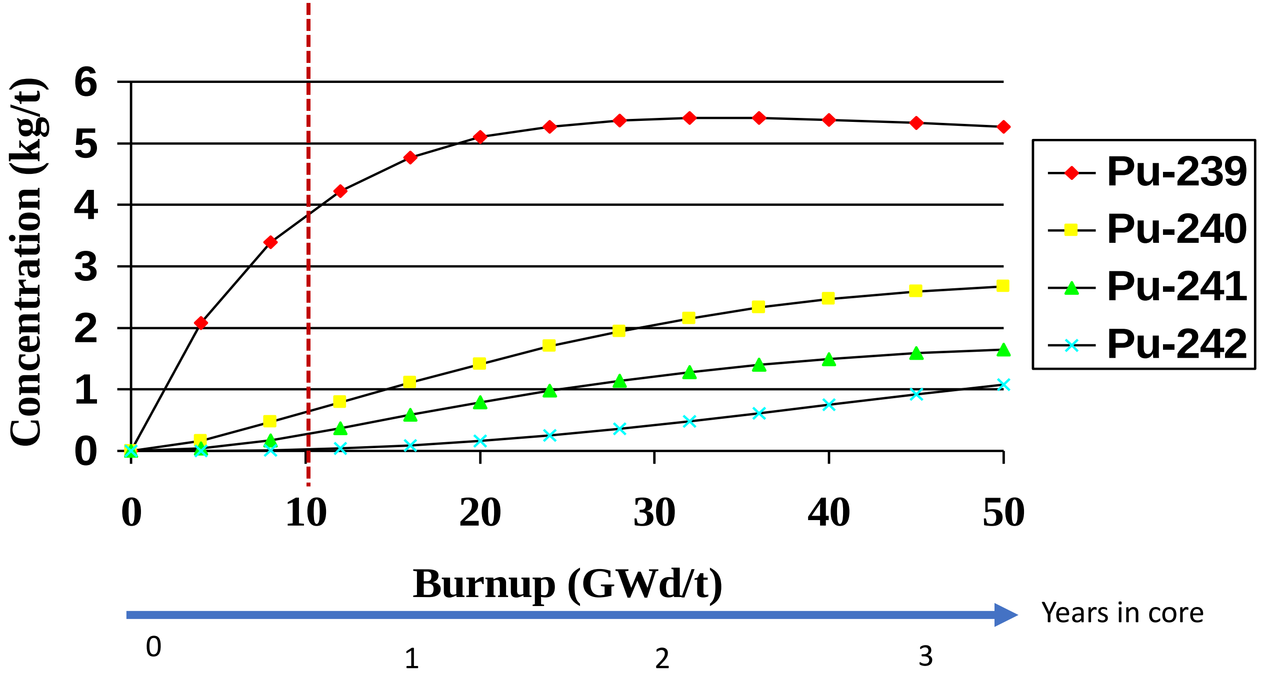
IAEA Safeguards

Spares

Burnup →Pu isotopes

- High burnup:
  - 53% Pu-239
  - 25% Pu-240
  - 15% Pu-241
  - 5% Pu-242
  - 2% of Pu-238
- Low burnup:
  - 89.7% Pu-239
  - 9.6% Pu-240
  - 0.6% Pu-241
  - 0.1% Pu-242
  - 0.02% Pu-238

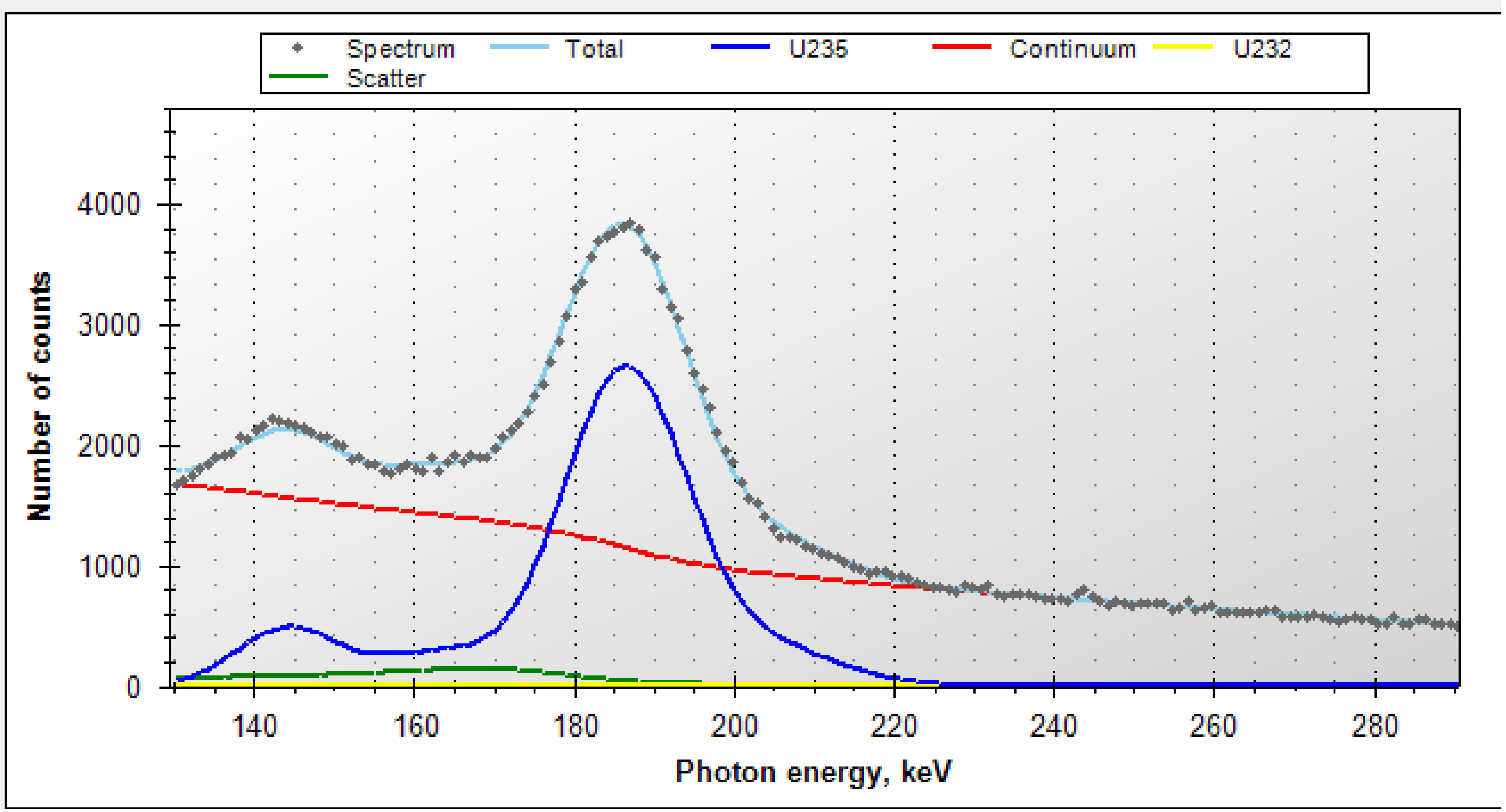
Build-up of Pu Isotopes with Burnup (PWR)

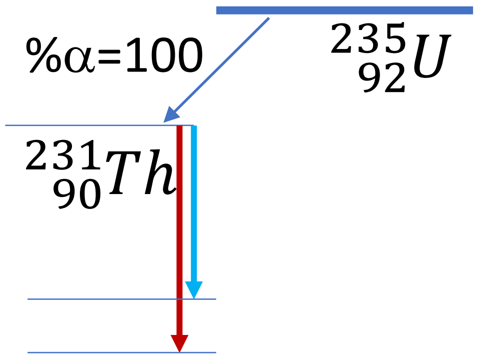


- Weapons-grade Pu → larger than 93% of Pu-239
- Reactor-grade Pu

Online enrichment monitor

- Low resolution spectroscopy (NaI)

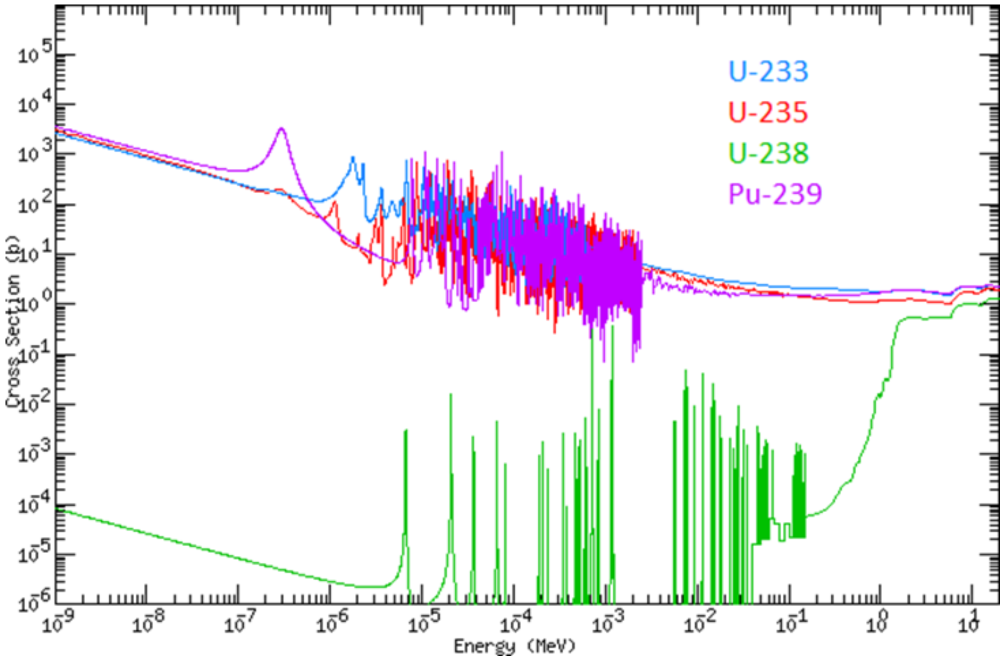




Fission cross-sections

- Fission
  - High at thermal neutron energies
  - Low at high neutron energies
  - Favoured in the low-energy neutron energy spectrum

- % ^{235}U and ^{239}Pu
  - High % = super-critical assembly in a fast spectrum; basis of fission weapons and fast reactors
  - Lower % = with a moderator to slow down the neutrons; basis of thermal reactors



Spontaneous fission neutrons

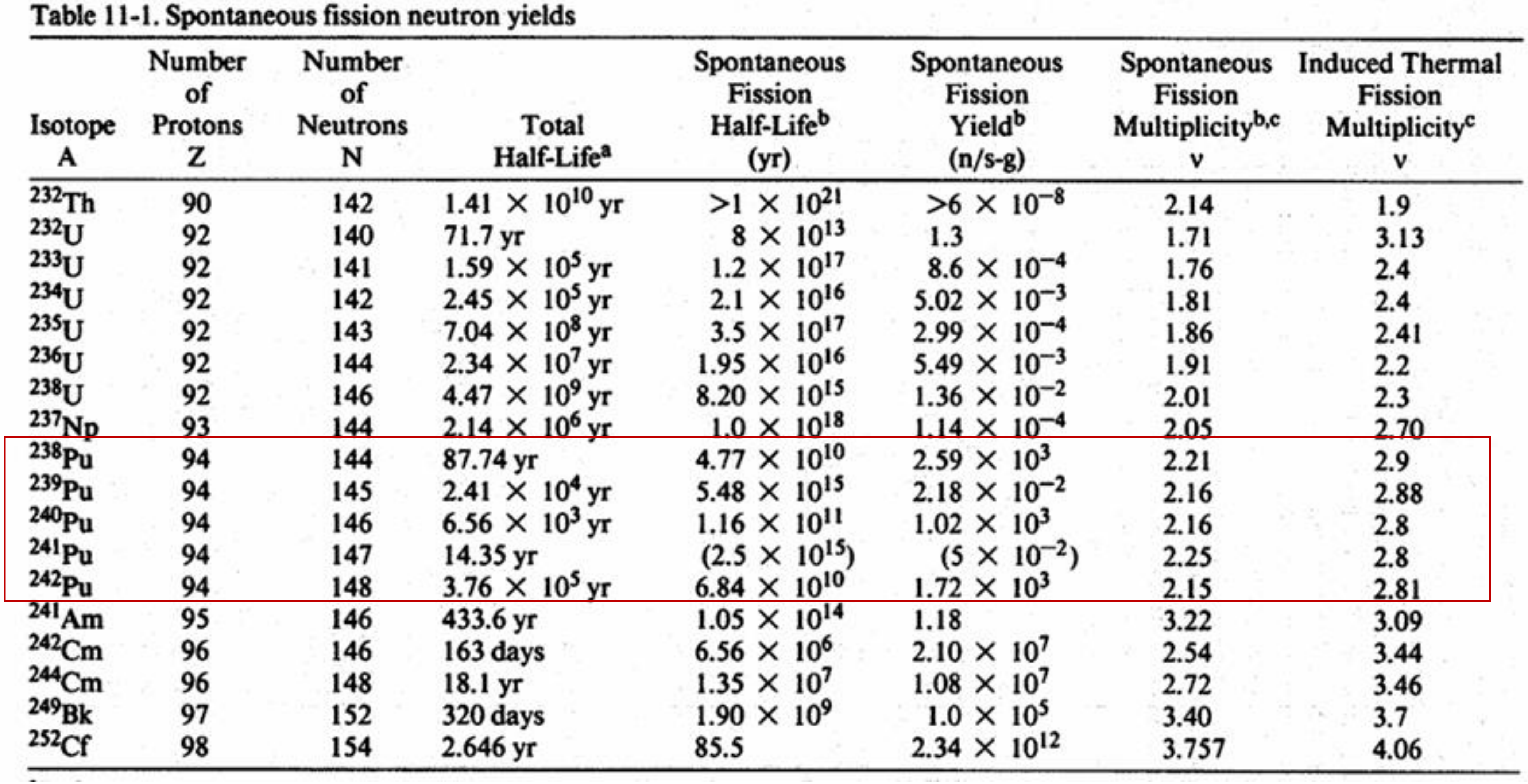


Table 11-1. Spontaneous fission neutron yields

Isotope A	Number of Protons Z	Number of Neutrons N	Total Half-Life[a]	Spontaneous Fission Half-Life[b] (yr)	Spontaneous Fission Yield[b] (n/s-g)	Spontaneous Fission Multiplicity[b,c] ν	Induced Thermal Fission Multiplicity[c] ν
^{232}Th	90	142	1.41×10^{10} yr	$>1 \times 10^{21}$	$>6 \times 10^{-8}$	2.14	1.9
^{232}U	92	140	71.7 yr	8×10^{13}	1.3	1.71	3.13
^{233}U	92	141	1.59×10^{5} yr	1.2×10^{17}	8.6×10^{-4}	1.76	2.4
^{234}U	92	142	2.45×10^{5} yr	2.1×10^{16}	5.02×10^{-3}	1.81	2.4
^{235}U	92	143	7.04×10^{8} yr	3.5×10^{17}	2.99×10^{-4}	1.86	2.41
^{236}U	92	144	2.34×10^{7} yr	1.95×10^{16}	5.49×10^{-3}	1.91	2.2
^{238}U	92	146	4.47×10^{9} yr	8.20×10^{15}	1.36×10^{-2}	2.01	2.3
^{237}Np	93	144	2.14×10^{6} yr	1.0×10^{18}	1.14×10^{-4}	2.05	2.70
^{238}Pu	94	144	87.74 yr	4.77×10^{10}	2.59×10^{3}	2.21	2.9
^{239}Pu	94	145	2.41×10^{4} yr	5.48×10^{15}	2.18×10^{-2}	2.16	2.88
^{240}Pu	94	146	6.56×10^{3} yr	1.16×10^{11}	1.02×10^{3}	2.16	2.8
^{241}Pu	94	147	14.35 yr	(2.5×10^{15})	(5×10^{-2})	2.25	2.8
^{242}Pu	94	148	3.76×10^{5} yr	6.84×10^{10}	1.72×10^{3}	2.15	2.81
^{241}Am	95	146	433.6 yr	1.05×10^{14}	1.18	3.22	3.09
^{242}Cm	96	146	163 days	6.56×10^{6}	2.10×10^{7}	2.54	3.44
^{244}Cm	96	148	18.1 yr	1.35×10^{7}	1.08×10^{7}	2.72	3.46
^{249}Bk	97	152	320 days	1.90×10^{9}	1.0×10^{5}	3.40	3.7
^{252}Cf	98	154	2.646 yr	85.5	2.34×10^{12}	3.757	4.06

Pu spectrometry

- Accurate measurement of Pu isotopic composition is required to interpret the results of the neutron coincidence measurements.
- Complex gamma ray spectrum requires high resolution gamma spectrometry with HPGe.

Pu spectrum with HPGe

IAEA Safeguards