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Title: Neutron Based Non-Destructive Assay (NDA) Measurement Systems for Safeguard

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OFFICE OF NONPROLIFERATION AND ARMS CONTROL (NPAC)

National Nuclear Security Administration

Neutron Based Non-destructive Assay (NDA) Measurement Systems for Safeguard

Fundamentals of Non-Destructive Assay for International Safeguards

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SAFEGUARD NUCLEAR MATERIALS TO PREVENT THEIR DIVERSION OR THEFT

CONTROL THE SPREAD OF WMD-RELATED MATERIAL, EQUIPMENT AND TECHNOLOGY

NEGOTIATE, MONITOR AND VERIFY COMPLIANCE WITH INTERNATIONAL NONPROLIFERATION AND ARMS CONTROL TREATIES AND AGREEMENTS

DEVELOP PROGRAMS AND STRATEGIES TO ADDRESS EMERGING NONPROLIFERATION AND ARMS CONTROL THREATS AND CHALLENGES

Terminal Learning Objectives

- Terminal Learning Objectives
  - Introduce the assay methods for plutonium measurements using the HLNC.
  - Introduce the assay method for bulk uranium measurements using the AWCC.
  - Introduce the assay method for fuel assembly measurements using the UNCL.

Enabling Learning Objectives

- Enabling Learning Objectives:
  - Review the processes that generate neutrons
  - Describe the concept of 240Pueff mass
  - Describe the design of the HLNC
  - Illustrate the passive calibration curve and known alpha analysis methods
  - Describe the design and operation modes of the AWCC
  - Show the active calibration curve analysis methods
  - Describe the design and operation principles of the UNCL
  - Discuss the analysis method for assay of fuel assemblies

Neutron Origins and Signatures - Summary

	TOTALS OR SINGLES COUNTING	COINCIDENCE OR DOUBLES COUNTING
PASSIVE ASSAY (for Pu)	• Spontaneous fission • Induced fission • (α,n)	• Spontaneous fission • Induced fission
ACTIVE ASSAY Interrogate with external neutron source (for U)	• Induced fission • (α,n) • Spontaneous fission ↑ Small	• Induced fission • Spontaneous fission ↑ Small

PASSIVE MEASUREMENTS (Pu)

Plutonium Mass and $^{240}Pu_{eff}$ mass

Most spontaneous fission in Pu is from ^{240}Pu, so we work in terms of $^{240}Pu_{eff}$

To determine the total Pu mass from the $^{240}Pu_{eff}$ mass returned from neutron assay, the item isotopic values need to be known

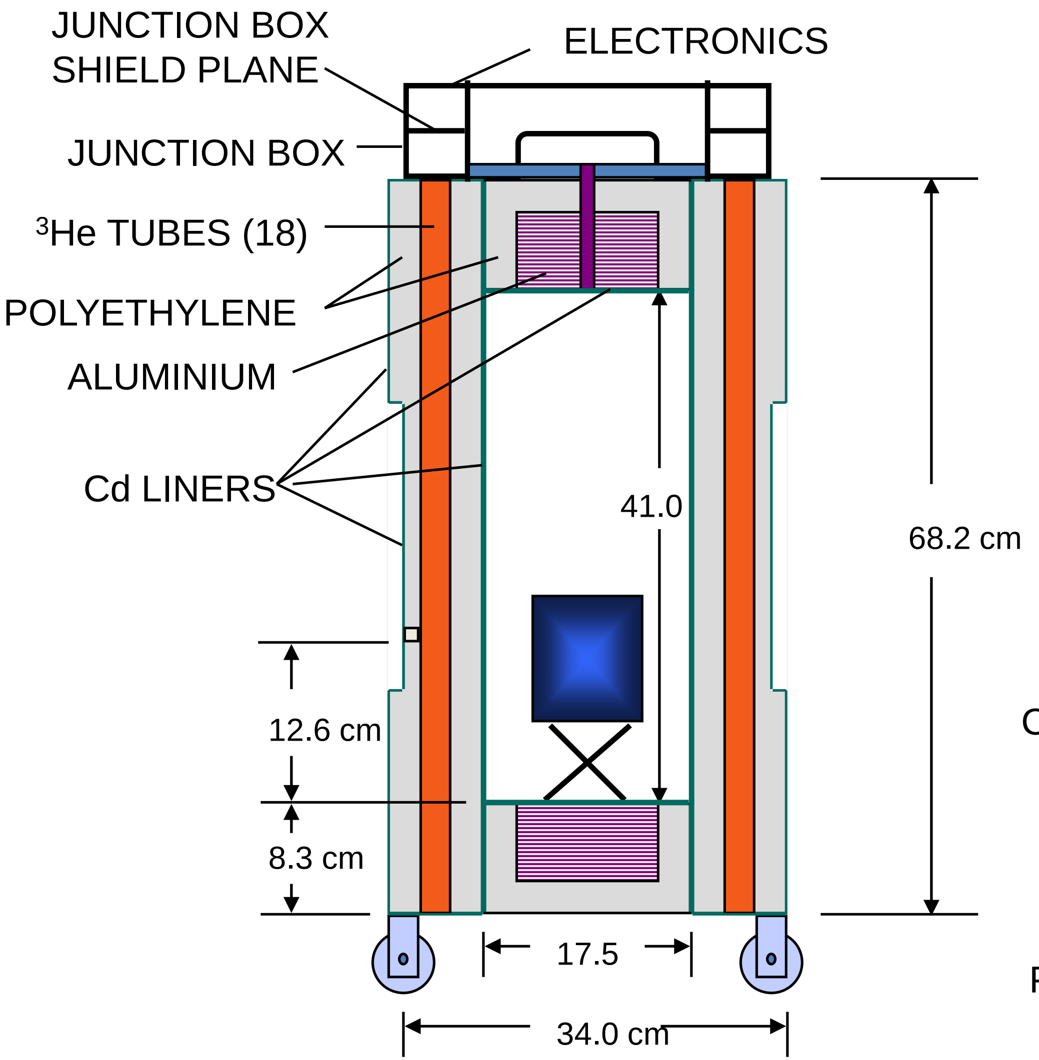
Example: 200g $^{240}Pu_{eff}$ with ^{238}Pu =2%, ^{240}Pu=24%, ^{242}Pu=6%

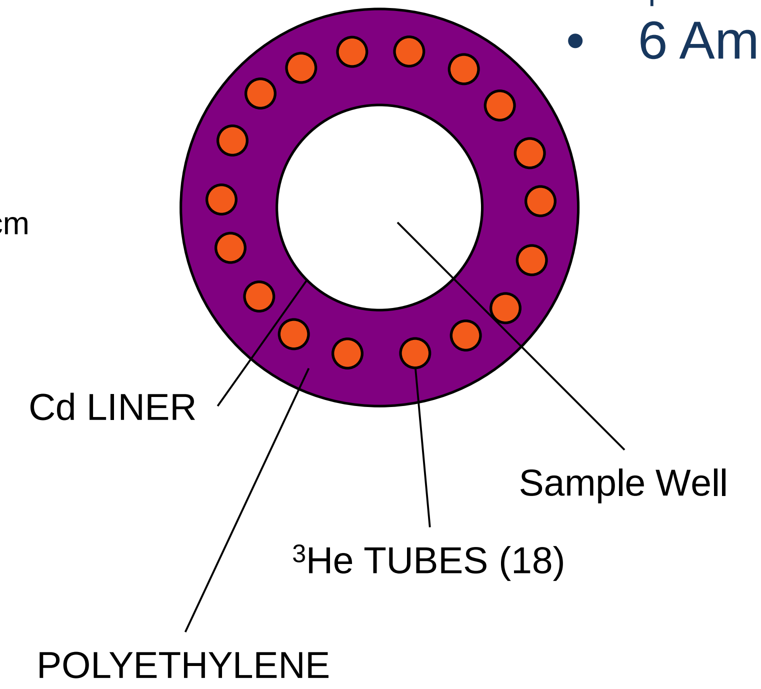
$$m_{Pu} = \frac{m_{^{240}Pu_{eff}}}{\left(2.52 f_{^{238}Pu} + f_{^{240}Pu} + 1.68 f_{^{242}Pu}\right)}$$

$$= \frac{200}{\left(2.52 \cdot 0.02 + 0.24 + 1.68 \cdot 0.06\right)}$$

$$= 511.25g$$

High-Level Neutron Coincidence Counter (HLNC)

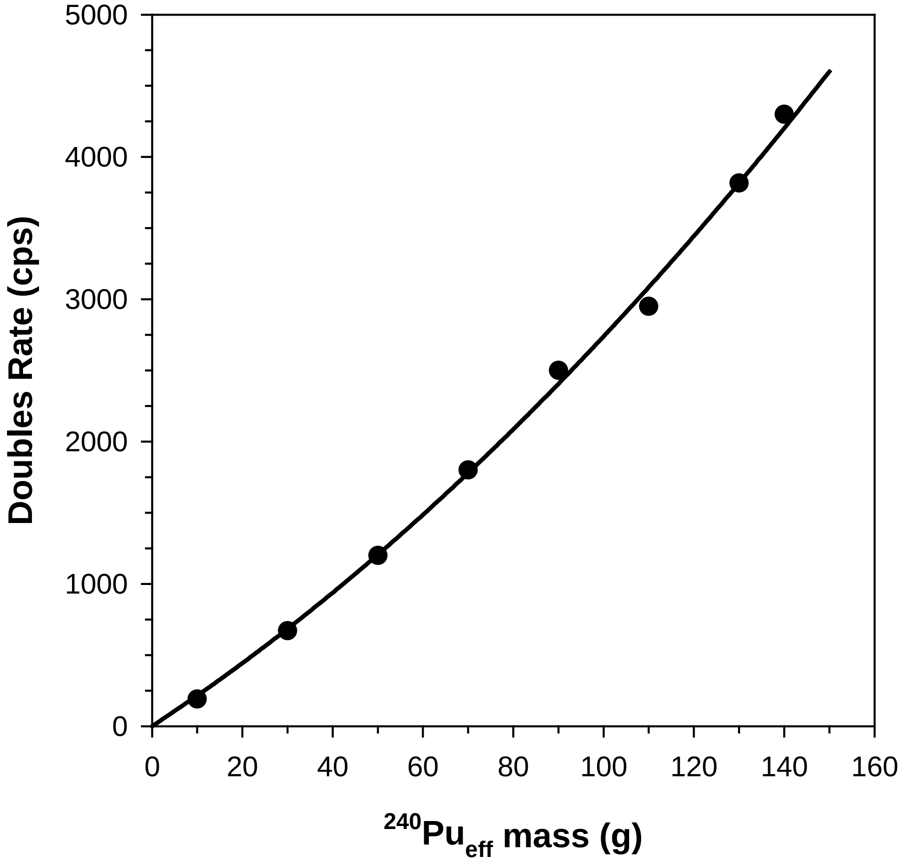




- $\varepsilon = 17.5\%$
- $\tau = 43\ \mu s$
- 18 detector tubes: 4-atm ^3He, 50.8-cm active-length, $\phi 2.54$cm
- 6 Amptek preamplifiers

Calibration Curve Method

Measure a series of representative standards to relate the measured doubles rate to the $^{240}Pu_{eff}$ mass

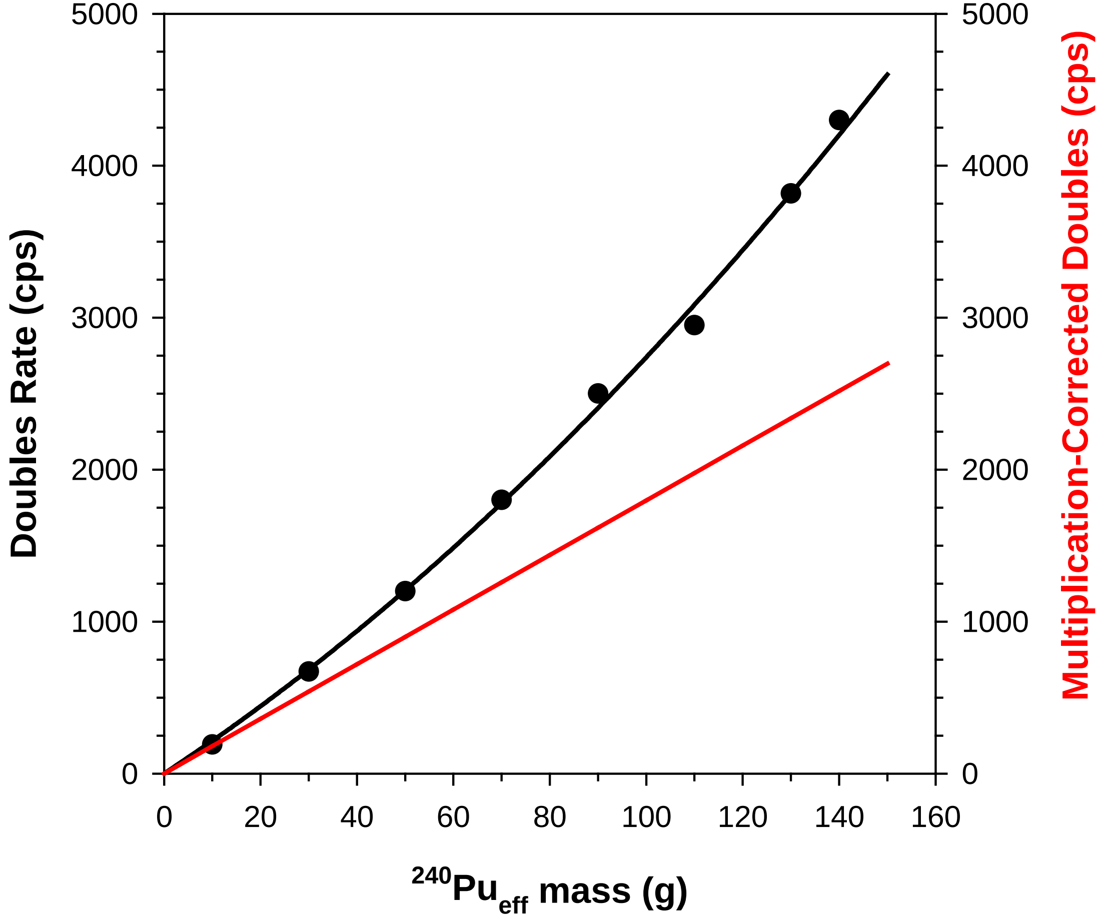


The calibration is dependent on:

- Material type
- Geometry
- Density
- Impurities (high M items)

Known Alpha Analysis Method

Use singles and doubles to deduce a “multiplication” correction that linearizes the calibration. Works well for pure oxides, metals, and fluorides. Still need standards.



The calibration is dependent on:

- Known material type
- Isotopic values

This technique does not work for impure items.

Known-Alpha Analysis Method - Details

1. Calculate alpha from the Pu isotopics and known yields values (PANDA eq. 16-35)
2. Combine the S and D point model equations to obtain:

$$K(1+\alpha)M^2 - (K(1+\alpha)-1)M - (D/S)(1+\alpha)/\rho_0 = 0$$

3. Use the quadratic formula to solve for M
4. Determine the multiplication corrected Doubles:

$$D_{Mult\ Corr} = \frac{D_{Measured}}{M^{\frac{D/S(1+\alpha)}{\rho_0}}}$$

5. Plot a linear calibration "curve" with $D_{mult\ corr}$ vs. $^{240}Pu_{eff}$

$\rho_0 = D_o/S_o \times (1+\alpha_o)$ — ρ_0 is treated as a detector parameter

$K = \nu_{s1}\nu_{i2}/\nu_{s2}(\nu_{i1}-1) = 2.166$ — Nuclear data

Passive Coincidence Counting Data Analysis Example

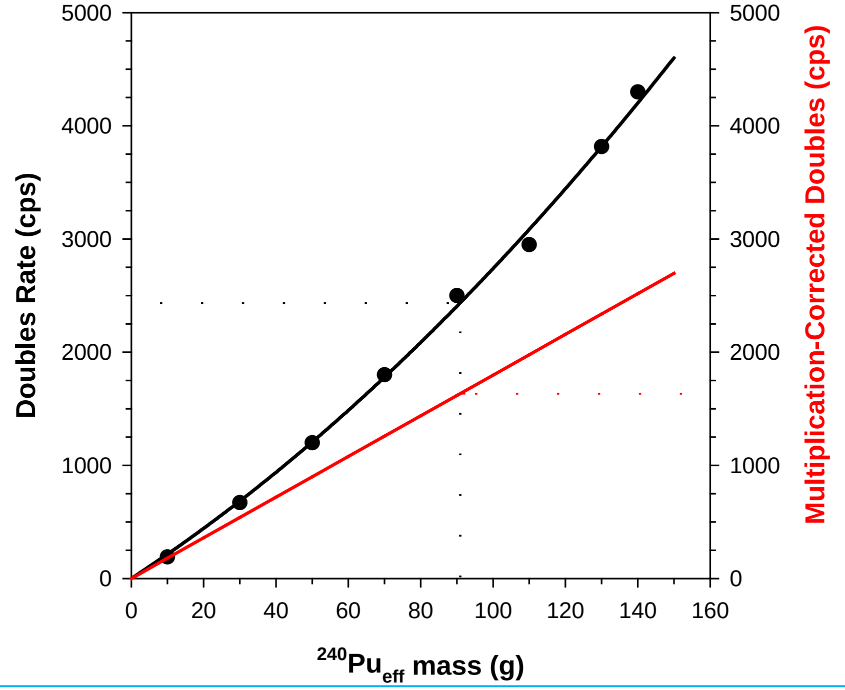
Pu oxide Declared Mass $^{240}Pu_{eff}$ = 92 g

<u>HLNC Measurement</u>:
Singles = 26176 cps
Doubles = 2434 cps

<u>From Calibration Curve</u>:
D = 2434cps ➡ m = 92g

Pure oxide ⇨ α = 0.525
(for this isotopic composition)

<u>Known-α Analysis</u>:
HLNC➡ ρ_0 = 0.103
Solve for M = 1.08
Calculate $D_{Mult\ Corr}$ = 1634 cps
From Known-α curve, m = 92g



Which method is "best"?
Known-α can only be applied when the item alpha-value can be reliably calculated (eg. pure Pu oxide), and works even if the item multiplication does not follow the passive calibration curve trend. For example:
- Calibrate on short-fat cans of oxide
  - Assay on tall-thin cylinders (cal curve fails, K-α works)
  - Assay on stacked short-fat cans (cal curve fails, K-α works)

The Problem with Standard Coincidence Counting

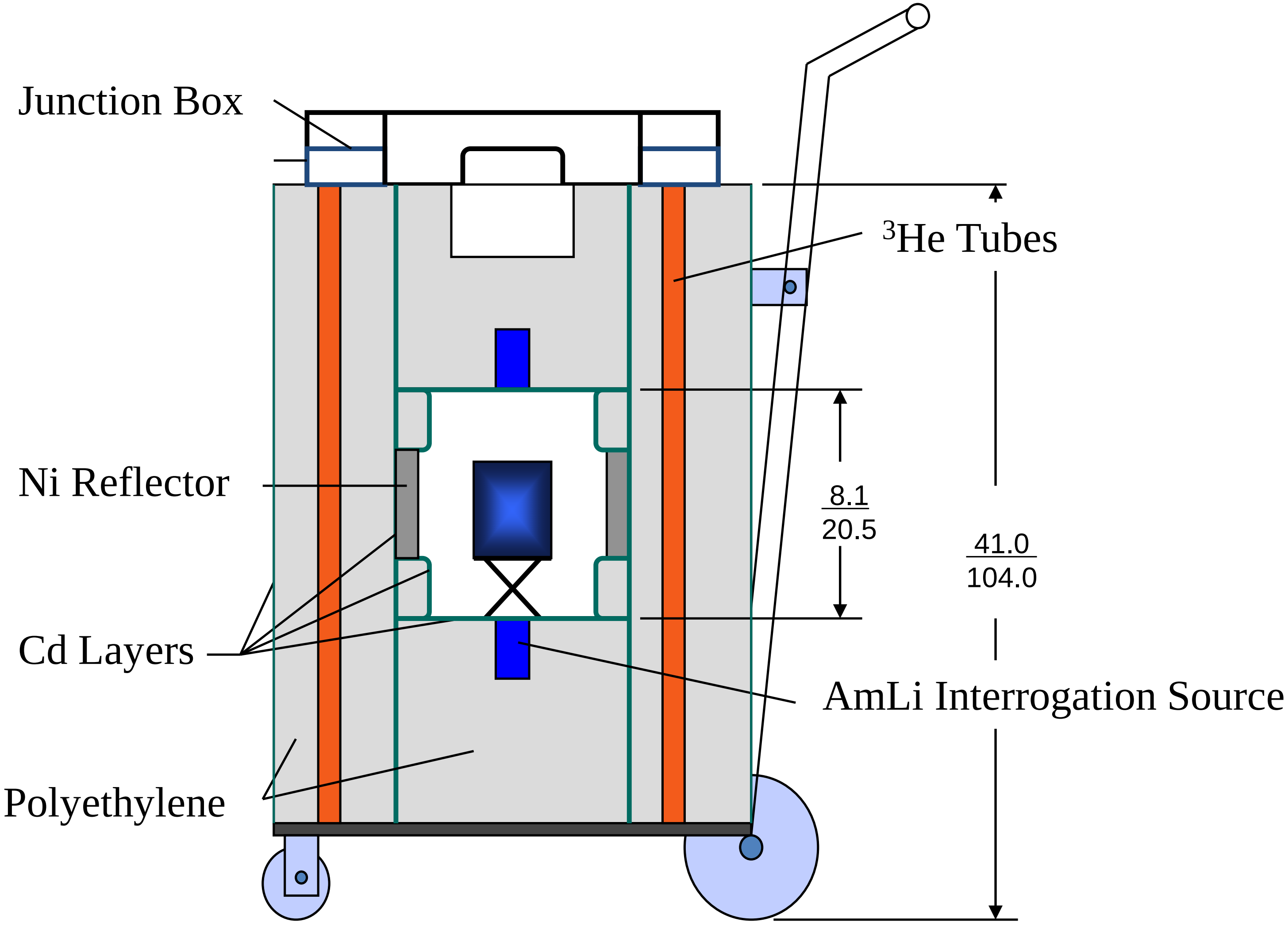
- There are 3 principal unknowns in neutron counting:
- ^{240}Pu-effective mass, α, and M.
- Standard Coincidence Counting provides only 2 pieces of measured information, singles and doubles (or totals and coincidences). To obtain an accurate assay, one must know a lot about the item.
- If the assumed information is not correct, large errors can occur.
- In Neutron Multiplicity Counting, 3 pieces of measured information are used with a mathematical model to deduce an assay that is far superior for most impure materials.

ACTIVE MEASUREMENTS (U)

Active Well Coincidence Counter (AWCC) - Design

- Assay range of few gram to several kg of ^{235}U (metal, oxide, …)
- Designed in 1984 (Mod II)
- Can be used in passive or active (thermal and fast) modes
- Portable
- Good efficiency – 42 ^{3}He tubes
- Uses 2 Americium-Lithium (AmLi) sources for uniform interrogation
- Several cavity configurations for optimization of performance

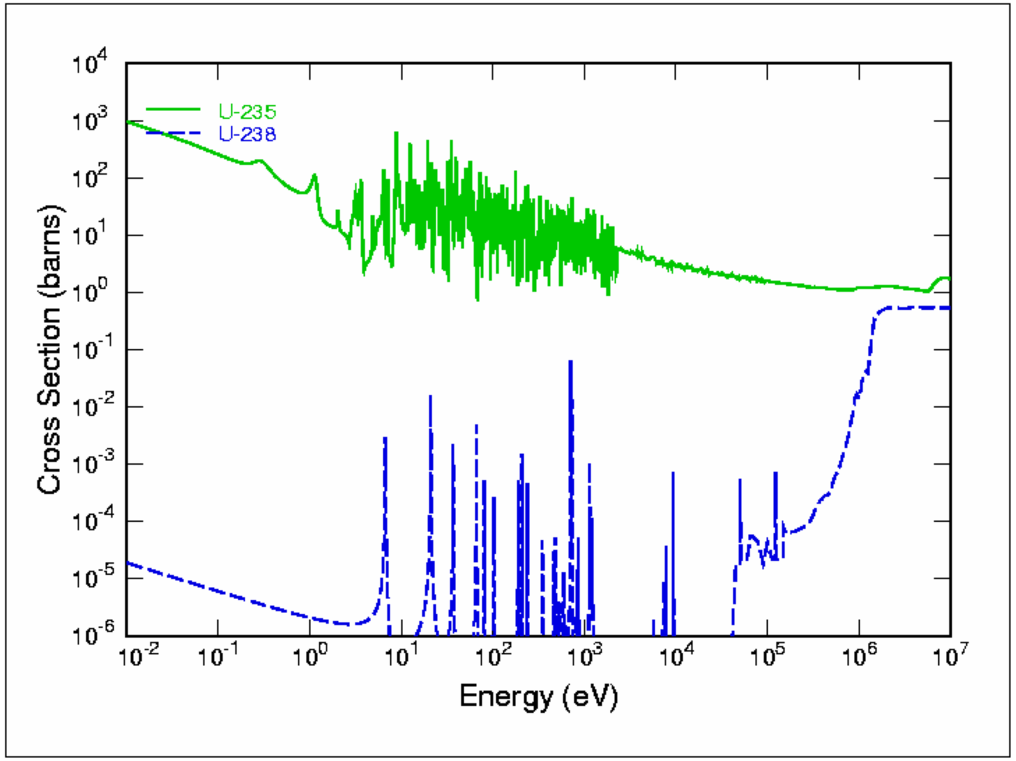
AWCC - Drawing



Why use AmLi source to induce fissions?

- AmLi produces random neutrons. Will not interfere with the coincidence signal from induced fission in ^{235}U.
- AmLi has a low energy spectrum and will only induce fissions on ^{235}U (not ^{238}U).

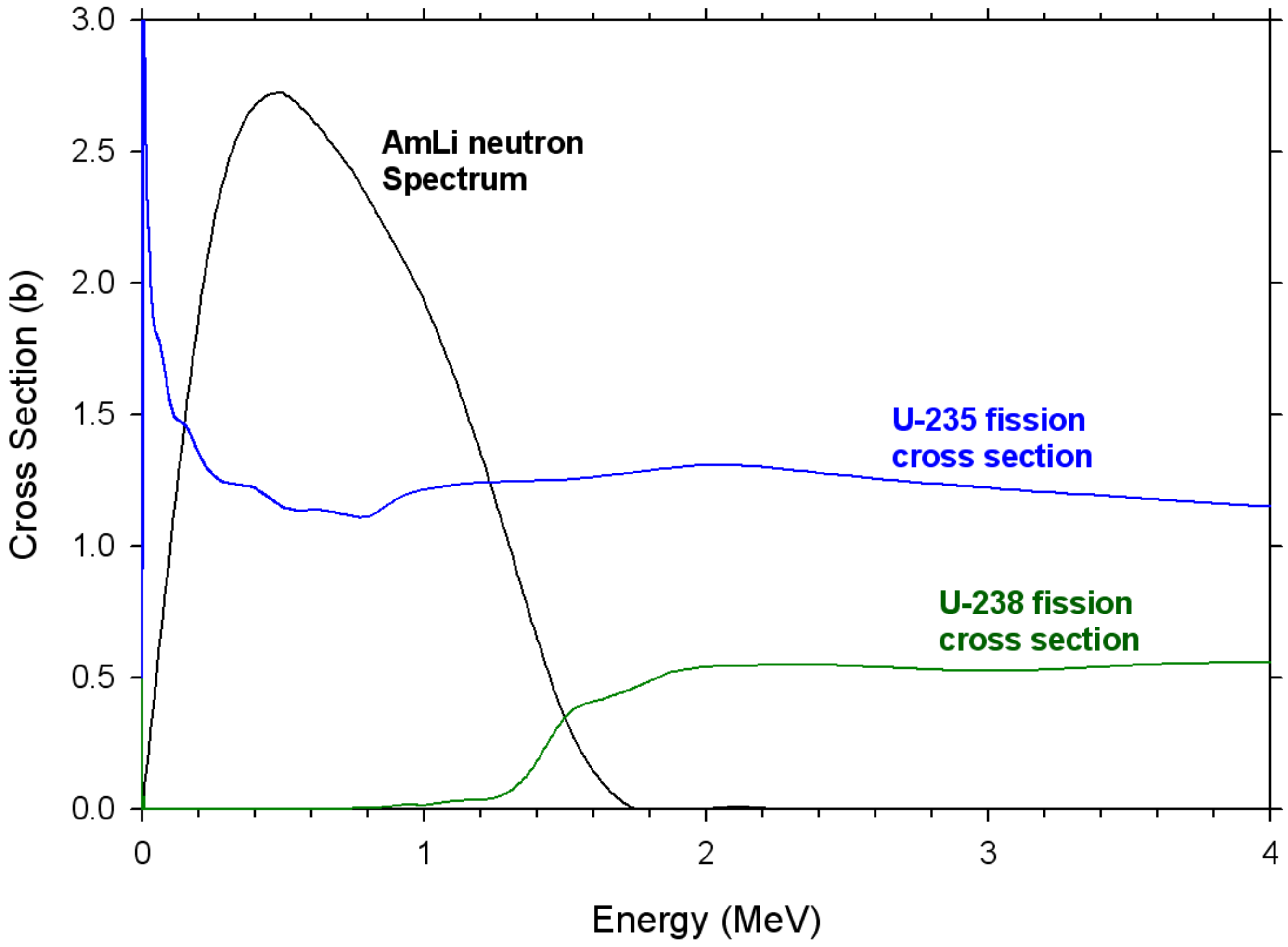
Plot of the induced fission cross section of ^{235}U and ^{238}U



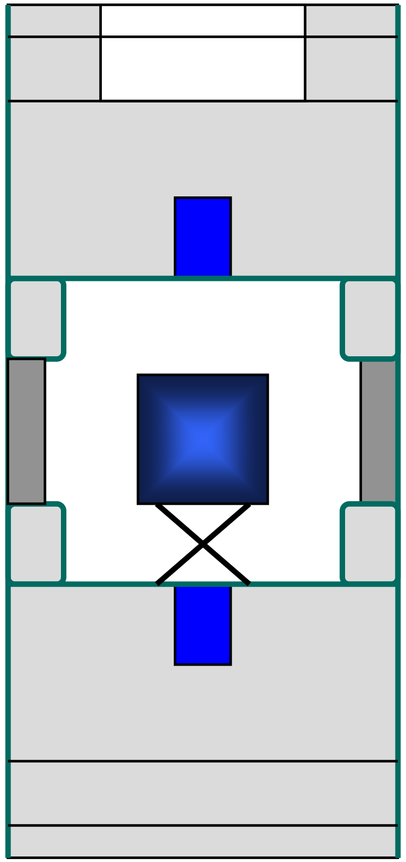
AmLi spectrum and Fission Cross Sections

AmLi neutron spectrum overlaid on uranium fission cross section plot

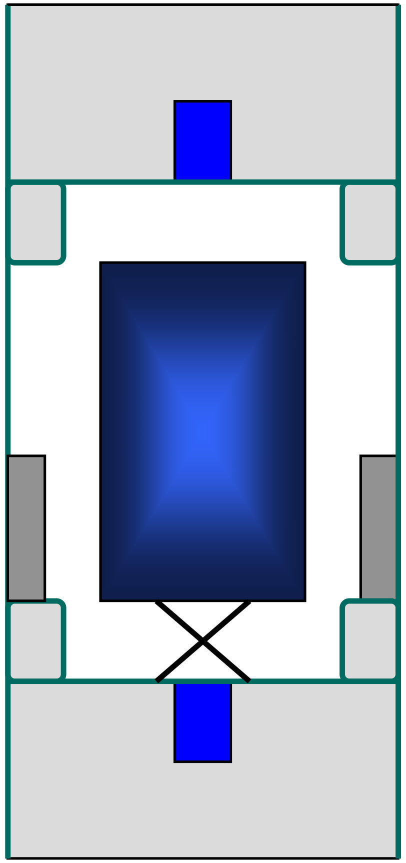
Only 3% of AmLi neutrons have energy ≥ 1.5MeV



AWCC Fast Modes



Mode F0

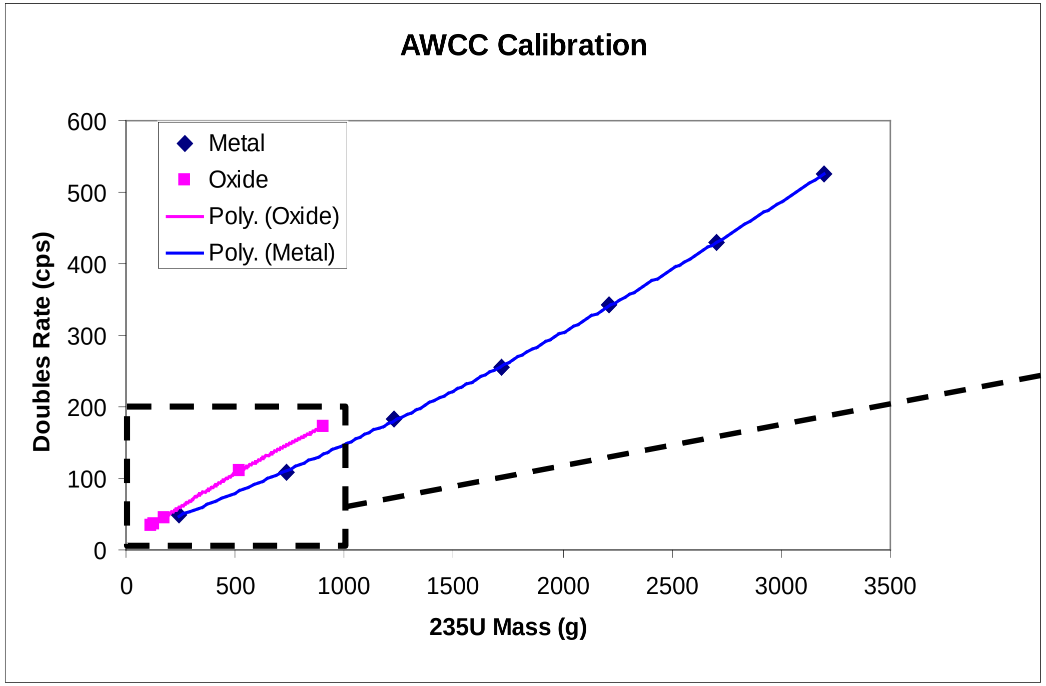


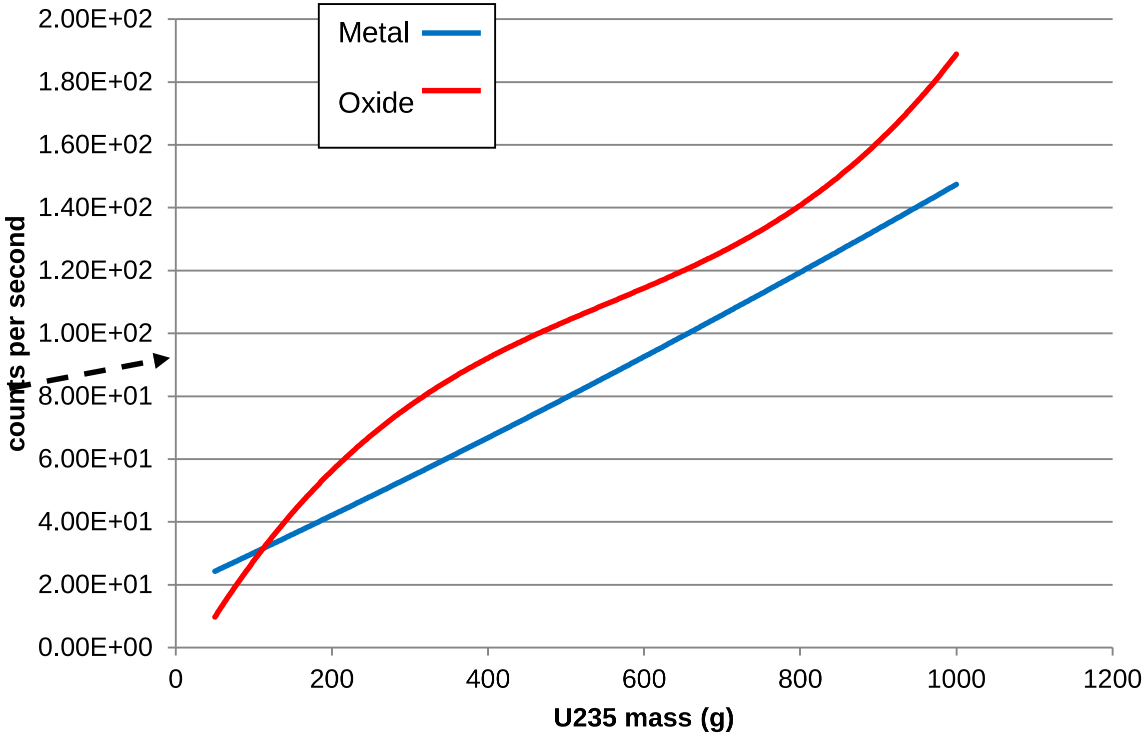
Mode F4

- Cd present
- Nickel Ring
- Interrogation with fast neutrons
- 5 modes of operation for different container sizes
- Optimum for medium to large mass items

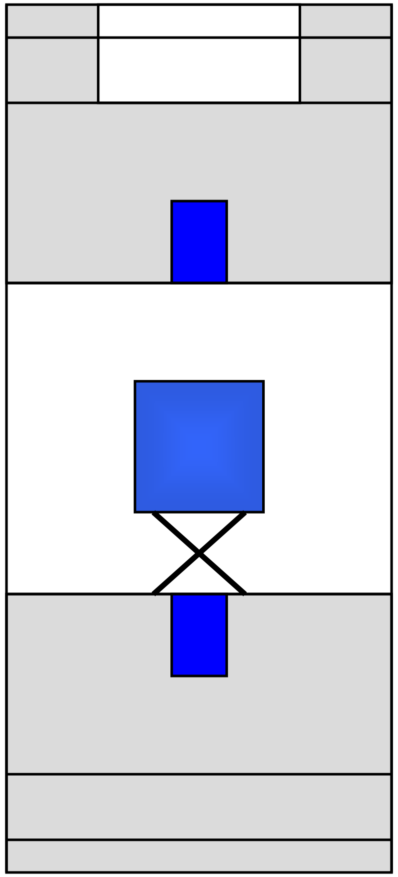
AWCC - Fast Mode Calibration

Sample calibration curve for mode F0 operation

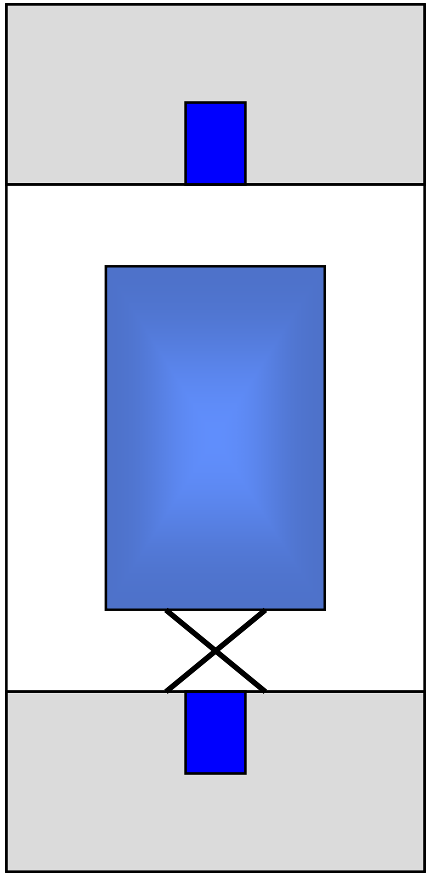




AWCC Thermal Modes



Mode T0



Mode T4

- No Cd present
- No Nickel Ring
- Interrogation with thermal neutrons
- 5 modes of operation for different container sizes
- Optimum for small mass items

AWCC Comparison of Fast and Thermal Modes

	Fast Mode	Thermal Mode
Cadmium Present	Yes	No
AmLi Item Interrogation	Entire Volume	Surface Layer
Optimum Mass Range	Medium to Large	Small Hydrogenous

AWCC Summary

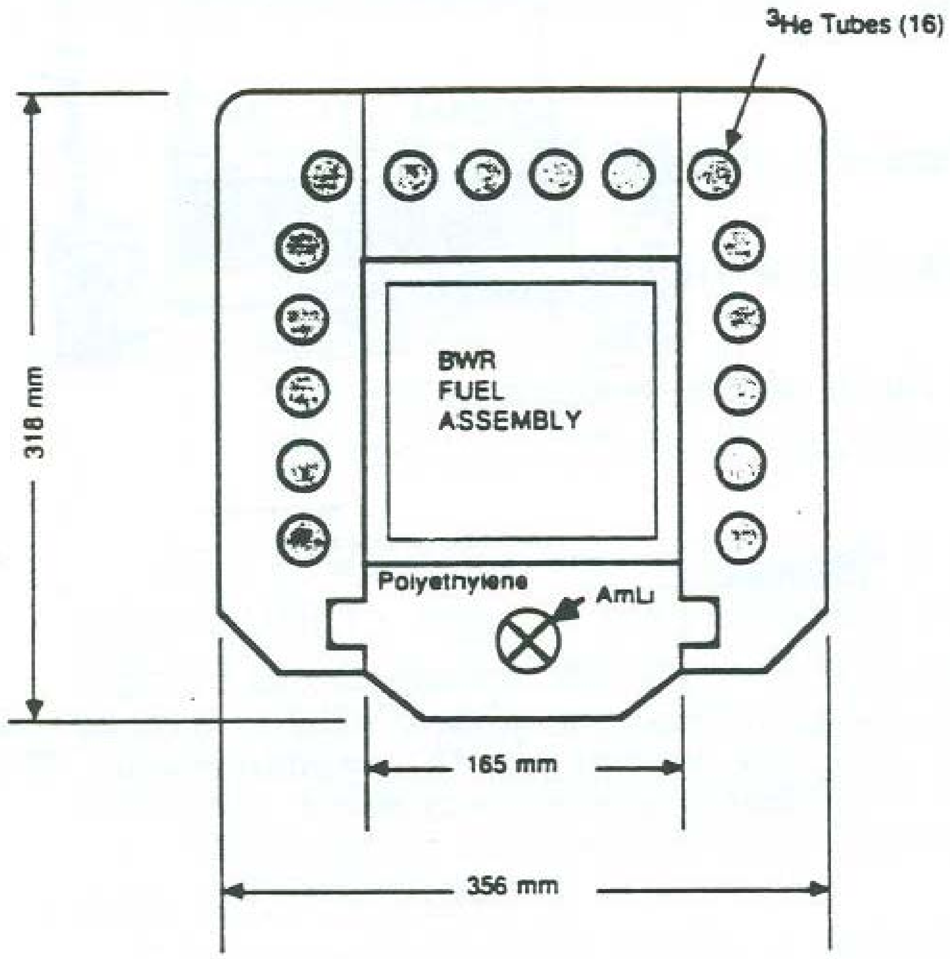
- AWCC utilizes the following physics:
  - Active-mode interrogation to determine fissile content
  - AmLi source neutrons produce no Doubles
  - AmLi source energy is below ^{238}U fission threshold
- Two Modes of Operation:
- “**Thermal Mode**” - better statistics, good for small and hydrogenous samples, BUT vulnerable to self-shielding and thermal neutron poisons,
- “**Fast Mode**” – longer counting times, good for larger samples, and less sensitive to thermal poisons
- Make sure calibration curve is for the correct mode and material type
- (AWCC used for Uranium Assay and can be used in passive mode for Pu/MOX measurement)

Uranium Neutron Collar (UNCL) Design

- Same principle of operation as AWCC but designed for the verification of fresh fuel assemblies (BWR and PWR)
- The UNCL-II was designed in 1989
- Uses 16 ^{3}He tubes
- Cd and no Cd modes
- Response cross-calibrated to an absolute calibration curve
- Different calibration curves for BWR and PWR
- Uses one AmLi interrogation source

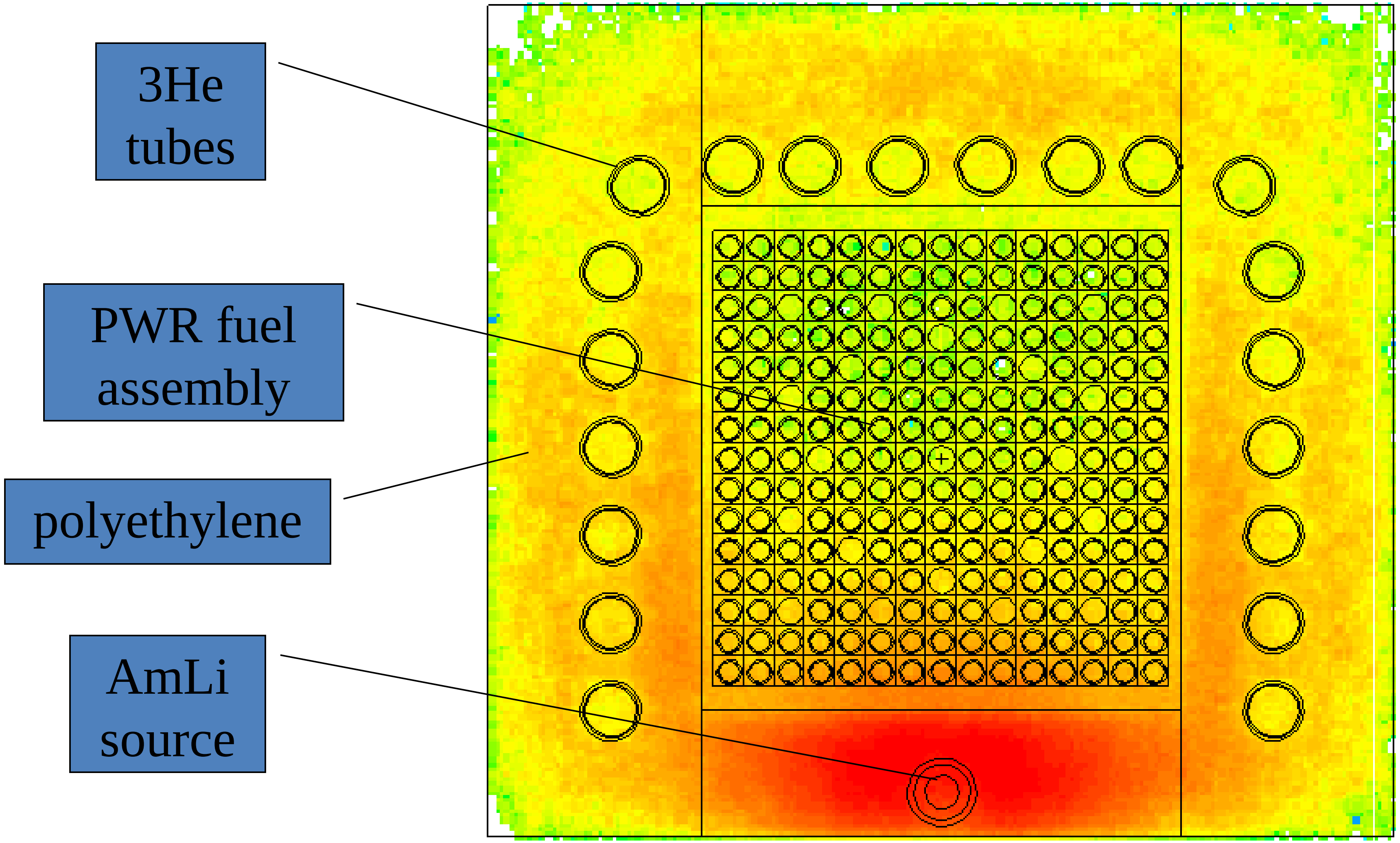
For complete details of the collar operation and calibration procedures refer to report LA-11965-MS “Neutron Collar Calibration and Evaluation for Assay of LWR Fuel Assemblies Containing Burnable Neutron Absorbers”

UNCL - Drawing



- 16 ^{3}He tubes
- Lift-out door
- Uses one AmLi source
- Polyethylene body

UNCL Neutron Collar (PWR)



UNCL – Basic Principles

- AmLi neutrons are (alpha,n) neutrons – no Doubles from source
- AmLi neutrons induce fissions in ^{235}U, giving Doubles
- Average AmLi neutron energy ~0.5 MeV (below fission threshold for ^{238}U)
- Interrogation flux gets less farther from source (fission neutron spread throughout assembly)
- Detection efficiency increases farther from source
- → Net result is that the detector responds equally to all pins in the assembly

UNCL Response Adjustments

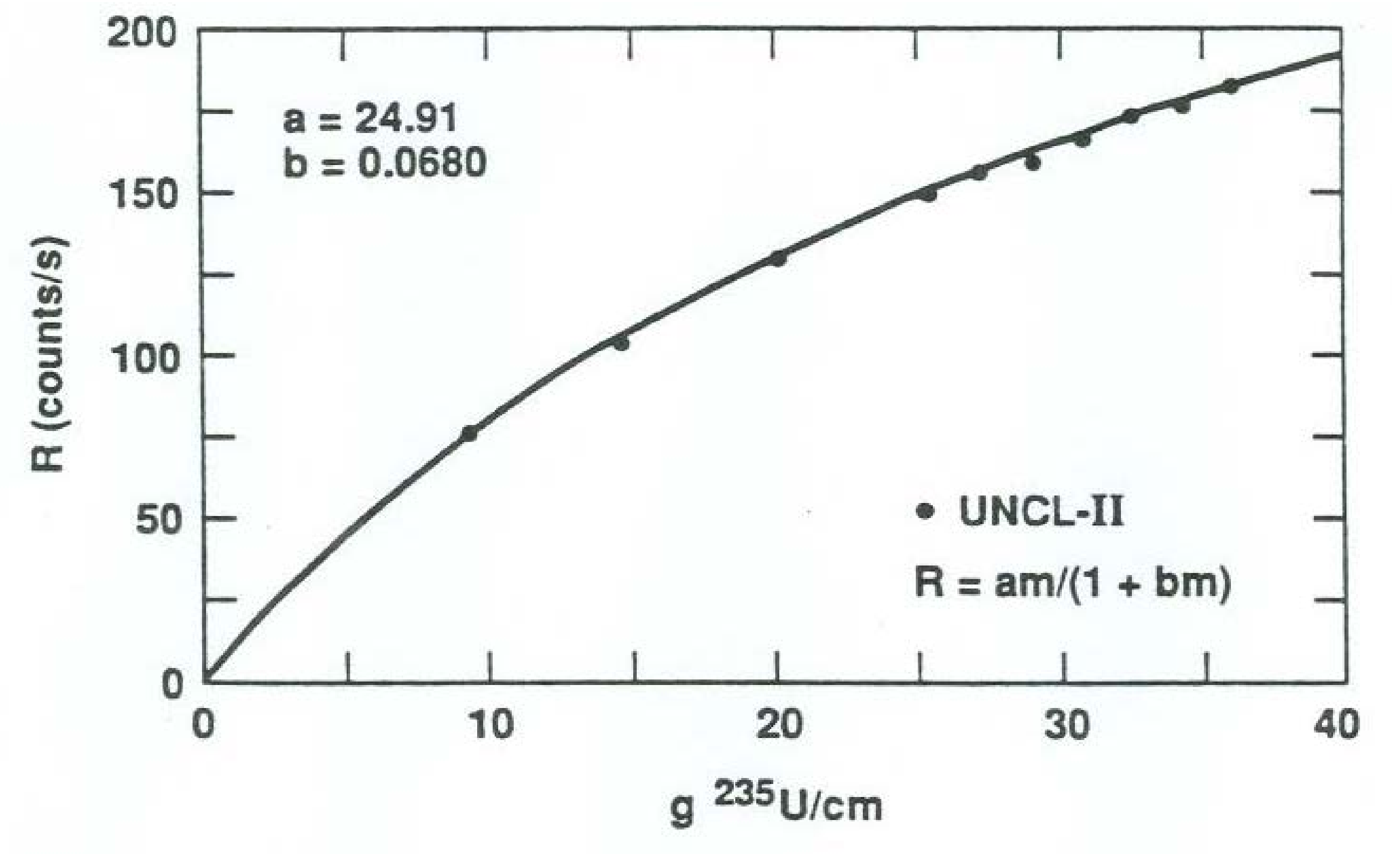
$$R = \left(k_0 k_1 k_2 k_3 k_4 k_5\right) R_M$$

- k_0 – AmLi source strength
- k_1 – Normalization
- k_2 – Detector efficiency
- k_3 – Burnable poison
- k_4 – Heavy metal loading
- k_5 – Other conditions
- R_M – Measured response

By adjusting the measured response we can use the absolute calibration curves for all collar detectors.

UNCL calibration curve

Calibration curve for BWR fuel (thermal mode)



UNCL Burnable Poisons

- Burnable poisons are thermal neutron absorbers used to extend the life of fuel assemblies in reactors (allows greater initial enrichment)
- A correction is needed - based on number of poison rods (and type)
- Correction is small for fast (Cd liner) mode because thermal neutrons are excluded - measurement time ~1 hour
- Correction larger for Thermal mode (no Cd liners) - measurement time ~10 mins
- (Measurements with and without Cd can verify burnable poison declaration)
- Euratom Fast Collar designed for fast (Cd liner) mode but short measurement time ~15 minutes

Neutron NDA Summary

- The mass of items of Special Nuclear Material SNM (Pu, U) can be measured by detecting the neutron emission.
- Different neutron source mechanisms (spontaneous fission, (alpha,n) and induced fission) can be distinguished by coincidence counting.
- Passive measurements are used for Pu with a couple of different analysis methods ("Difficult-to-measure" items need multiplicity counting)
- Different detectors accommodate different item sizes and shapes
- Active methods use an external source to induce fission (in ^{235}U)