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Data Needs for Nuclear Material Accounting and Safeguards in the HALEU Fuel Cycle

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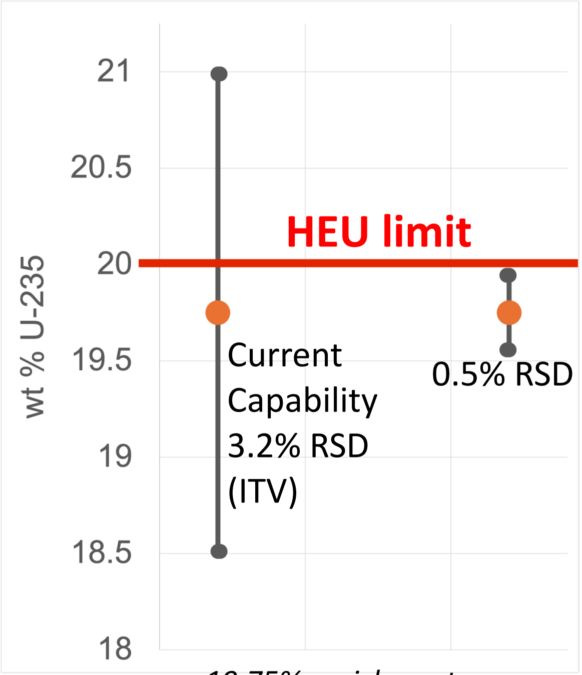
Effective Nuclear Material Accounting and Safeguards are essential to enable use of nuclear power

- US Nuclear Regulatory Commission: *"regulations require the licensee to maintain a nuclear material control and accounting (MC&A) program that tracks and verifies special nuclear material (SNM) that is on site"*
  - Requirements defined in 10 CFR Part 74
  - Special Nuclear Material: uranium enriched in the isotope ^{235}U
  - Strategic Special Nuclear Material: uranium enriched to 20% or more in the ^{235}U isotope (dramatically increased requirements and cost associated with HEU)
- Global Security: *"The objective of IAEA Safeguards is to deter the spread of nuclear weapons by the early detection of the misuse of nuclear material or technology"*
  - International Treaty on the Non-Proliferation of Nuclear Weapons requires each Non-Nuclear Weapon State to conclude a safeguards agreement with the IAEA

https://www.nrc.gov/materials/fuel-cycle-fac/nuclear-mat-ctrl-acctng.html
https://www.nrc.gov/reading-rm/doc-collections/cfr/part074/part074-0004.html
https://www.iaea.org/topics/basics-of-iaea-safeguards

We need improved nuclear data to implement advanced fuel cycles – uncertainty is cost

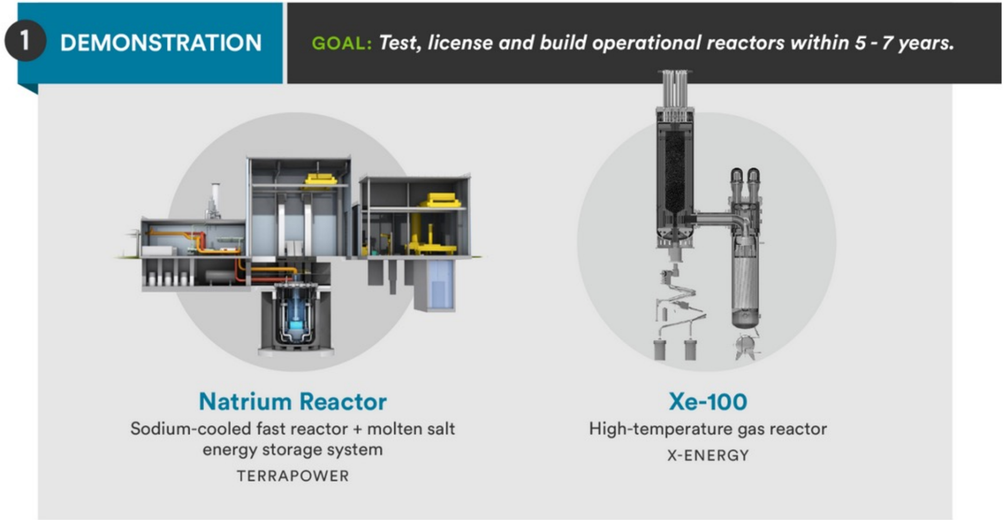
- Nuclear materials provide good passive signatures (gamma rays, neutrons, radioactive decay heat) for quantifying their isotopic composition and mass with rapid, inexpensive nondestructive assay
- Advanced fuel cycle developers will rely on nondestructive assay to meet licensing requirements for nuclear material accounting
- Measurement techniques are **limited by nuclear data**



19.75% enrichment
Error bars plotted at 95% CI

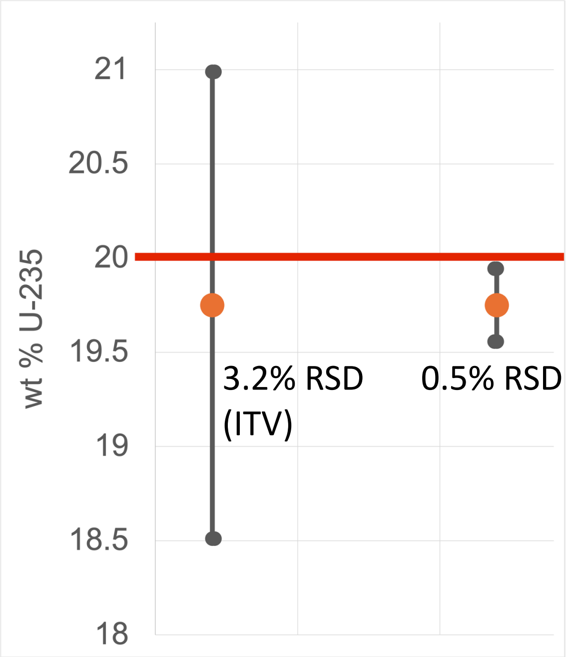
What is different about the HALEU fuel cycle?

- Enrichment (by definition)
  - ~19.75% vs ~3-5% ^{235}U enrichment
- Wide array of fuel forms being considered
  - Pebbles
  - Molten salt
  - Metallic fuel elements
  - And sometimes things that look like traditional fuel rods
- Advanced reactors can achieve very high fuel burnup
- Fuel recycling being considered



The U.S. Department of Energy is supporting 10 U.S. advanced reactor designs to help mature and demonstrate their technologies within the next 15 years.
https://www.energy.gov/ne/articles/infographic-advanced-reactor-development

Case study: gamma spectroscopy peak ratio method
Is it HEU or HALEU?



19.75% enrichment
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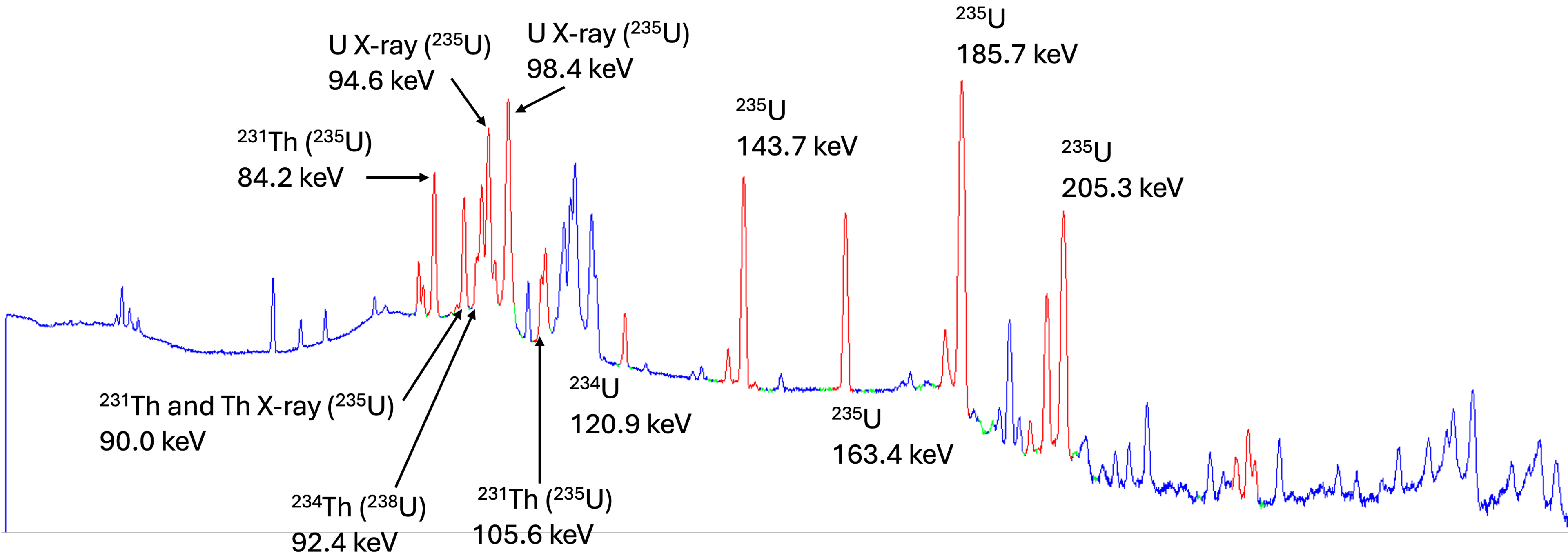
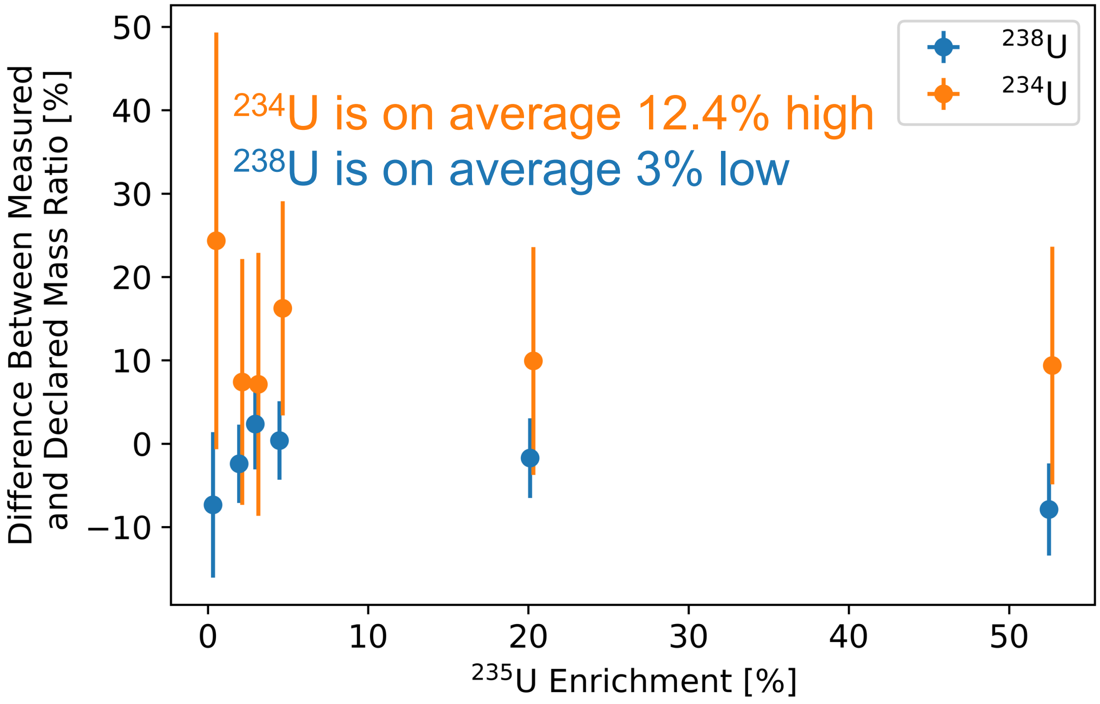
- Determines U enrichment from passive, nondestructive gamma spectroscopy
- Peak ratio method works for arbitrary sample geometry
- ITV target value: 3.2% RSD
- Really need <0.5% RSD for HALEU
- Alternative: sampling and costly laboratory analysis

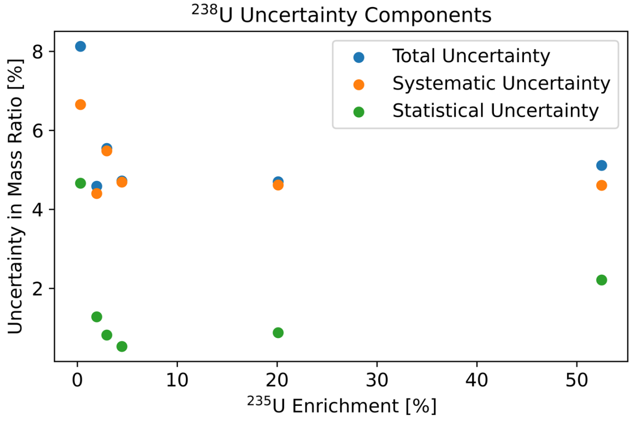
ITV: https://nucleus.iaea.org/sites/connect/ITVpublic/ITV%20tables/Table_5_b_U235%20Enrichment.pdf

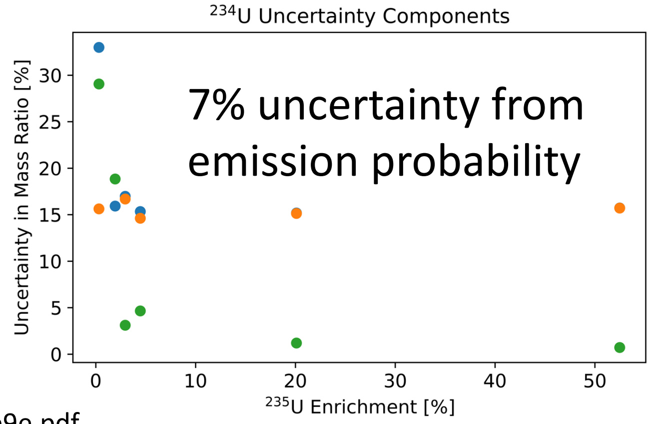
Uncertainty of this method depends on knowledge of gamma and X-ray emission probabilities



Uncertainty Analysis Study using FRAM method





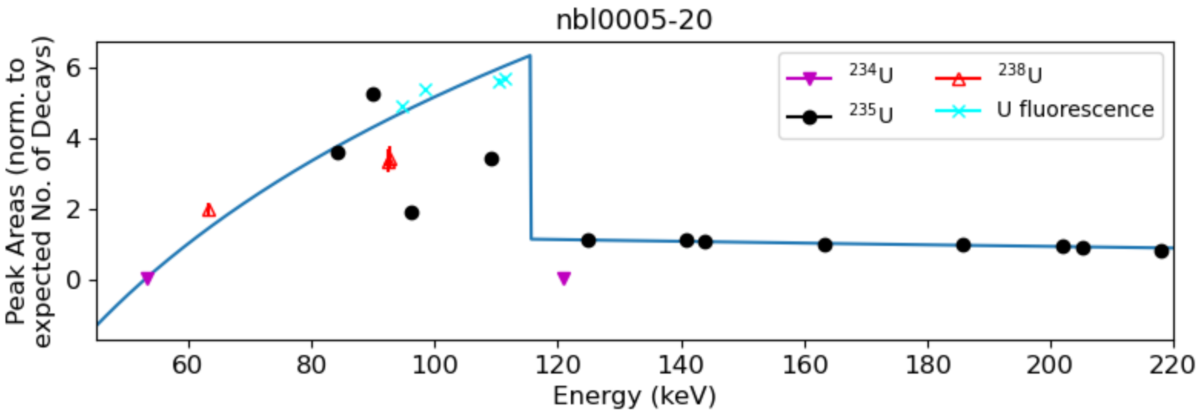


234, 235, 238 must all be accurately determined for accurate enrichment measurement

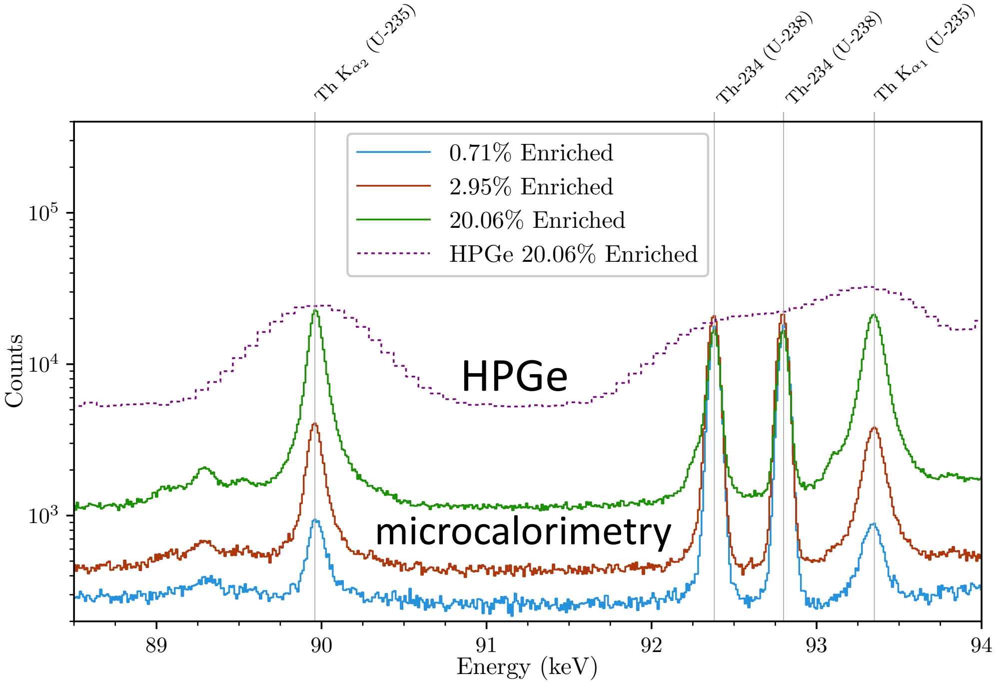
FRAM: https://cdn.lanl.gov/files/app-to-isotopic-analysis-using-fram_06e9e.pdf

Relative Efficiency Curve study highlights discrepancies

- Outliers suggest opportunities for improved emission probability data
- Peak ratio codes rely on empirical tuning of emission probabilities to generate accurate results for a category of nuclear material – **this approach breaks down for new materials**



We have the tools to improve this data ...and to make use of the improved data



SOFIA microcalorimeter gamma spectrometer

Typical 65 eV FWHM resolution at 100 keV (~8x better than HPGe)

Data improvements demonstrated

M. D. Yoho et al.,
NIM A 2020

Greater than 2x reduction in uncertainty for five Pu and Am branching ratios needed for isotopic analysis

Energy [keV]	Isotope	NNDC BR	μ_{BR} [%]	This work BR	μ_{BR} [%]	μ_{BR} Agreement
125.21	^{239}Pu	5.63×10^{-5}	2.7	5.51×10^{-5}	13	-0.2
125.3	^{241}Am	4.08×10^{-3}	2.5	4.08×10^{-3}	1.0	0.0
144.201	^{239}Pu	2.83×10^{-4}	2.1	2.87×10^{-4}	1.0	0.6
146.094	^{239}Pu	1.19×10^{-4}	2.5	1.22×10^{-4}	1.4	0.7
146.55	^{241}Am	4.61×10^{-4}	2.6	4.75×10^{-4}	0.75	1.2
150.04	^{241}Am	7.40×10^{-5}	3.0	7.76×10^{-5}	1.3	1.5
152.72	^{238}Pu	9.29×10^{-4}	0.75	9.46×10^{-4}	0.78	1.7
159.955	^{241}Pu	6.68×10^{-6}	1.1	6.87×10^{-6}	2.0	1.2
160.19	^{239}Pu	6.20×10^{-6}	19	5.82×10^{-7}	331	-2.5
161.45	^{239}Pu	1.23×10^{-4}	1.6	1.20×10^{-4}	1.6	-1.1
161.54	^{241}Am	1.50×10^{-6}	20.0	3.52×10^{-6}	19.9	2.7
164.61	^{241}Pu	4.56×10^{-5}	1.6	4.46×10^{-5}	2.0	-0.9
164.69	^{241}Am	6.67×10^{-5}	3.7	7.78×10^{-5}	4.9	2.4
169.56	^{241}Am	1.73×10^{-4}	2.3	1.72×10^{-4}	0.9	-0.3
171.393	^{239}Pu	1.10×10^{-4}	1.8	1.12×10^{-4}	1.4	0.9
175.07	^{241}Am	1.82×10^{-5}	5.5	1.85×10^{-5}	2.8	0.3
188.23	^{239}Pu	1.09×10^{-5}	10	8.63×10^{-6}	10.8	-1.6
189.36	^{239}Pu	8.30×10^{-5}	1.2	7.91×10^{-5}	1.4	-2.6
191.96	^{241}Am	2.16×10^{-5}	4.6	2.01×10^{-5}	2.8	-1.3
208.005	^{241}Pu	5.19×10^{-4}	1.4	5.34×10^{-4}	1.9	1.2
208.01	^{241}Am	7.91×10^{-4}	2.4	8.08×10^{-4}	5.4	0.4

Improved data directly translates to improved nondestructive assay and reduced cost of the HALEU fuel cycle

Gamma-ray data (especially emission probabilities):

- **Urgent need**: Low Enriched Fuel Fabrication Facility (LEFFF) making commercial HALEU TRISO fuel in 2026 (use as testbed), operational reactors in next few years
- **High impact**: enables maximum use of cost-effective measurement tools to meet licensing requirements
- **Widely applicable**: more robust analysis with germanium detectors, achieve uncertainty limits with ultra-high-resolution microcalorimeters
- **Demonstrated path forward**
- **Method applies to general need for improved photon emission probabilities (e.g. ^{135}Xe, ^{133m}Xe, ^{131m}Xe…)**