April 5, 2022

Luis Ocampo Giraldo
Tommy Holschuh
Scott Thompson
Jay Hix
James Johnson
David Chichester

Design and Validation of a Gamma-ray Scanning System for Measuring Irradiated Nuclear Fuel

Twelfth International Conference on Methods and Applications of Radioanalytical Chemistry

KAILUA-KONA, HAWAII

INL/CON-22-66516

Idaho National Laboratory

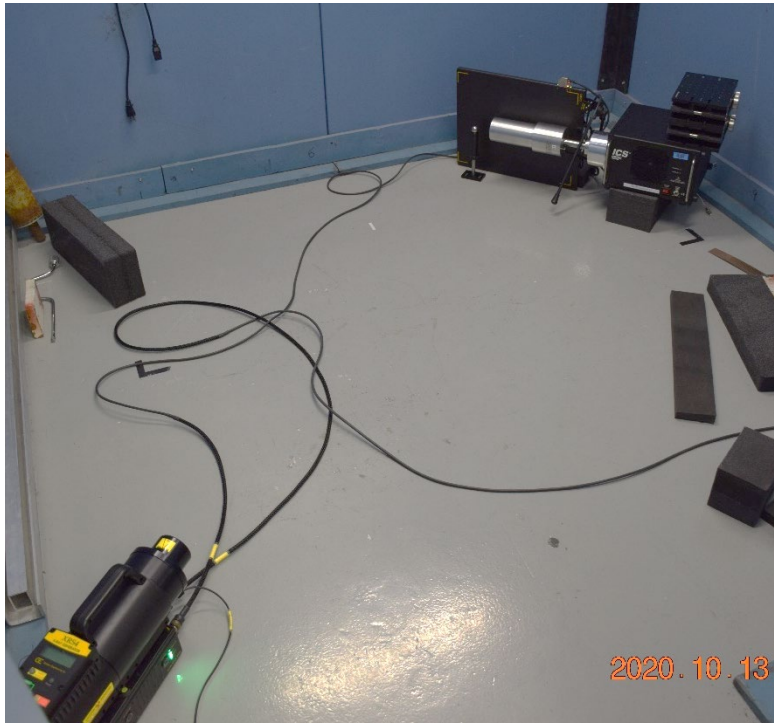
Gamma-ray Emission Tomography Assessment (GRETA-0) System

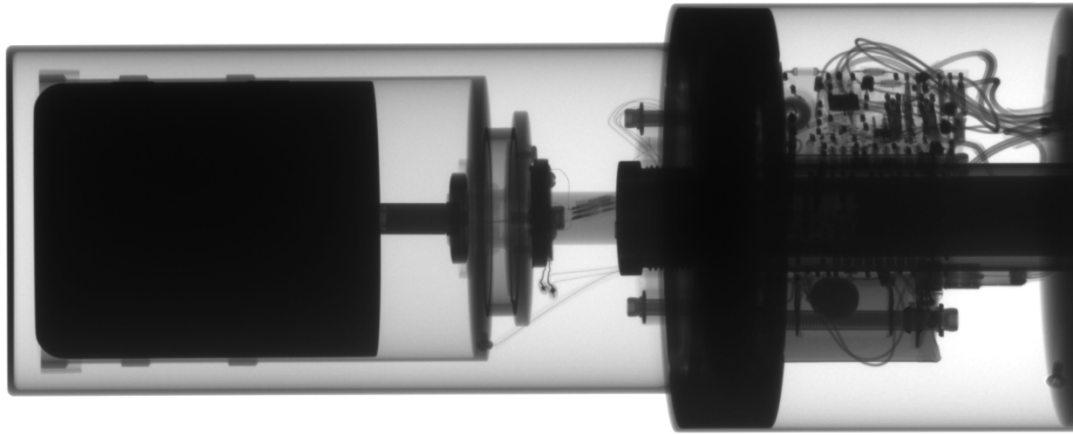
- Designed by the Applied Radiation Measurements and Systems Group
- Perform post irradiation measurements of fuel samples that were irradiated at the Transient Reactor Test (TREAT) facility.

- GRETA-0 is primarily composed of :
  - High-purity germanium detector (HPGe) system manufactured by ORTEC
  - An adjustable collimators assembly
  - Three high precision mechanical positioning stages

HPGe Characterization

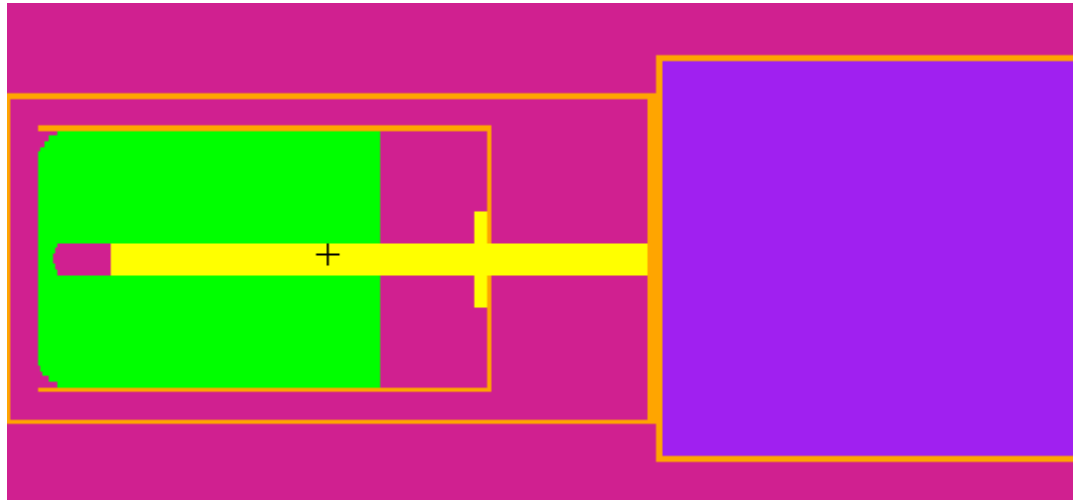
- Need further detailed information to create a high-fidelity model
- Several x-ray images were taken of the detector and used to measure and understand internal component geometry and composition
- The x-rays provide more information than the vendor specifications. X-rays drastically increase the reliability of MCNP models of the detector response

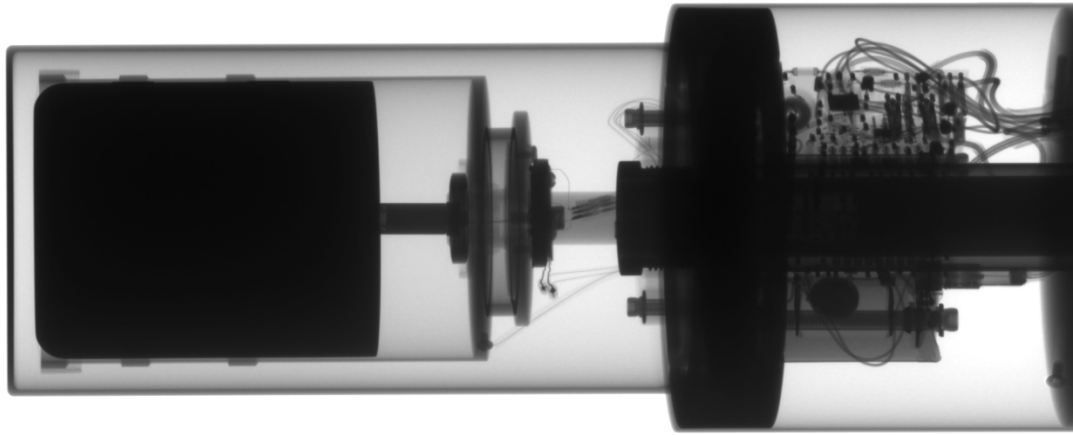


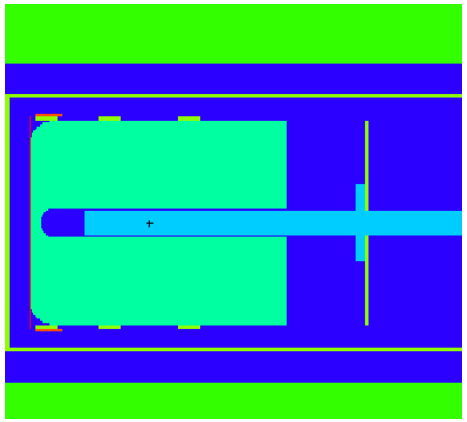


GRETA-0 MCNP model

- Monte Carlo N-Particle (MCNP) modeling
  - Include details of the hardware surrounding the crystal
    - Plastic rings
    - Housing thickness
    - Cold finger geometry
    - Connectors
    - Miscellaneous items surrounding the crystal



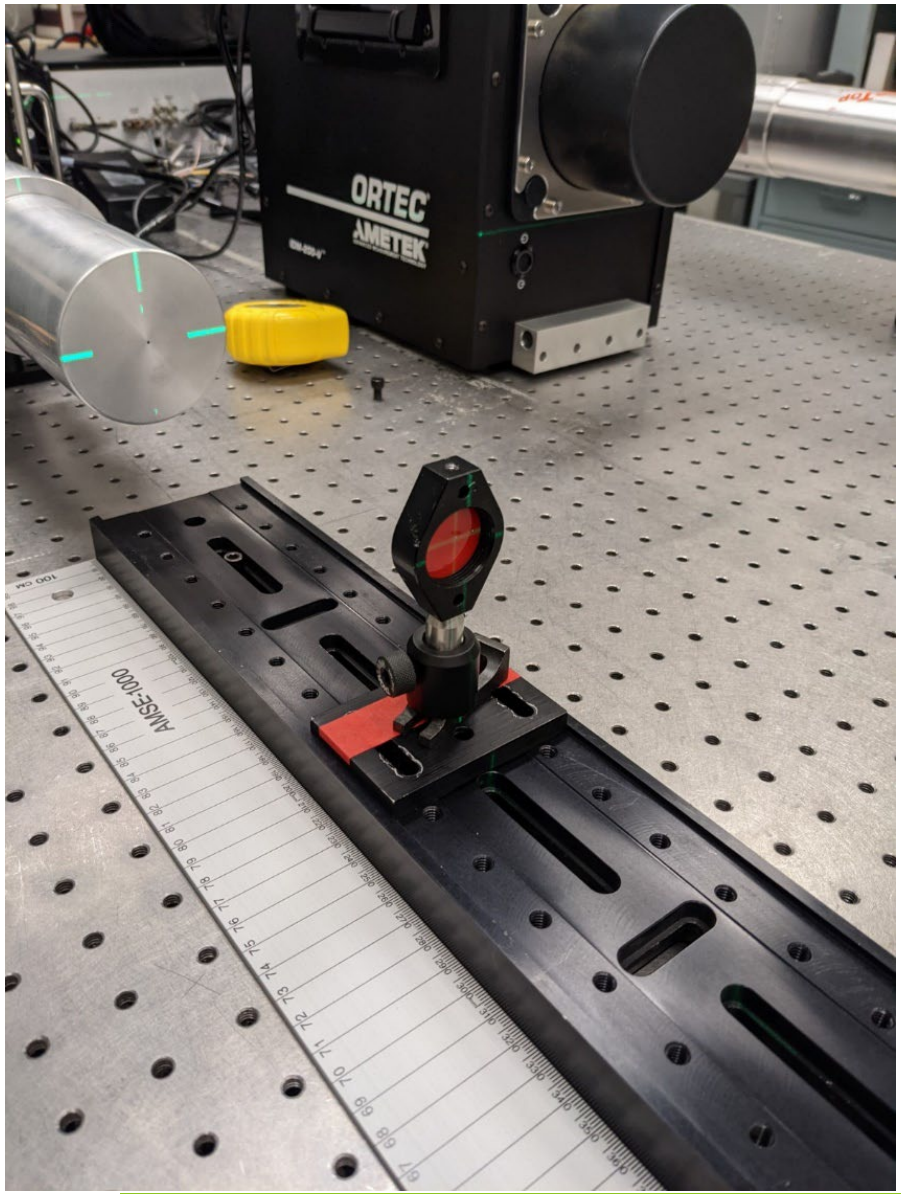




Detector Efficiency

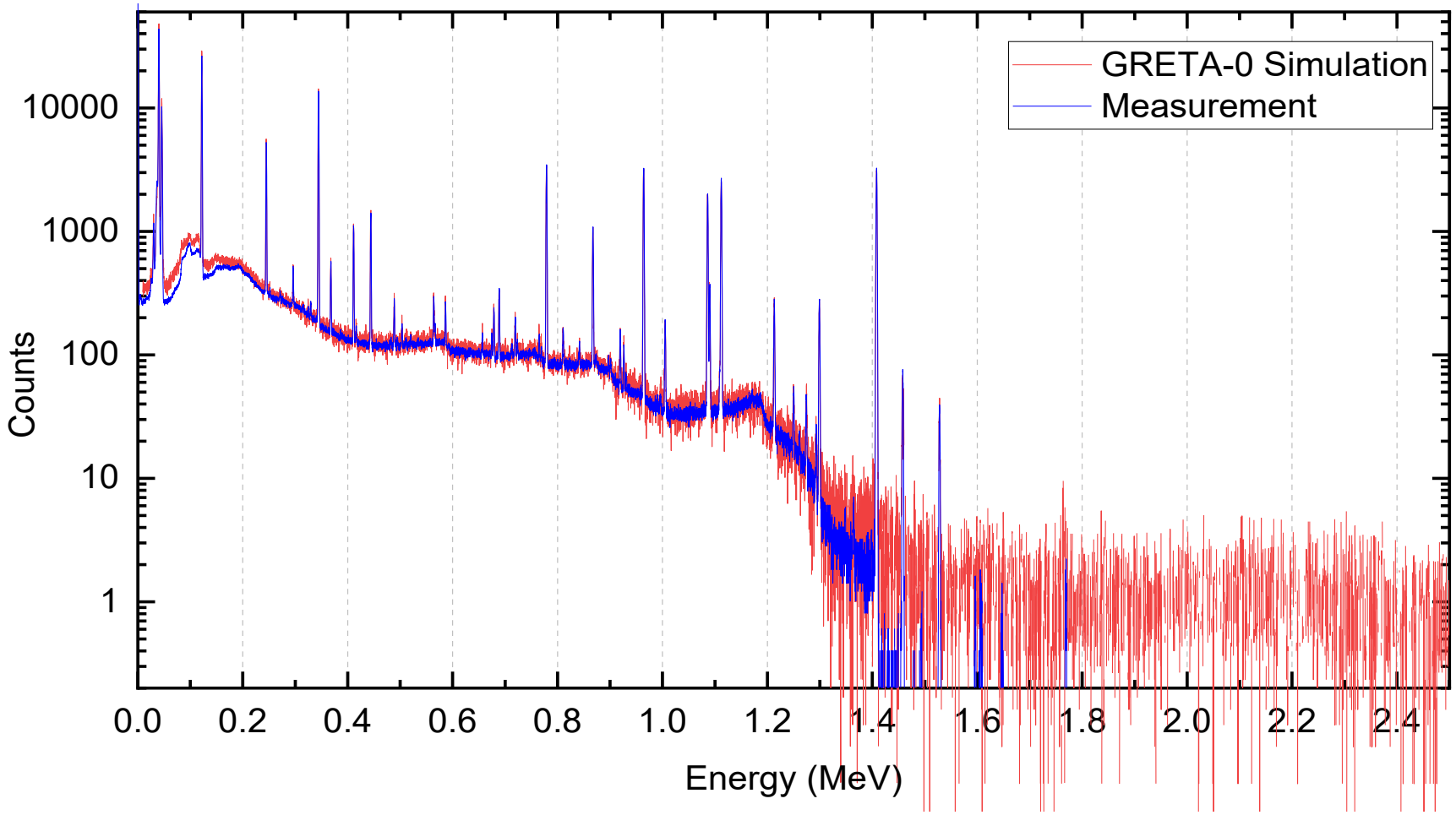
- **Laboratory Measurements**
  - Perform measurements using several NIST-traceable sources
  - Including:
    - ^{152}Eu
    - ^{137}Cs
    - ^{60}Co
- **Efficiency Evaluation**
  - ^{152}Eu emits several photons with a wide range of energies

Half-Life (sec)	Half-Life Error (sec)	Energy (keV)	E error (keV)	Intensity	Intensity error
427195200	189345.6	121.7817	0.0003	0.2866779	0.00145604
		244.6975	0.0008	0.07606616	0.000402742
		344.2785	0.0012	0.2655801	0.005128899
		778.904	0.0018	0.1296031	0.001413882
		867.373	0.003	0.04258416	0.000274025
		964.079	0.018	0.147847042	0.000719583
		1112.069	0.003	0.1368547	0.000675892
		1408.006	0.003	0.2106923	0.001015776
		1769.09	0.05	9.58546E-05	3.78571E-06



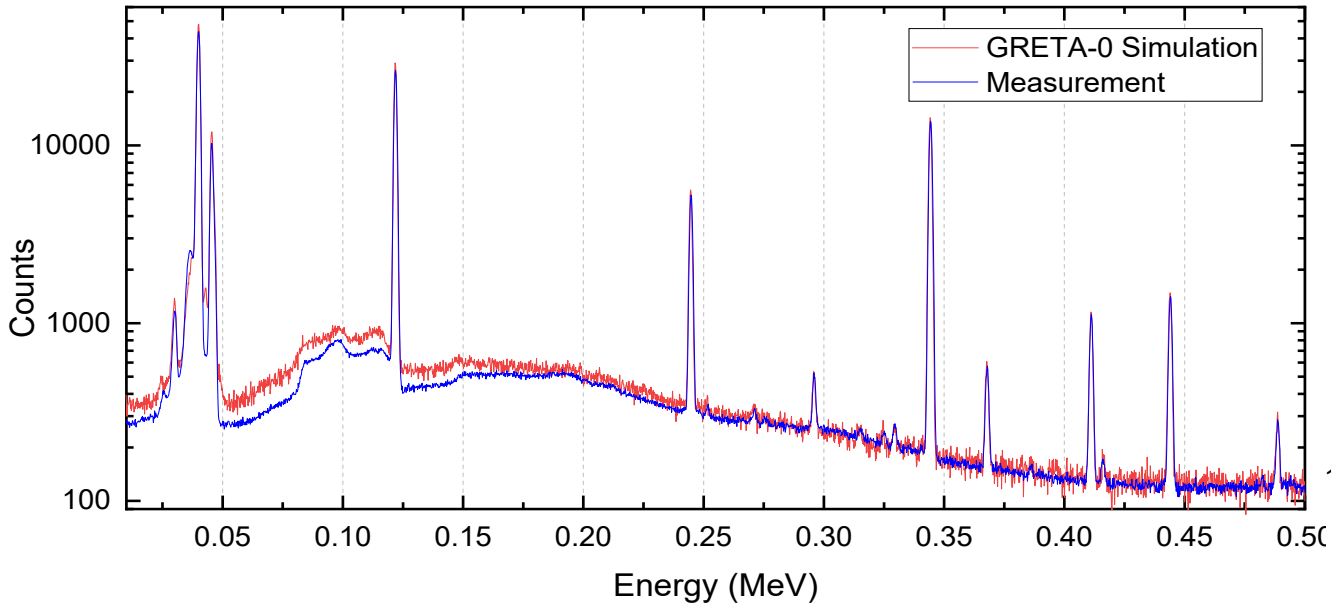
Detector Efficiency - Continued

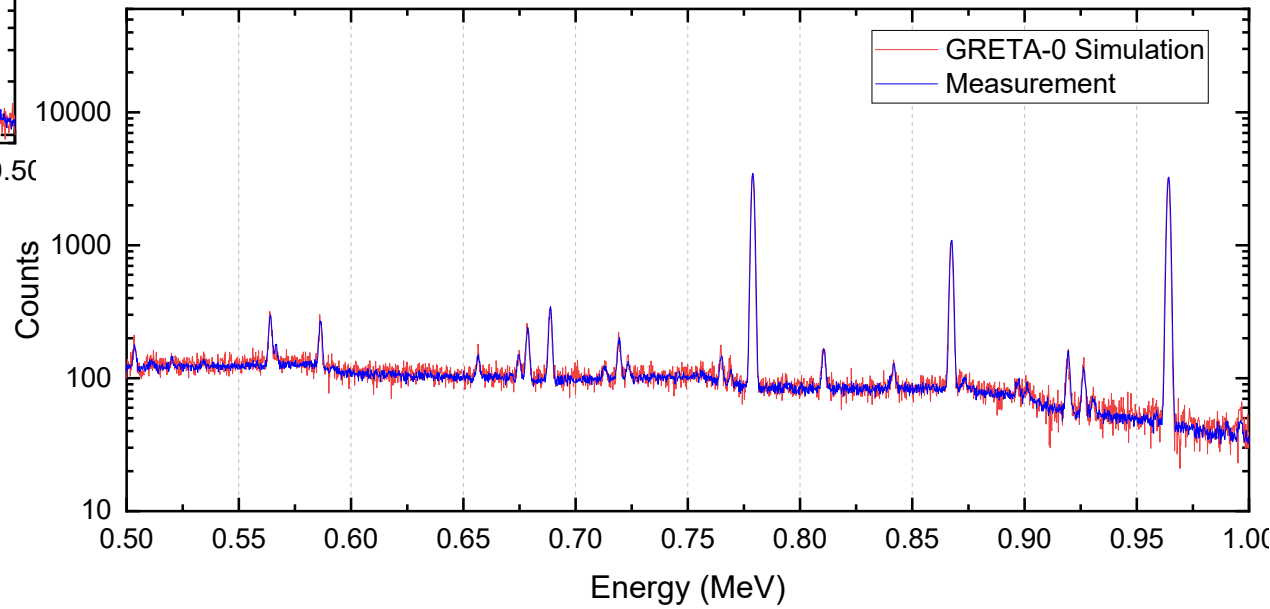
- The source was placed 50-cm away from the center of the detector front face.
- A detailed MCNP model of the ^{152}Eu check source was completed



Model Vs. Measurement – Eu-152

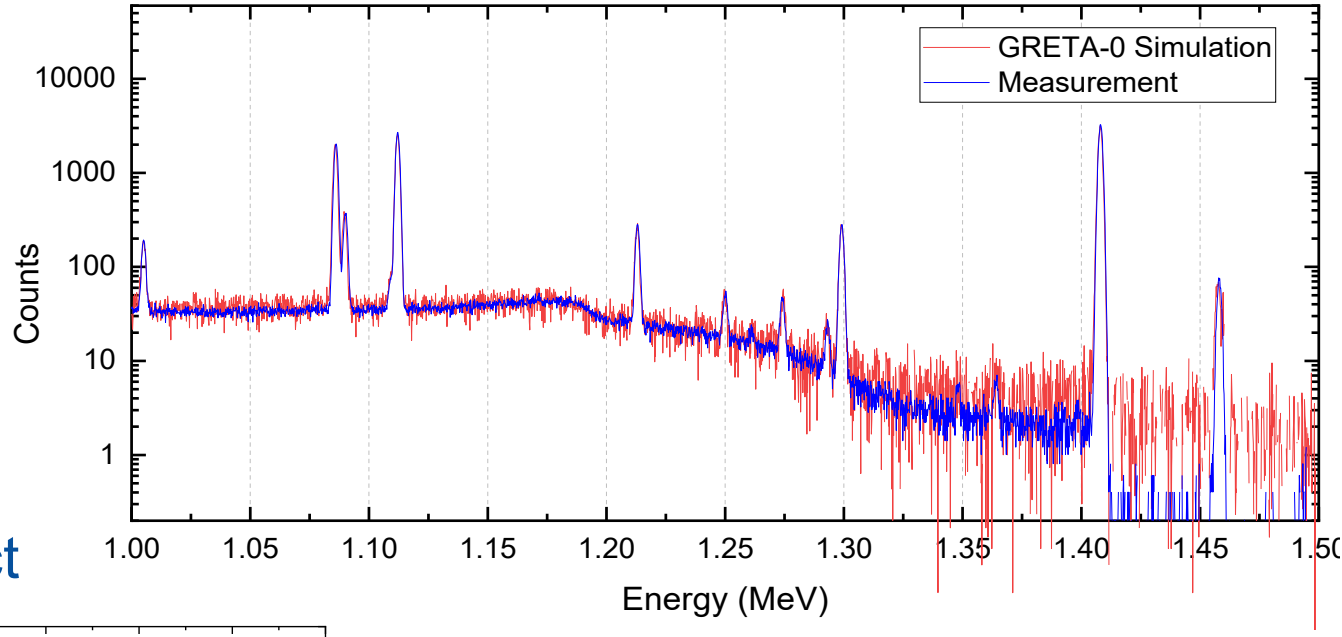
Comparison of select energy ranges



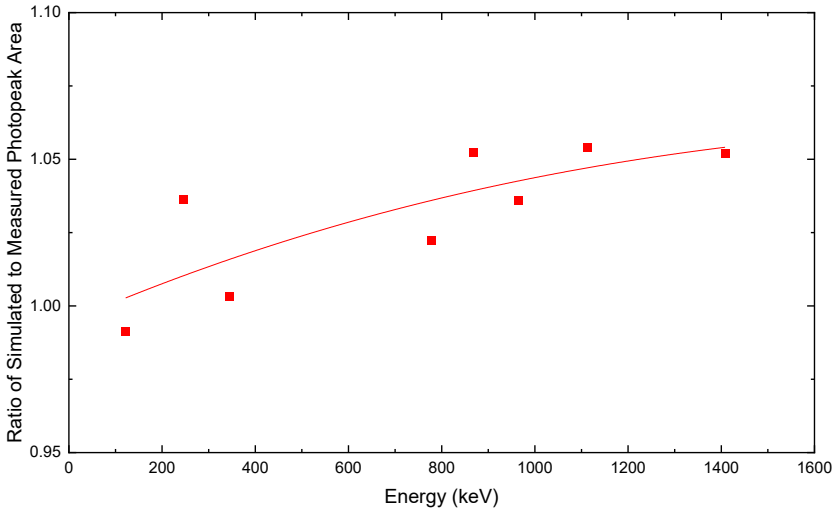


Model Vs. Measurement – Eu-152 (continued)

- Comparison between source spectrum measured and simulated for energies between 1000 and 1500 keV

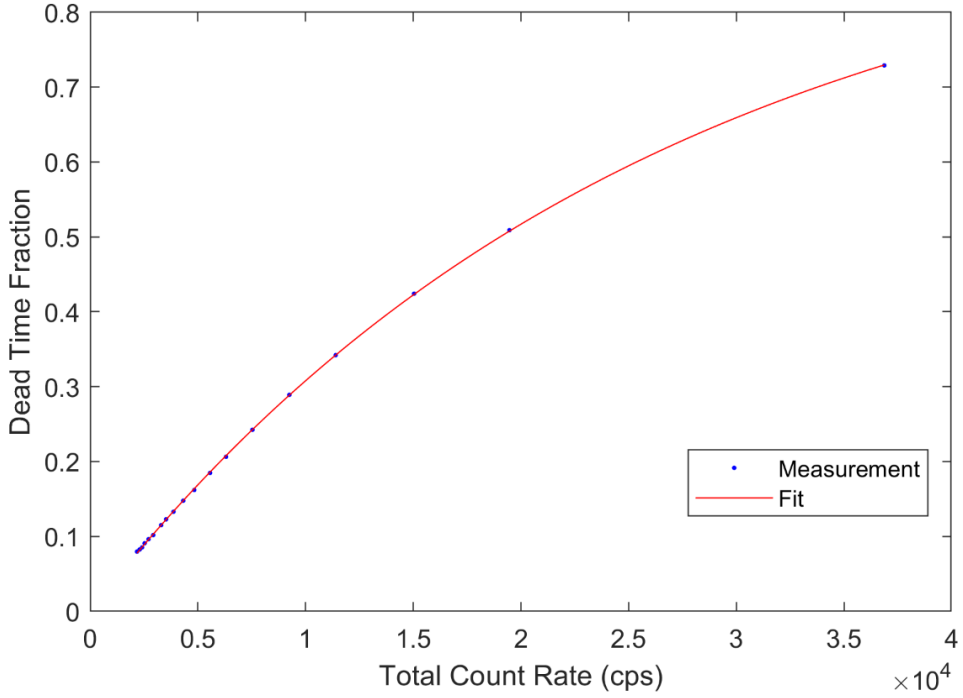


- Comparison of photopeak area for select gamma energies



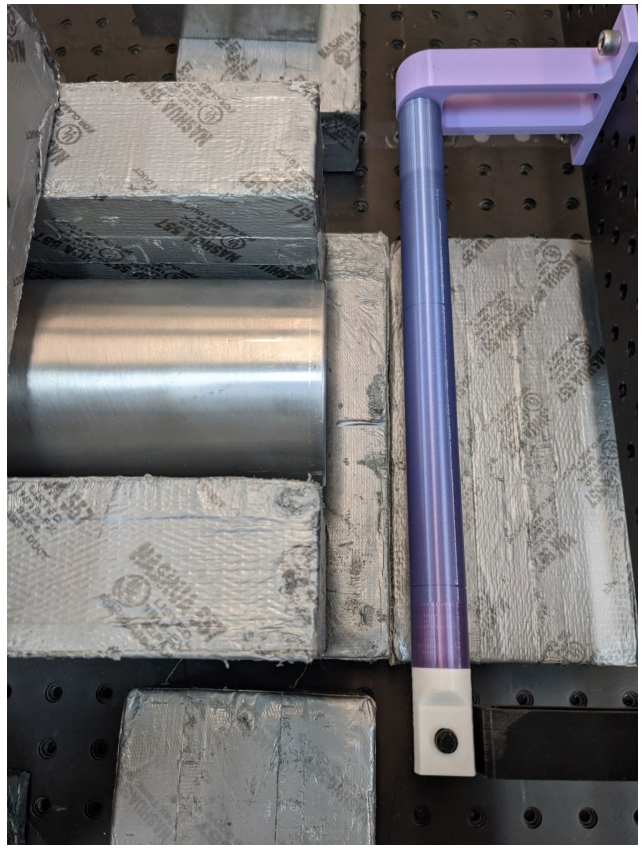
Dead Time Evaluation

- The measurement of dead time was performed using two sources, ^{60}Co and ^{152}Eu
- The ^{152}Eu source was kept at a consistent distance from the detector face while the ^{60}Co source was moved to assess the effect of the increased count rate on the detector's dead time
- The area of three photopeaks from the ^{152}Eu (121, 778, and 1408 keV) were used to discern the dead time

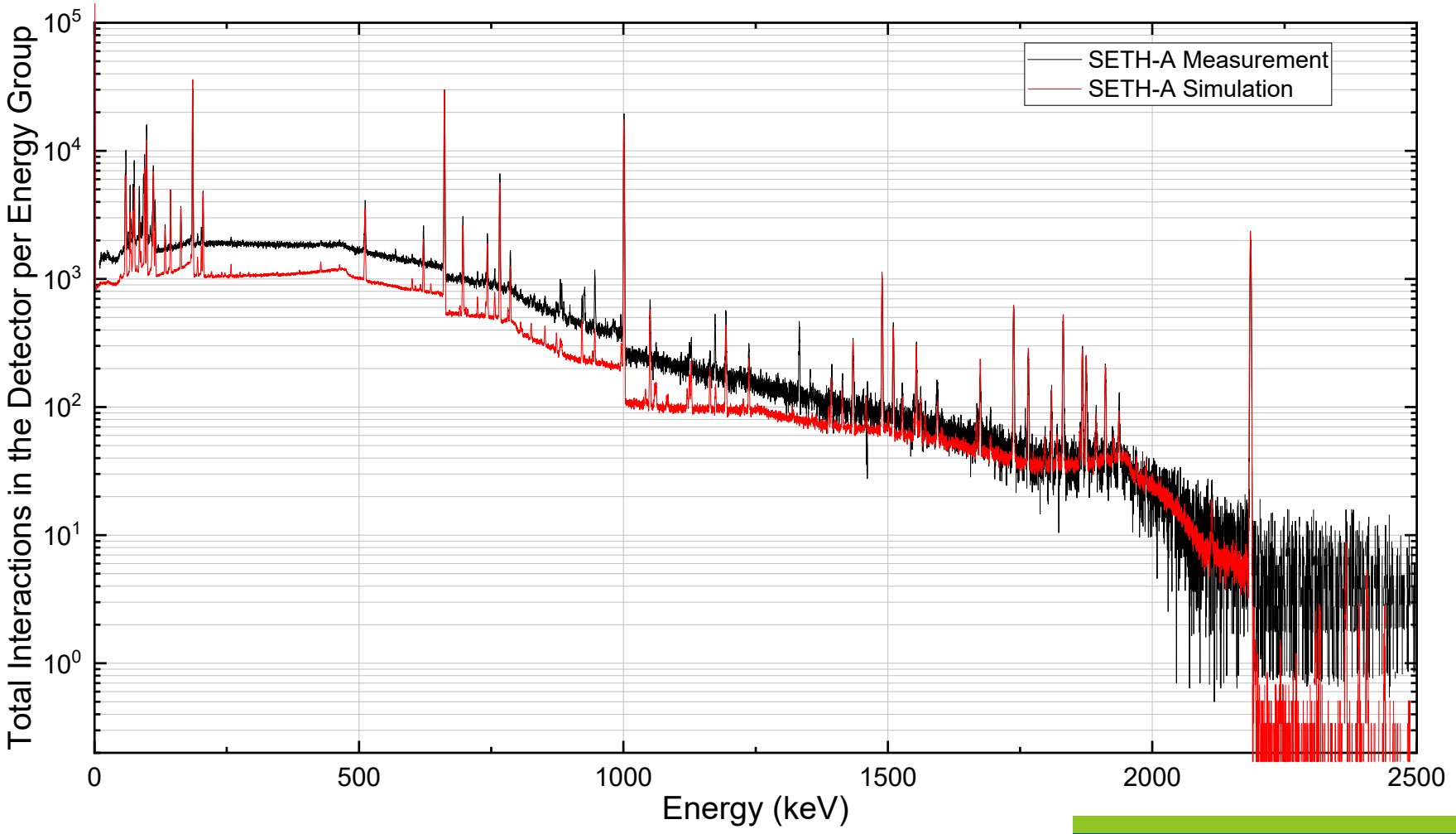


Separate Effect Test Holder (SETH) capsule

- Contains a rodlet composed of 10-pellets of 4.9% enriched fresh UO_2 fuel in Zircaloy cladding
- The SETH-A capsule was extracted for post irradiation examination after its irradiation
- To determine the number of fissions independently of previous measurements with other detectors, a separate measurement of the SETH-A rodlet was conducted with the shielding removed
- Data was recorded for 3000 seconds



SETH-A Spectrum



Calculating Number of Fissions

- Number of fissions can be calculated using[1]:

$$N = \frac{Ae^{\lambda t_d}}{C\eta\varepsilon mg\left(1-e^{-\lambda t_r}\right)}$$

$$J = fissions \times \frac{MeV}{fission} \times \frac{1.602e-13\ J}{MeV}$$

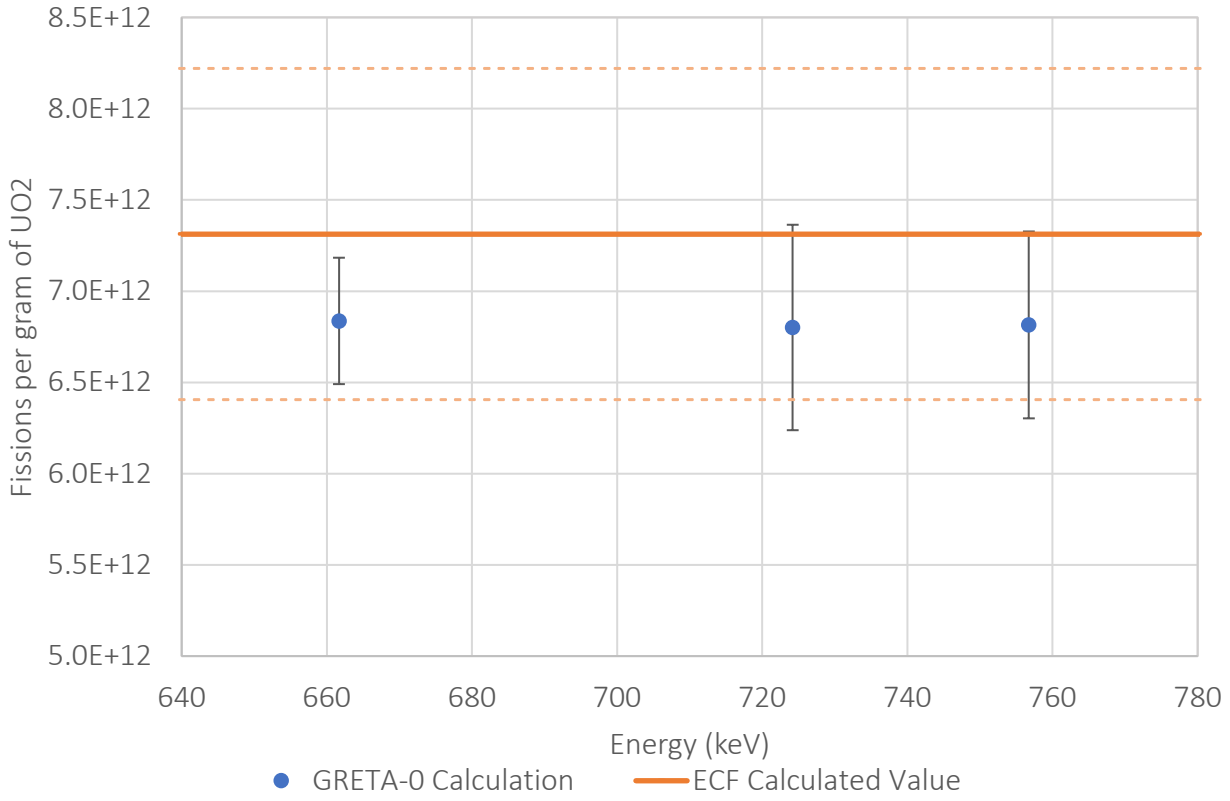
$$CF \equiv \frac{\text{Energy deposited in sample}}{(\text{material mass})(\text{Reactor Energy})} = \frac{J}{g-MJ}$$

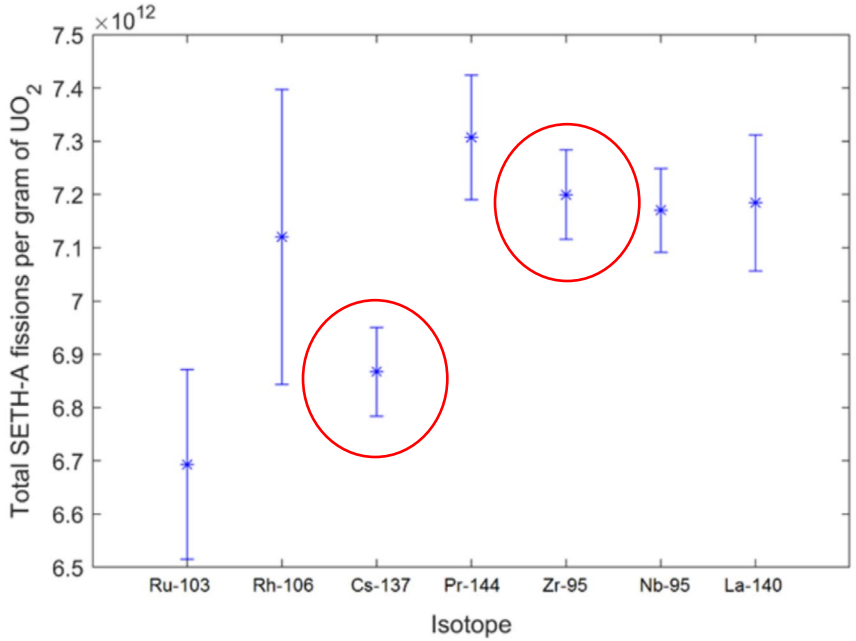
Variable	Description
N	Number of fissions per gram of fissile isotope
A	Area of photopeak that corresponds to gamma of interest (counts)
t_r	Real time of measurement by detector (s)
t_d	Time between beginning of irradiation to beginning of detector measurement (s)
η	Quantum yield of gamma ray per disintegration
ε	Absolute efficiency at desired energy
g	Self-shielding factor
λ	Decay constant (s^{-1})
C	Cumulative fission yield
m	Mass of parent isotope in sample (g) (i.e. ^{235}U)

- Total number of fissions per gram of UO_2 were previously published by N. Woolstenhulme[2]

[1] Holschuh, T., Watson, S., Chichester, D., "TREAT Reactor Metrology Results from CTFW-4 and CTFW-5," INL/EXT-20-57177, March 2020. Idaho National Laboratory, External Report.
[2] Woolstenhulme, N., Fleming, A., Holschuh, T., Jensen, C., Kamerman, D., Wachs, D., "Core-to-specimen energy coupling results to the first modern fueled experiments in TREAT," Annals of Nuclear Energy 140 (2020) 107117.

Number of Fissions Comparison

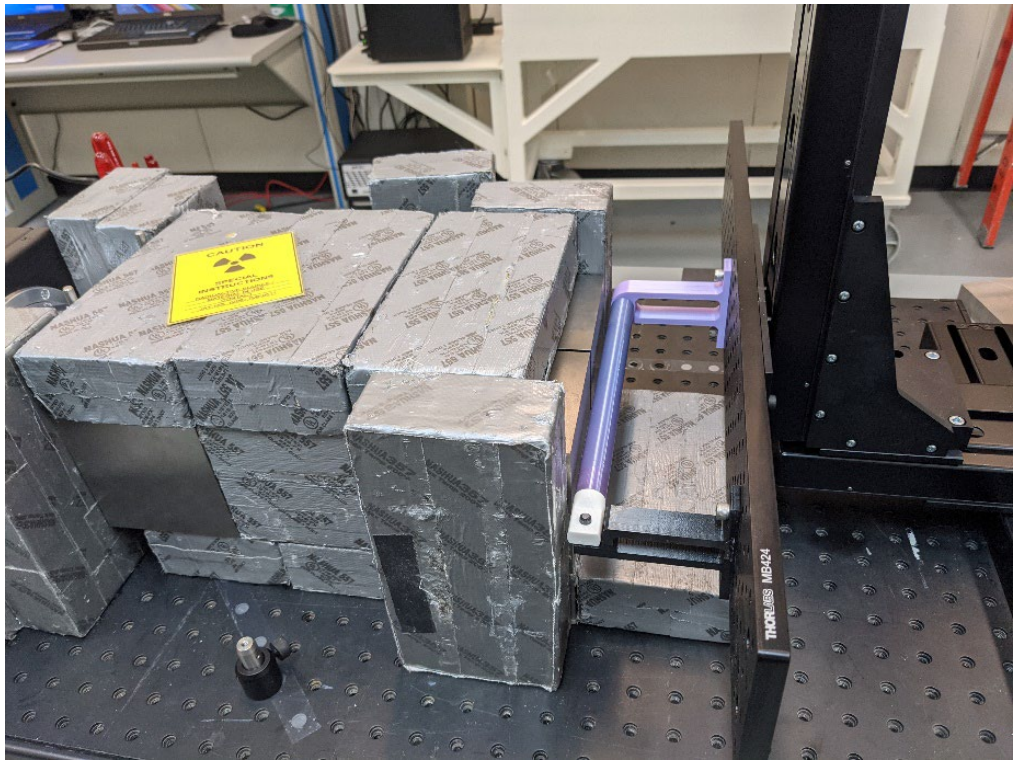


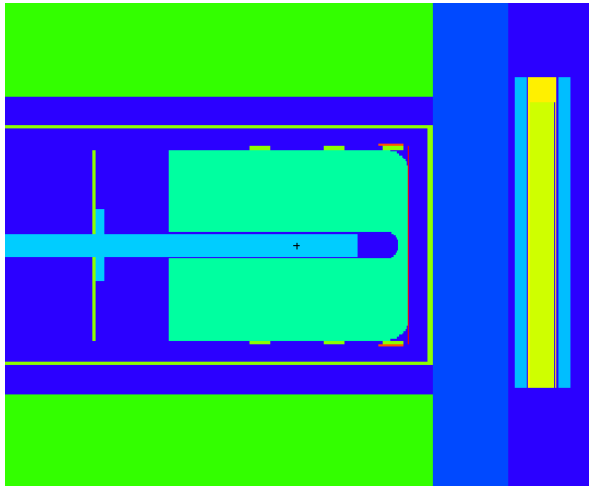


Fission events from SETH-A gamma spectroscopy by Woolstenhulme et al.

SETH-A Scan

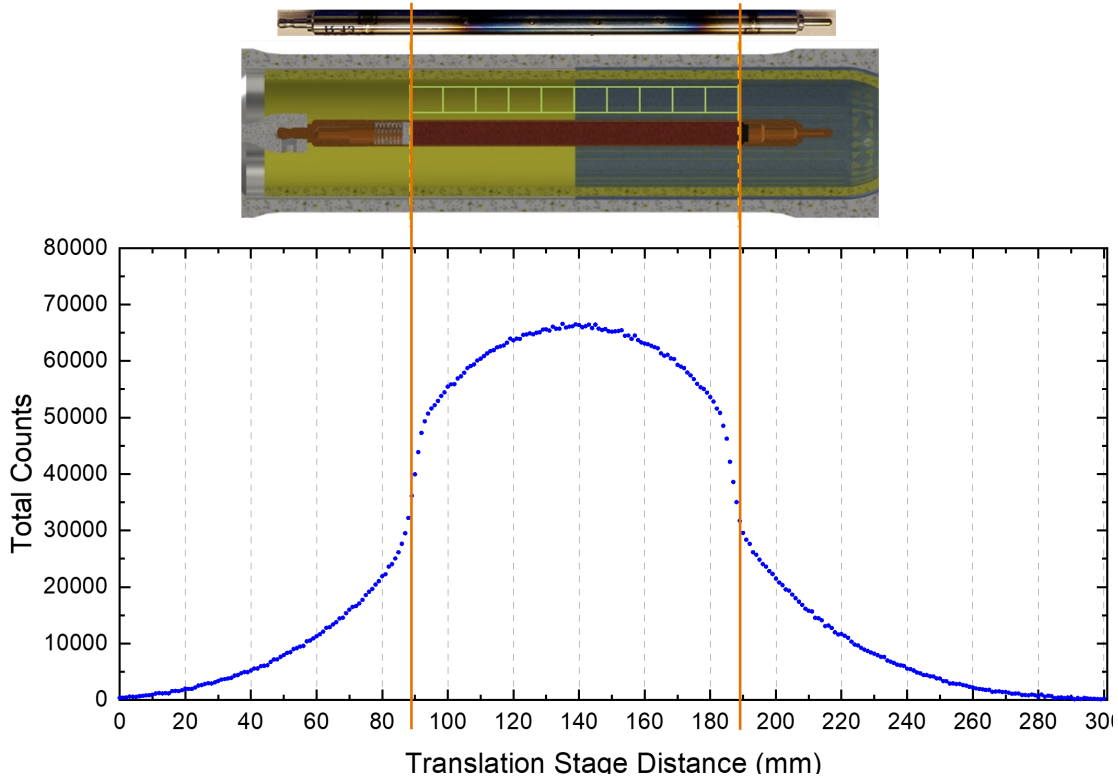
- Shielded Scan
  - Shielding with tungsten and lead blocks
  - 3-mm slit
  - Rodlet is 2-mm away from the face of the tungsten blocks
  - Calculated dead time was approximately 1%
  - 600 second dwells

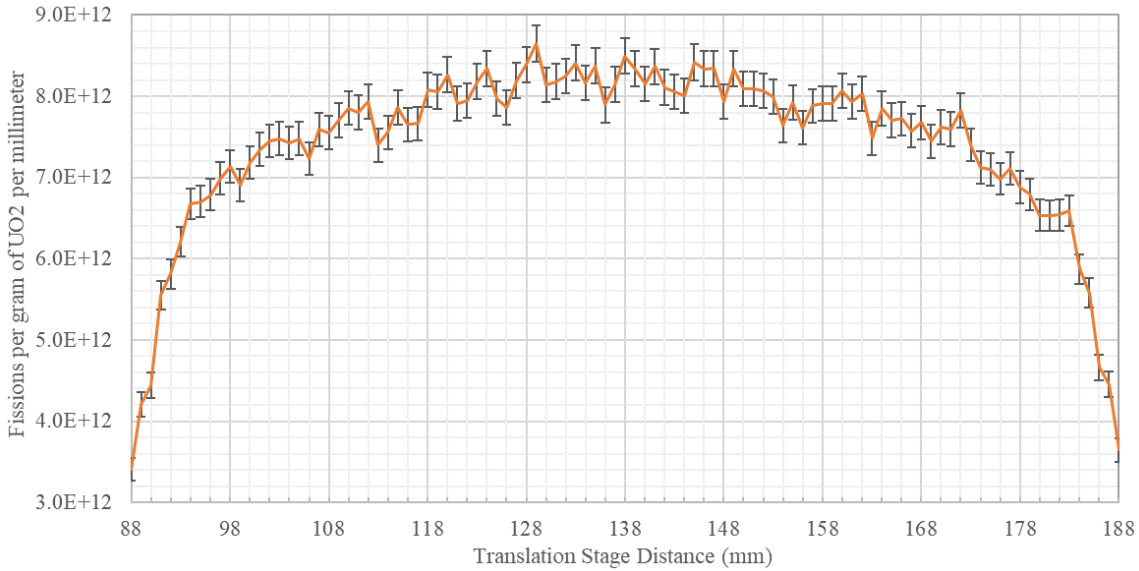




SETH-A Scanning Results

- The average number of fissions for the entire rodlet was determined to be 7.37 x 10^{12} with an uncertainty of 2 x 10^{11}





Summary

- The model was benchmarked against measurements to ensure its fidelity
- Efficiency and dead time calculations were performed to further characterize the detector
- An irradiated fuel rodlet was used to perform benchmark measurements and calculation of the number of fissions per gram of UO_2
- A scan of the rodlet enabled calculation of the number of fissions per millimeter
- This showed agreement with the unshielded GRETA-0 number of fissions and the previously estimated results.
- The next step for this work will be to perform gamma-ray assays on other fuel samples with various geometries, this will help test the limits of the model-based efficiency determination method, and to test the system's mechanical stage range
- Longer term, a new scanning system (GRETA-1) is under development that will support 3-D gamma-ray tomography of irradiated fuel samples

Acknowledgements

This research was supported by the Advanced Fuels Campaign and the Office of Nuclear Energy of the U.S. Department of Energy. INL is operated for the U.S. Department of Energy by Battelle Energy Alliance under DOE contract DE-AC07-05-ID14517.

Idaho National Laboratory

Battelle Energy Alliance manages INL for the U.S. Department of Energy's Office of Nuclear Energy. INL is the nation's center for nuclear energy research and development, and also performs research in each of DOE's strategic goal areas: energy, national security, science and the environment.