Benchmarking and Sensitivity Analysis of the UNM AGN-201M

Rowdy Davis, Ph.D – Reactor Administrator

TRTR 2024, Albuquerque, NM

UNM NUCLEAR ENGINEERING

Outline

- Introduction
  - Goal
  - Foundation and Motivation
  - Execution

Methodology
  - WHISPER
  - TSUNAMI-IP
  - TSURFER
- Benchmarking the UNM AGN-201M
- General Results
- Concluding Statements
- Extra Slides

Introduction - Goal

- Improve benchmark coverage of ICSBEP handbook via
  - Understanding how HALEU systems can address gaps in coverage
  - Understanding impact of uncertainty in graphite moderated systems
  - Understanding impact of nuclear data uncertainty on TRISO Fuel

Introduction – Foundation and Motivation

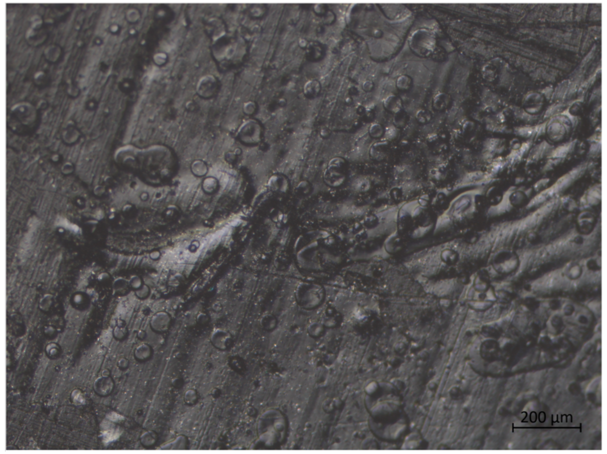
- The ICSBEP:
  - International Criticality Safety Benchmark Evaluation Project
  - Tasked by WPNCS/NEA on compiling critical and subcritical experimental data
  - Used for validation and safety analysis
  - Creates a handbook of evaluated benchmarks

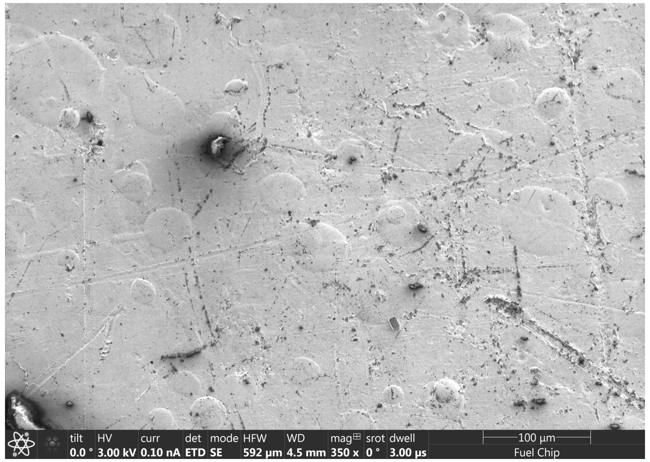
Introduction – Foundation and Motivation

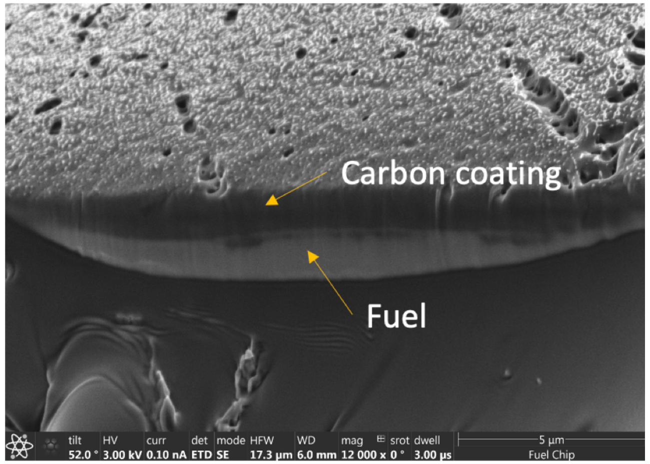
Experimental Category	Evaluation Count
PU (Plutonium)	801
HEU (Highly Enriched Uranium)	1433
IEU (Intermediate Enriched Uranium)	278
Non-HALEU LEU (Low Enriched Uranium)	1296
HALEU (High-Assay Low Enriched Uranium)	526
^{233}U	244
MIX (Pu/U)	536
SPEC (Other Actinides)	20
ALARM (Shielding)	46
FUND (Physics)	238
TOTAL	5,428

Introduction - Execution

- The AGN-201M was used to assist in coverage for TRISO/HALEU
  - Nominally 19.5% ^{235}U
  - UO_2 loaded
  - “TRISO-type” fuel
  - Large volume of graphite





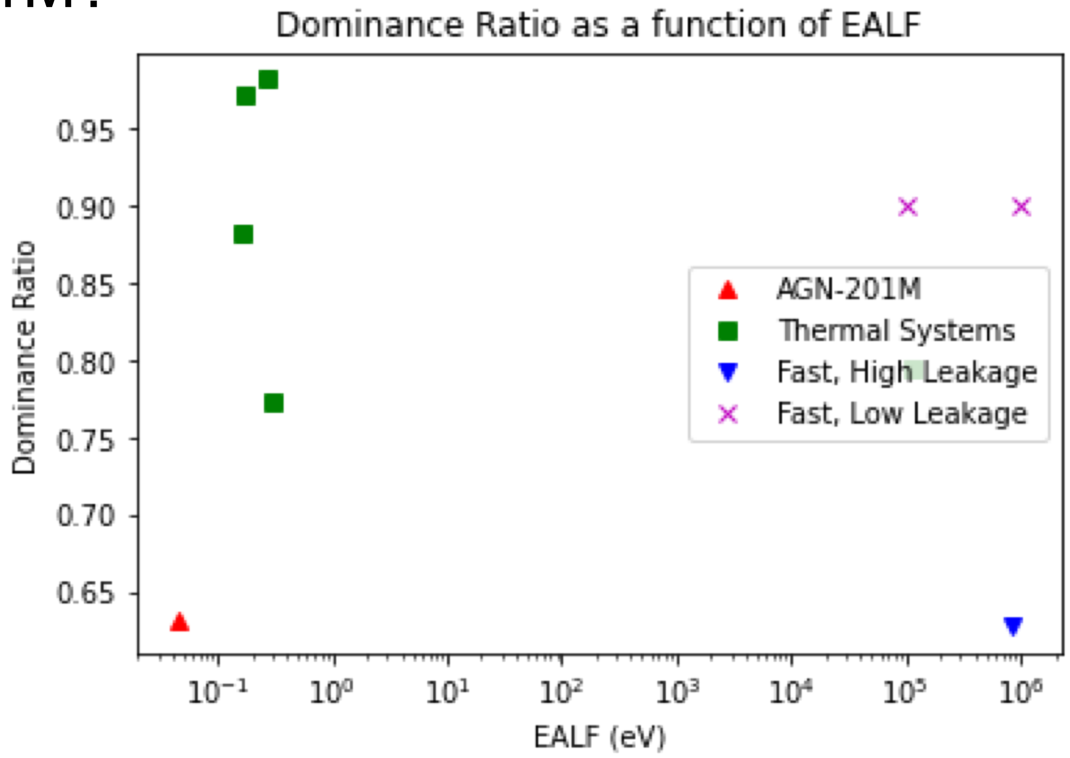


Introduction - Execution

- Microspheres are between 5 and 25 microns
  - Nominally 15 microns
- Should exhibit similar physics properties (resonance energy flux depressions) with TRISO due to size, shape and composition
- Should serve as a useful comparison for NCS application (fuel production and storage) due to fuel composition and geometry

Introduction – Review

- What else do we know about the AGN-201M?
  - Low Dominance Ratio (0.6244)
  - Very thermal spectrum (EALF of 0.045 eV)
  - Avg. Neutron Temperature of 522 K



Methodology – Benchmarking Overview

- The Benchmarking Process
  - A Year to Multi-Year long process
  - Includes historical research, measurement identification, collection, and evaluation
  - Benchmark writing to the standards of the ICSBEP
  - Internal Review
  - External Review
  - Working Group Review
  - Final Edits
  - Final Submission

Methodology – AGN Process

- Benchmarking the AGN-201M
- Identified as a key candidate due to material and physics properties
- Significant measurements had been performed
  - Wetzel, Busch, Carpenter, Bowen
- Raw model already existed (Henderson)
- Extensive historical knowledge existed

Methodology – AGN Process

- Benchmarking broken down into multiple steps
  - Identify missing measurements and uncertainties for
    - Access ports, rod drive
  - Verify Wetzel's measurements from 2019 w/ higher accuracy of uncertainties
  - Repeat Bowen's 36 measurements with additional measurements
  - UQ analysis on measurements w/ ICSBEP Unc. Guide
  - Direct perturbation and total uncertainty calculations

Methodology - WHISPER

- WHISPER 1.1
- A package with MCNP6.2
- Utilizes covariance files and sensitivity profiles to calculate *S*
- Uses the BLO data (~1100 experiments)
- Matches sensitivity profiles from an application against the catalog of experimental data
- Used to:
  - Identify similar experiments with the AGN-201M
  - Calculate nuclear data uncertainty in the model

Methodology – TSUNAMI-IP

- Tools for Sensitivity and Uncertainty Analysis Methodology Implementation – Indices and Parameters
- Uses sensitivity data generated from TSUNAMI and covariance data from SCALE
- SCALE 6.2.2 used
- Looked at c_k values (similarity coefficients) to quantify unc. based similarity on nuclide-specific reactions
- Used 2,929 benchmarks from the NEA (ICSBEP / IRPhEP)

Methodology – TSUNAMI-IP

- Compared the 2,929 experiments and the AGN against 36 applications
- Wanted to answer where the AGN-201 was a better fit than current benchmarks for these 36 applications
- Investigated the following nuclide-specific reactions:
  - ^{1}H total
  - ”c-graphite” total
  - ^{235}U fission
  - ^{238}U total

Methodology - TSURFER

- Tool for Sensitivity/Uncertainty analysis of Response Functionals using Experimental Results
- Module within the SCALE 6.2.2 code
- Does 3 things:
  - Computes uncertainties in integral responses (k_{eff})
  - Reduce discrepancies between measured and calculated responses via adjusting nuclear data and experimental values
  - Analyze measured responses from benchmark experiments (2,929) to establish bias and uncertainty in calculated responses
- Ran with and without the AGN-201 included

Benchmarking

- Benchmark is Broken into 4 Parts
- A Detailed Description of the System
- Evaluation of Experimental Data
  - The “Calcs” section
- Description of the Model
  - Difference between the system and model, if any
- Sample Calculation Results
  - Sims

Developing the Benchmark

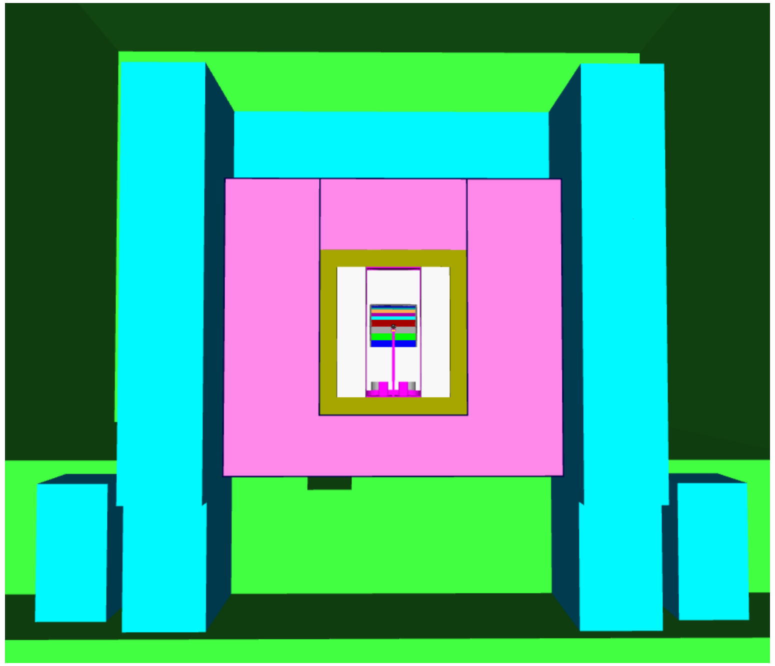
- Needed to figure out what a benchmark looked and sounded like
- Disassembled reactor in 7/2022
- Rod UQ in 10/2022
- Measurements (Experimental) in 10/2022
- Finalized measurements and analysis in 10/2023
    - Access ports, fuel

Uncertainty Quantification Items

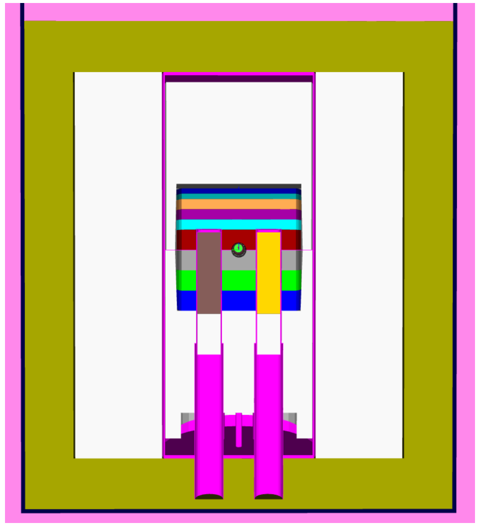
- Nuclear data
  - WHISPER1.1 / MCNP6.2
- Lower and Upper Graphite Density
- Concrete Shielding
- Water Impurities
- Homogeneity
- Lead, Graphite, and Fuel Impurities
- Rod Bounds
- Temperature
- Enrichment
  - Bounding and Realistic

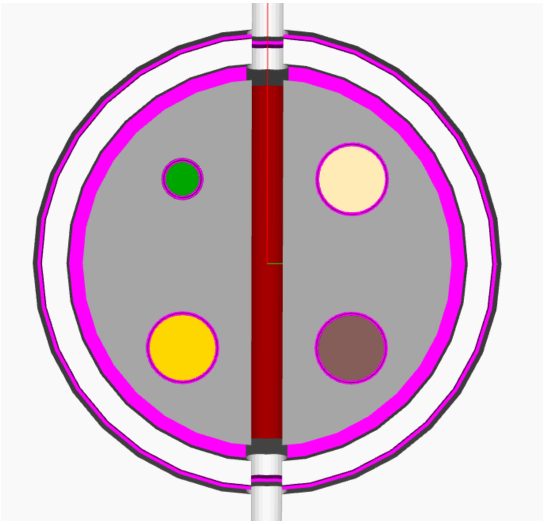
Model and Reality

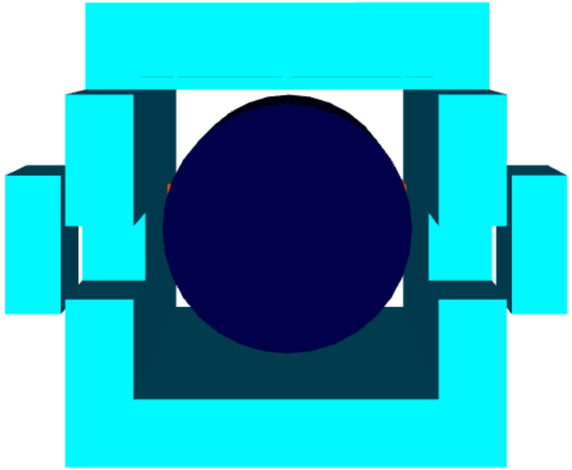
- Rod Positions Corrected for:
    - Limit Switch Offset of 0.46 cm
    - Console Error (0.06 cm for CCR and 0.13 cm for FCR)
- Contains Access Port Loadings
    - No 2-Ci PuBe Startup Source
    - No Cd Shield or Al Container
    - Modeled as Ponderosa Pine
- Contains Shielding and Reactor Room
- Contains material impurities, where known
    - Lead/Graphite: U of Utah
    - Water/Fuel: UNM

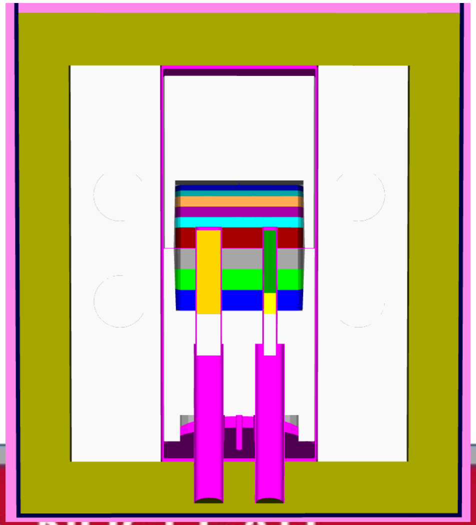


Color	Material
	Fuel Disk 097
	Fuel Disk 098
	Fuel Disk 099
	Fuel Disk 100
	Fuel Disk 101
	Fuel Disk 102
	Fuel Disk 103
	Fuel Disk 104
	Fuel Disk 105
	SR1 Fuel
	SR2 Fuel
	CCR Fuel
	FCR Fuel
	Thermal Fuse
	Water
	Graphite
	Lead
	Aluminum
	Steel
	Wood (Pine)
	Polyethylene
	Concrete (Shielding)
	Concrete (Room)

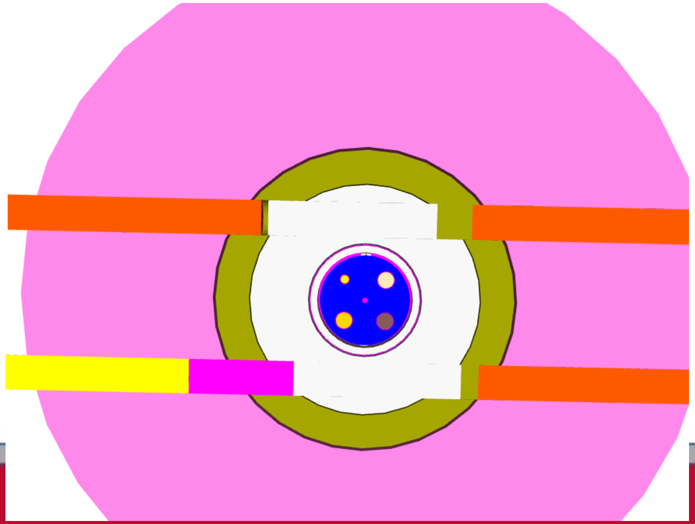








Color	Material
	Fuel Disk 097
	Fuel Disk 098
	Fuel Disk 099
	Fuel Disk 100
	Fuel Disk 101
	Fuel Disk 102
	Fuel Disk 103
	Fuel Disk 104
	Fuel Disk 105
	SR1 Fuel
	SR2 Fuel
	CCR Fuel
	FCR Fuel
	Thermal Fuse
	Water
	Graphite
	Lead
	Aluminum
	Steel
	Wood (Pine)
	Polyethylene
	Concrete (Shielding)
	Concrete (Room)



Notable Benchmark Findings

- Graphite Impurities offer highest uncertainty
- Water shielding accounts for +0.02 on the eigenvalue
- Upper graphite density has a higher effect on uncertainty than lower graphite density
- Able to lower uncertainty from ISU’s AGN of 846 pcm to 241 pcm

Validation

- How did adding the AGN-201M quantitatively improve benchmark coverage?
  - Is the AGN a better fit than other benchmarks?
  - How does the AGN affect cross section adjustment?
- Using WHISPER, TSUNAMI-IP, and TSURFER to answer these questions

WHISPER

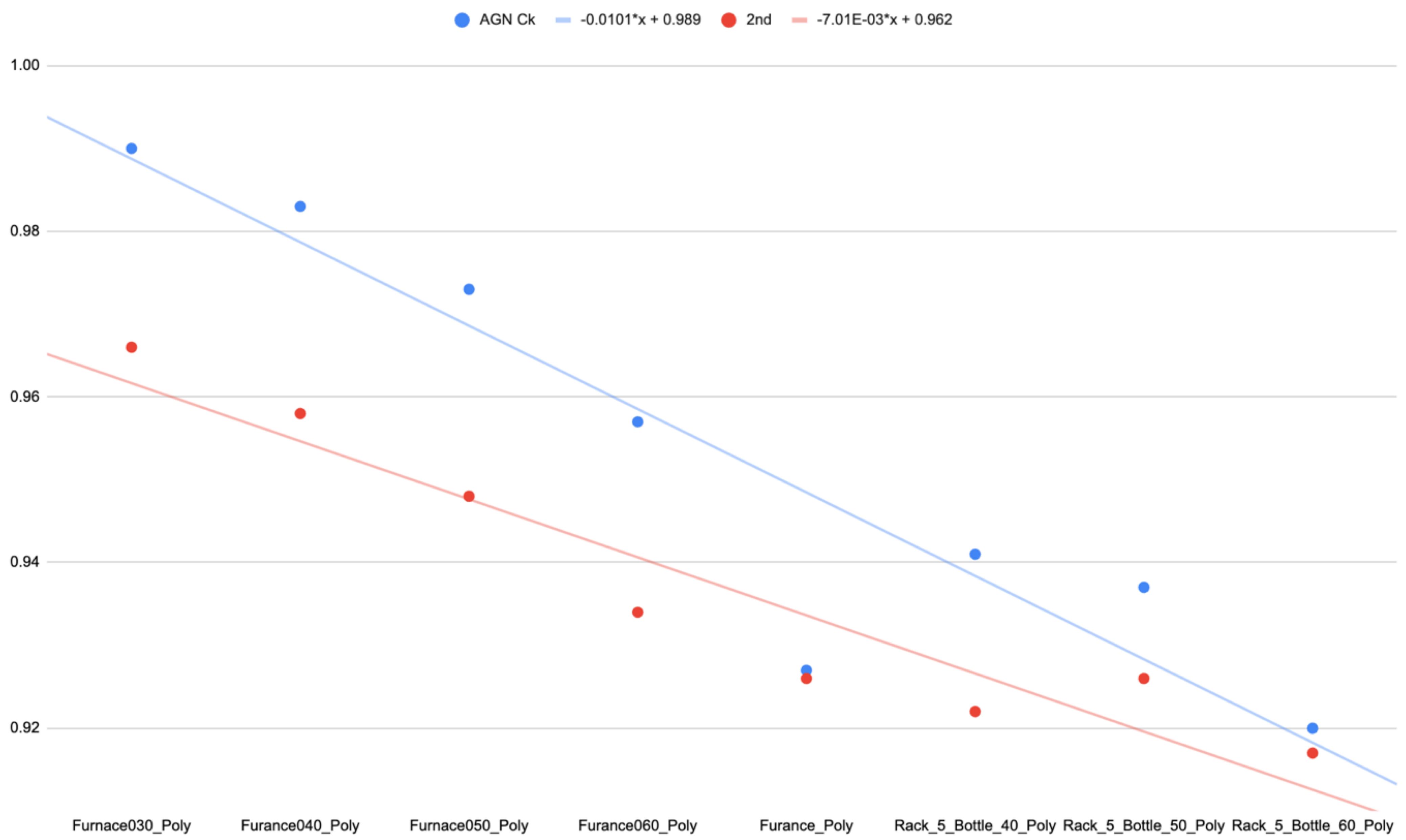
- Used to identify similar experiments to aid in library creation for TSUNAMI and TSURFER
- Uses Extreme Value Theory to estimate worst-case bias based on observed biases in similar experiments
- Identified a nuclear data uncertainty of 670 pcm
- 65 benchmarks were identified to be similar down to a c_k of 0.92
- 52 of 65 were HEU
- All 65 were thermal spectrum

TSUNAMI-IP

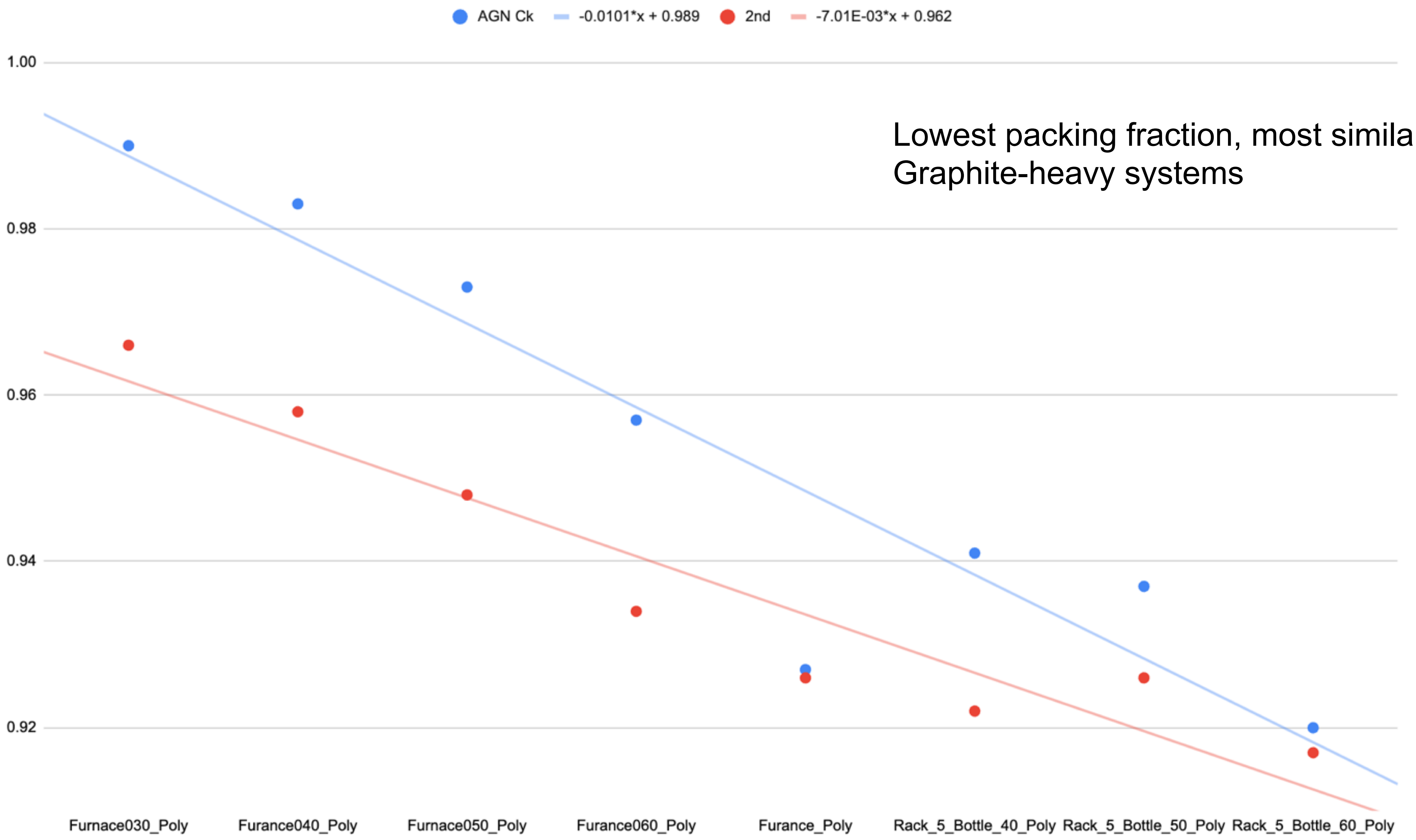
- Used to investigate similarity coefficients between the AGN and other experiments and cases
- Estimates similarity coefficients, then uses linear regression to extrapolate bias based on the observed biases from similar experiments
- 2,929 experiments from the NEA
- 36 applications
- AGN-201M as an experiment
- AGN performed better than the 2,929 experiments on 8 of the 36 applications

TSUNAMI-IP

Application ID	AGN-201 C_k	2^{nd} Best Experiment	2^{nd} Best C_k	Delta C_k (AGN – 2^{nd} Best Exp.)
Furnace030_Poly	0.990	ICT-001-027	0.966	0.024
Furnace040_Poly	0.983	ICT-001-025	0.958	0.025
Furnace050_Poly	0.973	ICT-001-025	0.948	0.025
Furnace060_Poly	0.957	ICT-001-025	0.934	0.023
Infinite (Poly)	0.927	ICT-001-013	0.926	0.001
Rack_5_Bottle_40_Poly	0.941	ICT-001-027	0.922	0.019
Rack_5_Bottle_50_Poly	0.937	ICT-001-025	0.926	0.011
Rack_5_Bottle_60_Poly	0.920	HST-005-004	0.917	0.003



AGN Ck
-0.0101*x + 0.989
2nd
-7.01E-03*x + 0.962
1.00
0.98
0.96
0.94
0.92
Furnace030_Poly
Furance040_Poly
Furnace050_Poly
Furance060_Poly
Furance_Poly
Rack_5_Bottle_40_Poly
Rack_5_Bottle_50_Poly
Rack_5_Bottle_60_Poly



Lowest packing fraction, most similar Graphite-heavy systems

Future Research

- Better fuel qualification
- Better graphite and lead quantification
- Integral experiments for Cu, Cl, Xe, N, and other isotopes of interest

Closing

- Goal: Bridge the gap of the ICSBEP and IRPhEP benchmark handbooks
- Quantify the improvement
- HALEU and TRISO are becoming more present
- Advanced Reactors need current comparisons
- Benchmark expected to go to review group and get accepted in 7/2024
- AGN most similar to systems with high volumes of moderator
  - ~11 kg of polyethylene compared to 666.76 g of ^{235}U
  - May be useful for NCS upset conditions

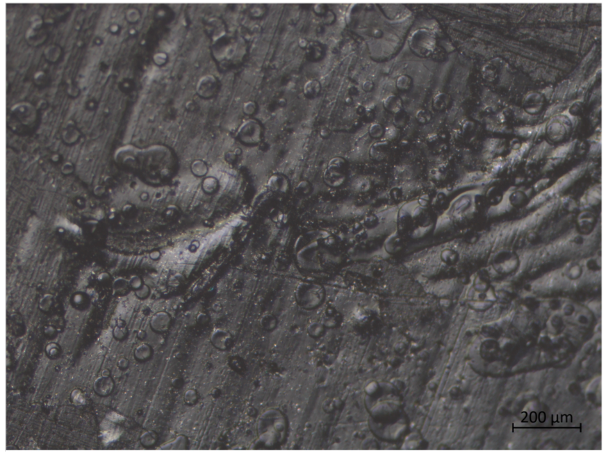
Closing

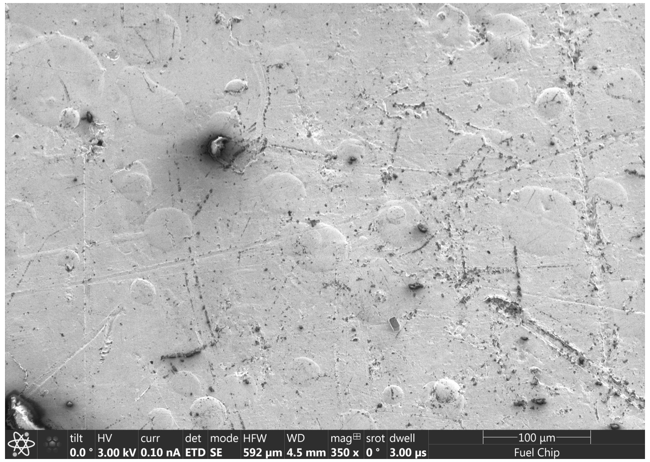
- The AGN benchmark more similar than all of 2,929 cases in benchmark library for 8 of 36 applications
- The AGN produced top 1,000 c_ks for 20/36 applications
- Lowered XS adjustments and uncertainty in those adjustments

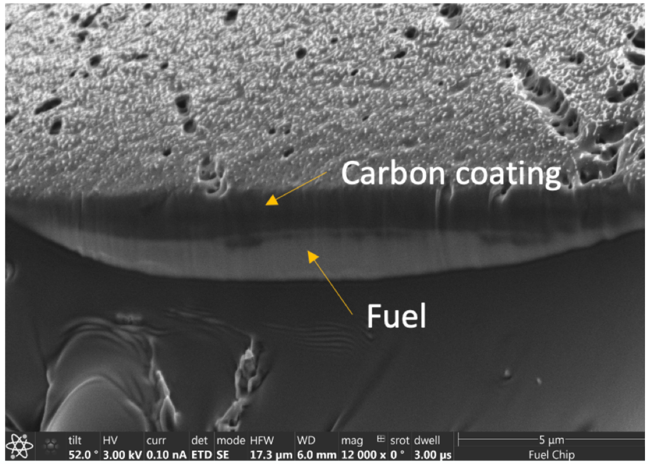
EXTRA SLIDES AND DUPLICATES

Introduction - Execution

- The AGN-201M was used to assist in coverage for TRISO/HALEU
  - Nominally 19.5% ^{235}U
  - UO_2 loaded
  - “TRISO-type” fuel
  - Large volume of graphite







Introduction - Execution

- Microspheres are between 5 and 25 microns
  - Nominally 15 microns

Introduction - Execution

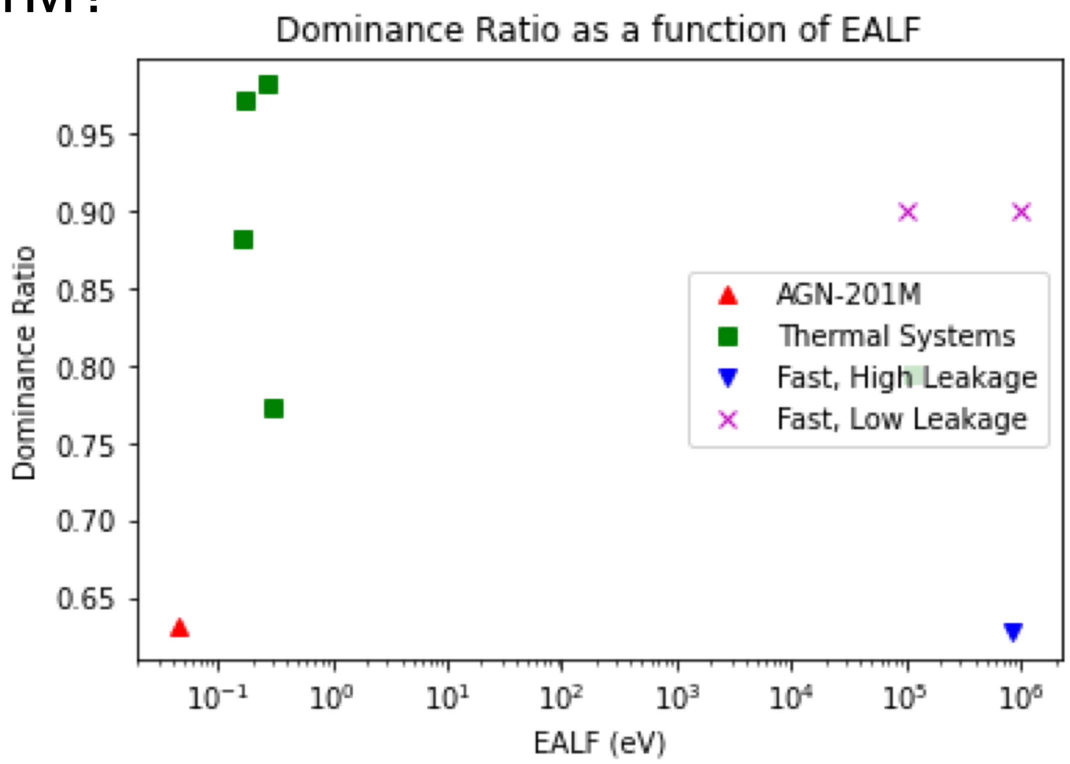
- Microspheres are between 5 and 25 microns
  - Nominally 15 microns
- Should exhibit similar physics properties (resonance energy flux depressions) with TRISO due to size, shape and composition

Introduction - Execution

- Microspheres are between 5 and 25 microns
  - Nominally 15 microns
- Should exhibit similar physics properties (resonance energy flux depressions) with TRISO due to size, shape and composition
- Should serve as a useful comparison for NCS application (fuel production and storage) due to fuel composition and geometry

Introduction – Review

- What else do we know about the AGN-201M?
  - Low Dominance Ratio (0.6244)
  - Very thermal spectrum (EALF of 0.045 eV)
  - Avg. Neutron Temperature of 522 K



Introduction - Review

- How do we know what we know?

Introduction - Review

- How do we know what we know?
    - Gorham's IRPhEP submission
    - AGN Publications
    - Bowen's work on Space-Time Kinetics of the UNM AGN-201M
    - Wetzel's work on documenting properties of UNM's AGN-201M
    - Brown and Olguin's work on the DR of the AGN
    - Cooke's work on kinetic parameters of the AGN at Naval Post Graduate School
    - Multitude of publications and experiments on the AGN (void coefficients, Rossi-alpha measurements, rod worths, etc.)

Methodology – Benchmarking Overview

- The Benchmarking Process
  - A Year to Multi-Year long process
  - Includes historical research, measurement identification, collection, and evaluation
  - Benchmark writing to the standards of the ICSBEP
  - Internal Review
  - External Review
  - Working Group Review
  - Final Edits
  - Final Submission

Methodology – AGN Process

- Benchmarking the AGN-201M
- Identified as a key candidate due to material and physics properties
- Significant measurements had been performed
  - Wetzel, Busch, Carpenter, Bowen
- Raw model already existed (Henderson)
- Extensive historical knowledge existed

Methodology – AGN Process

- Benchmarking broken down into multiple steps
  - Identify missing measurements and uncertainties for
    - Access ports, rod drive
  - Verify Wetzel's measurements from 2019 w/ higher accuracy of uncertainties
  - Repeat Bowen's 36 measurements with additional measurements
  - UQ analysis on measurements w/ ICSBEP Unc. Guide
  - Direct perturbation and total uncertainty calculations

Methodology - WHISPER

- WHISPER 1.1
- A package with MCNP6.2
- Utilizes covariance files and sensitivity profiles to calculate *S*
- Uses the BLO data (~1100 experiments)
- Matches sensitivity profiles from an application against the catalog of experimental data
- Used to:
  - Identify similar experiments with the AGN-201M
  - Calculate nuclear data uncertainty in the model

Methodology – TSUNAMI-IP

- Tools for Sensitivity and Uncertainty Analysis Methodology Implementation – Indices and Parameters
- Uses sensitivity data generated from TSUNAMI and covariance data from SCALE
- SCALE 6.2.2 used
- Looked at c_k values (similarity coefficients) to quantify unc. based similarity on nuclide-specific reactions
- Used 2,929 benchmarks from the NEA (ICSBEP / IRPhEP)

Methodology – TSUNAMI-IP

- Compared the 2,929 experiments and the AGN against 36 applications
- Wanted to answer where the AGN-201 was a better fit than current benchmarks for these 36 applications
- Investigated the following nuclide-specific reactions:
  - ^{1}H total
  - ”c-graphite” total
  - ^{235}U fission
  - ^{238}U total

Methodology - TSURFER

- Tool for Sensitivity/Uncertainty analysis of Response Functionals using Experimental Results
- Module within the SCALE 6.2.2 code
- Does 3 things:
  - Computes uncertainties in integral responses (k_{eff})
  - Reduce discrepancies between measured and calculated responses via adjusting nuclear data and experimental values
  - Analyze measured responses from benchmark experiments (2,929) to establish bias and uncertainty in calculated responses
- Ran with and without the AGN-201 included

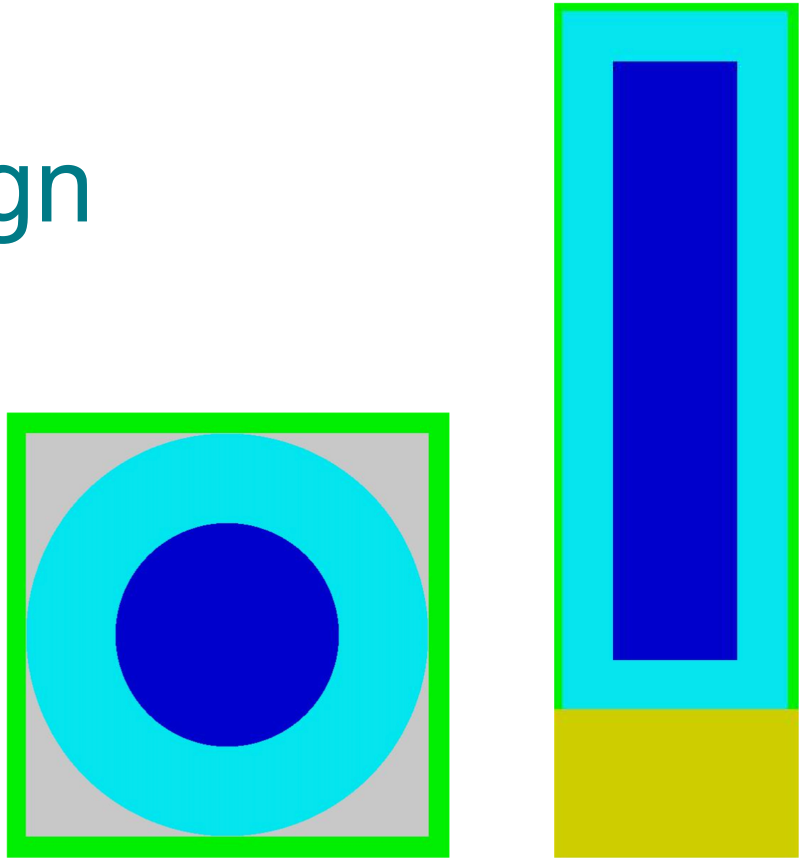
Methodology– Application Design

- Wanted to answer: Extent of AGN addition help benchmarking?
- Applications of HALEU and TRISO for NCS?
- Larry Wetzel, P.E. identified three primary areas:
  - Production of TRISO
  - Storage of HALEU
  - Transportation of HALEU/TRISO

Methodology – Application Design

- 2 Process systems discussed and selected
  - TRISO Furnace for fuel production
  - TRISO storage in Polyethylene bottles on Racks
- Created 36 applications for these 2 processes
  - Perturbed packing fraction of TRISO and infinite wet and dry cases

Methodology – Application Design



TRISO Furnace

- Composed of 2" Graphite walls
- 1” Cuboid of water surrounds the graphite
- 12” concrete slab added to bottom of furnace
- 1 kg of ^{235}U as TRISO
- TRISO modeled as homogenous spheres
- Upset condition was a water ingress from the top of the furnace

Methodology – Application Design

	Radius [cm]	Volume [cm^3]	Density [g/cm^3]	Mass [g]	Mass [wt. frac.]	*Material*	*Weight Fraction*
Kernel	0.02	3.351E-05	10.935	0.000366	0.393	*UO_2*	*0.393682*
Buffer	0.03	7.958E-05	1.130	8.99E-05	0.096	*Si*	*0.135908*
IPyC	0.034	5.153E-05	2.260	0.000116	0.125	*C*	*0.470410*
SiC	0.0375	5.626E-05	3.210	0.000181	0.194	---	---
OPyC	0.0415	7.849E-05	2.260	0.000177	0.190	---	---

TRISO Properties in SCALE 6.2.2

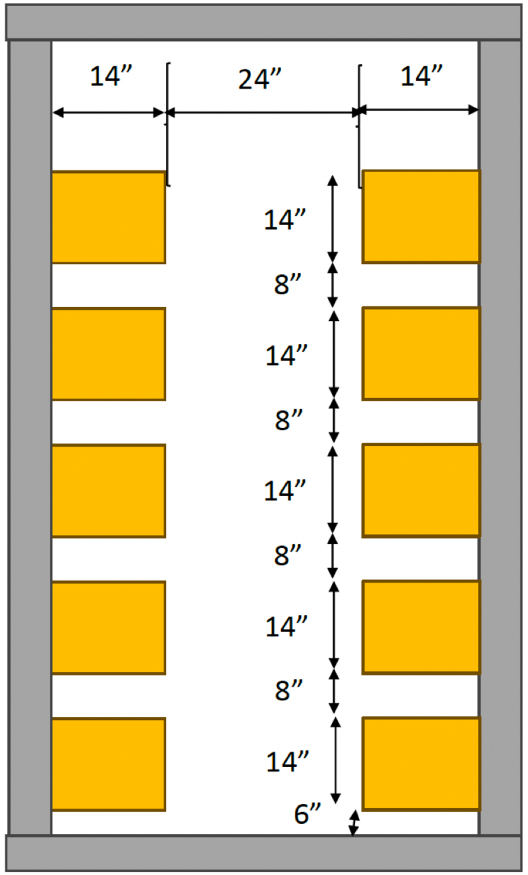
Methodology – Application Design

Storage of TRISO Fuel

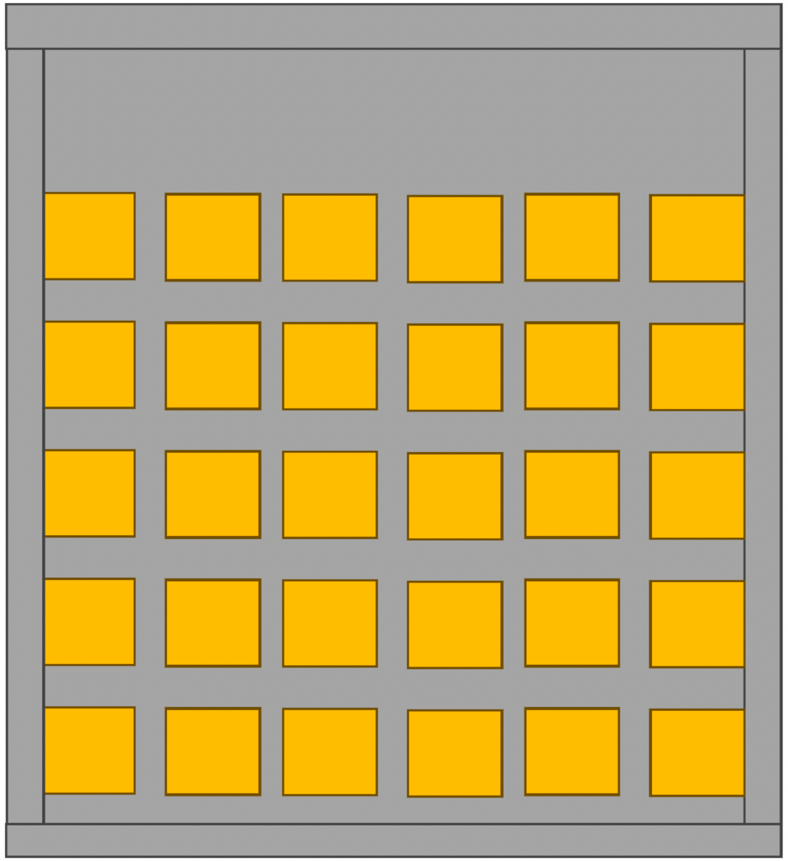
- Racks in a concrete cubicle
- Six slots long and five slots wide
- Each slot contains 4 polyethylene bottles containing TRISO fuel
- Bottles are in a square pitch (2x2)
- 12” thick concrete walls
- Racks start 6” above ground
- 24” between the racks in the room

Methodology – Application Design

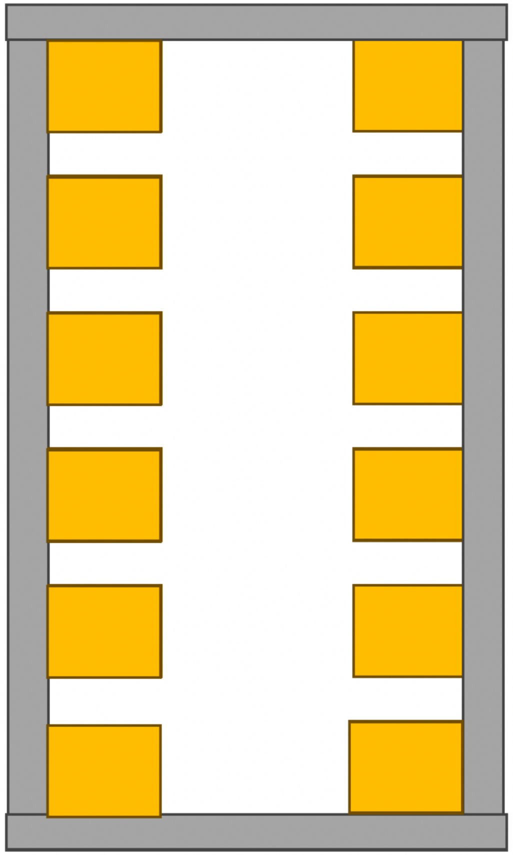
View into the cubicle



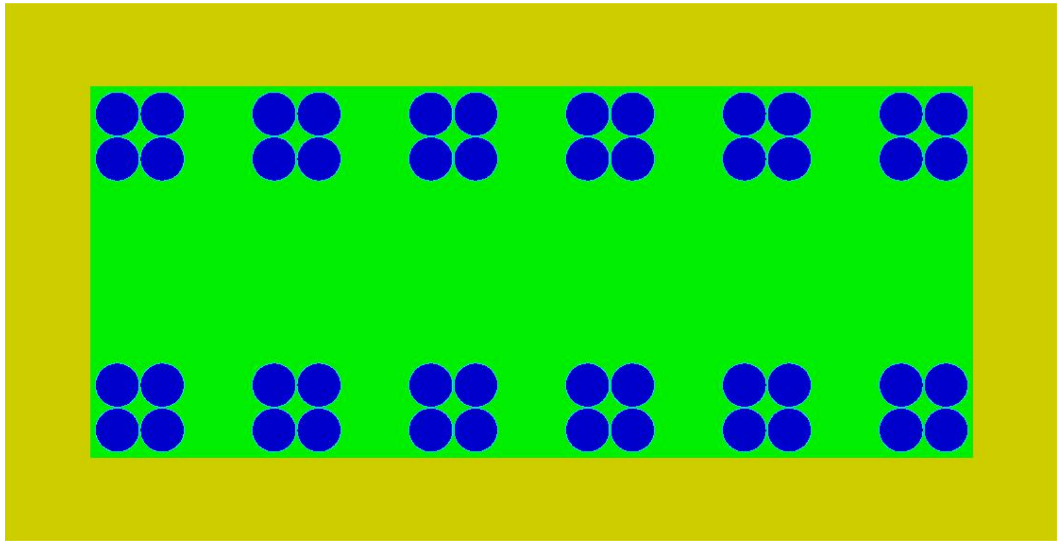
Side View of one rack



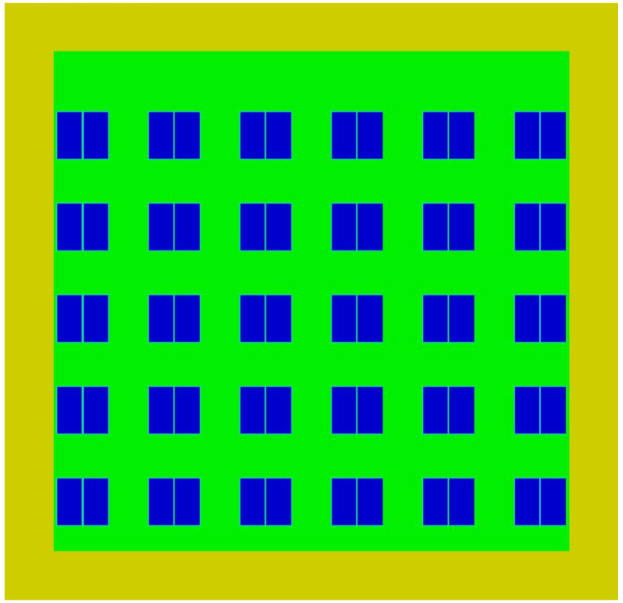
Plan View Under the Ceiling



Methodology – Application Design



XY View of the Rack Cubicle. Dark blue represents the polyethylene bottles containing TRISO in a 2x2 pitch.
Green represents the air. Gold represents the concrete walls.



XZ view of the storage rack. Dark blue represents the polyethylene bottles. Green represents the air. Gold represents the concrete walls.

Benchmarking

- Benchmark is Broken into 4 Parts
- A Detailed Description of the System
- Evaluation of Experimental Data
  - The “Calcs” section
- Description of the Model
  - Difference between the system and model, if any
- Sample Calculation Results
  - Sims

Benchmarking

- AGN-201M Properties:
  - 5-Watt Thermal TRTR
  - Plastic, Polyethylene core with a Polystyrene, doubly-loaded fuse
  - 24 cm tall, 26 cm wide
  - 19.5% ^{235}U**
  - 666.76 g of ^{235}U in system (~626 in core, ~40 in rods)
  - Reflected by graphite, treated to minimize boron concentration
  - Surrounded by lead (shield) and water (shield)

Developing the Benchmark

- Needed to figure out what a benchmark looked and sounded like

Developing the Benchmark

- Needed to figure out what a benchmark looked and sounded like
- Disassembled reactor in 7/2022

Developing the Benchmark

- Needed to figure out what a benchmark looked and sounded like
- Disassembled reactor in 7/2022
- Rod UQ in 10/2022

Developing the Benchmark

- Needed to figure out what a benchmark looked and sounded like
- Disassembled reactor in 7/2022
- Rod UQ in 10/2022
- Measurements (Experimental) in 10/2022

Developing the Benchmark

- Needed to figure out what a benchmark looked and sounded like
- Disassembled reactor in 7/2022
- Rod UQ in 10/2022
- Measurements (Experimental) in 10/2022
- Finalized measurements and analysis in 10/2023
  - Access ports, fuel

Benchmark Assumptions

- Enrichment is uniform

Benchmark Assumptions

- Enrichment is uniform
- Fuel distribution is uniform
  - Process of how fuel is made
  - Rotation
  - Flipping
  - Swapping

Benchmark Assumptions

- Enrichment is uniform
- Fuel distribution is uniform
  - Process of how fuel is made
  - Rotation
  - Flipping
  - Swapping
- Graphite gaps are minimal

Benchmark Assumptions

- Enrichment is uniform
- Fuel distribution is uniform
  - Process of how fuel is made
  - Rotation
  - Flipping
  - Swapping
- Graphite gaps are minimal
- Fuel plates are uniformly positioned

Benchmark Assumptions

- Enrichment is uniform
- Fuel distribution is uniform
  - Process of how fuel is made
  - Rotation
  - Flipping
  - Swapping
- Graphite gaps are minimal
- Fuel plates are uniformly positioned
- Core temperature is uniform

Benchmark Assumptions

- Enrichment is uniform
- Fuel distribution is uniform
  - Process of how fuel is made
  - Rotation
  - Flipping
  - Swapping
- Graphite gaps are minimal
- Fuel plates are uniformly positioned
- Core temperature is uniform
- Graphite and Pb composition is uniform

Uncertainty Quantification Items

- Nuclear data
  - WHISPER1.1 / MCNP6.2

Uncertainty Quantification Items

- Nuclear data
  - WHISPER1.1 / MCNP6.2
- Lower and Upper Graphite Density

Uncertainty Quantification Items

- Nuclear data
  - WHISPER1.1 / MCNP6.2
- Lower and Upper Graphite Density
- Concrete Shielding

Uncertainty Quantification Items

- Nuclear data
  - WHISPER1.1 / MCNP6.2
- Lower and Upper Graphite Density
- Concrete Shielding
- Water Impurities

Uncertainty Quantification Items

- Nuclear data
  - WHISPER1.1 / MCNP6.2
- Lower and Upper Graphite Density
- Concrete Shielding
- Water Impurities
- Homogeneity

Uncertainty Quantification Items

- Nuclear data
  - WHISPER1.1 / MCNP6.2
- Lower and Upper Graphite Density
- Concrete Shielding
- Water Impurities
- Homogeneity
- Lead, Graphite, and Fuel Impurities

Uncertainty Quantification Items

- Nuclear data
  - WHISPER1.1 / MCNP6.2
- Lower and Upper Graphite Density
- Concrete Shielding
- Water Impurities
- Homogeneity
- Lead, Graphite, and Fuel Impurities
- Rod Bounds

Uncertainty Quantification Items

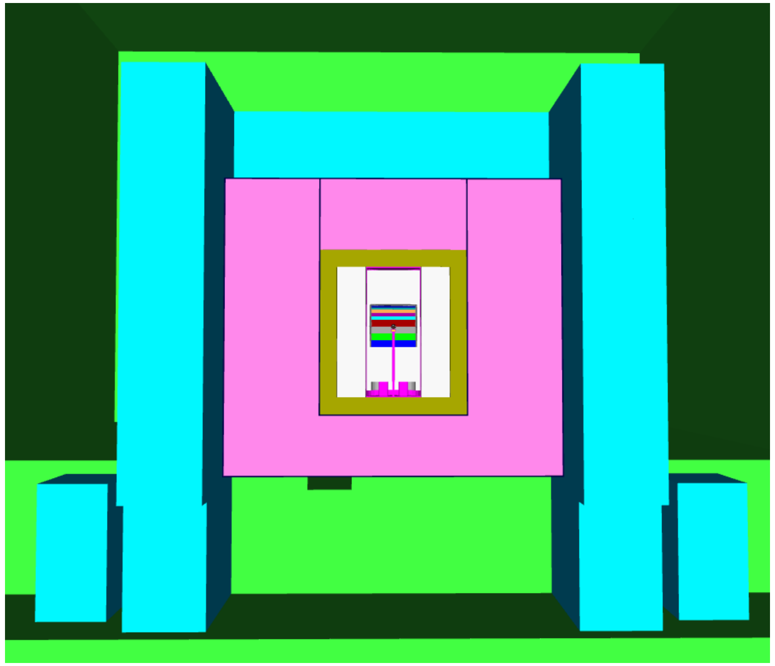
- Nuclear data
  - WHISPER1.1 / MCNP6.2
- Lower and Upper Graphite Density
- Concrete Shielding
- Water Impurities
- Homogeneity
- Lead, Graphite, and Fuel Impurities
- Rod Bounds
- Temperature

Uncertainty Quantification Items

- Nuclear data
  - WHISPER1.1 / MCNP6.2
- Lower and Upper Graphite Density
- Concrete Shielding
- Water Impurities
- Homogeneity
- Lead, Graphite, and Fuel Impurities
- Rod Bounds
- Temperature
- Enrichment
  - Bounding and Realistic

Model and Reality

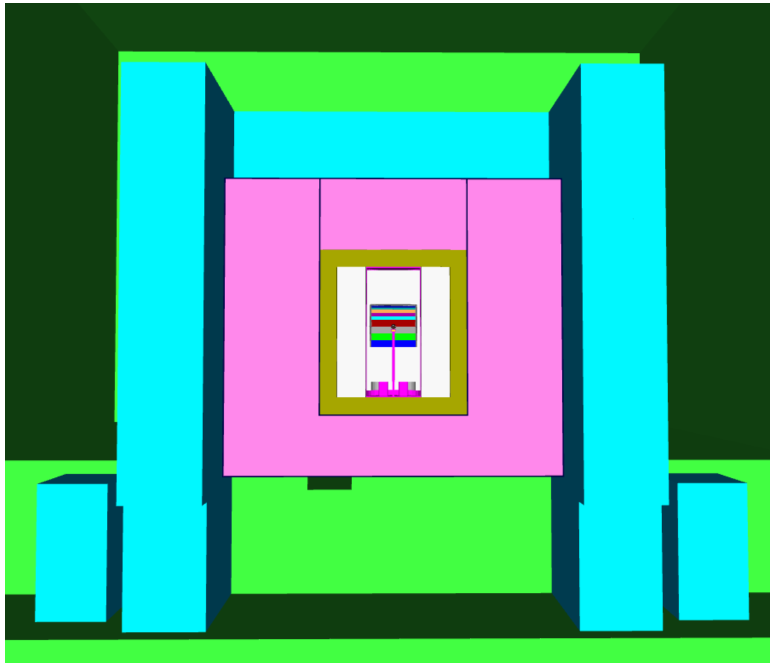
- Rod Positions Corrected for:
  - Limit Switch Offset of 0.46 cm
  - Console Error (0.06 cm for CCR and 0.13 cm for FCR)



Color	Material
	Fuel Disk 097
	Fuel Disk 098
	Fuel Disk 099
	Fuel Disk 100
	Fuel Disk 101
	Fuel Disk 102
	Fuel Disk 103
	Fuel Disk 104
	Fuel Disk 105
	SR1 Fuel
	SR2 Fuel
	CCR Fuel
	FCR Fuel
	Thermal Fuse
	Water
	Graphite
	Lead
	Aluminum
	Steel
	Wood (Pine)
	Polyethylene
	Concrete (Shielding)
	Concrete (Room)

Model and Reality

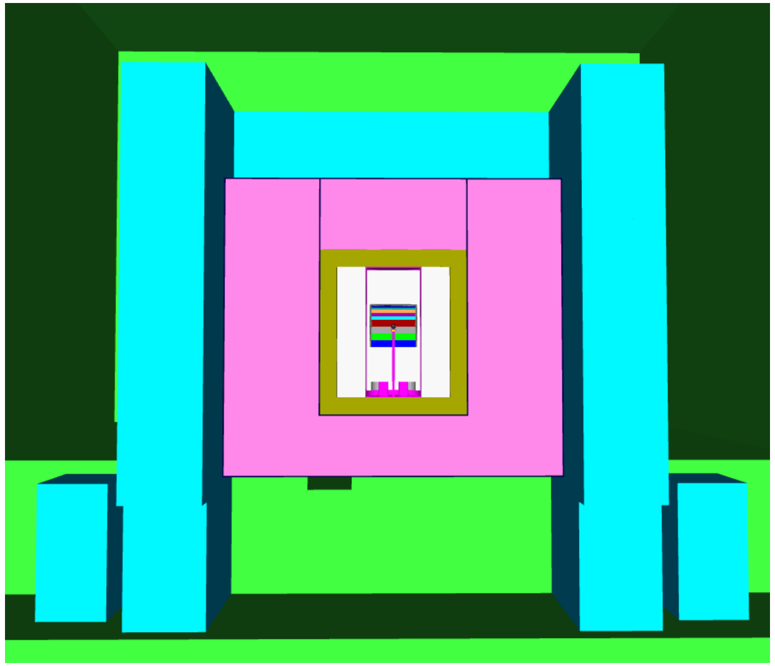
- Rod Positions Corrected for:
  - Limit Switch Offset of 0.46 cm
  - Console Error (0.06 cm for CCR and 0.13 cm for FCR)
- Contains Access Port Loadings
  - No 2-Ci PuBe Startup Source
  - No Cd Shield or Al Container
  - Modeled as Ponderosa Pine
  - Rest match



Color	Material
	Fuel Disk 097
	Fuel Disk 098
	Fuel Disk 099
	Fuel Disk 100
	Fuel Disk 101
	Fuel Disk 102
	Fuel Disk 103
	Fuel Disk 104
	Fuel Disk 105
	SR1 Fuel
	SR2 Fuel
	CCR Fuel
	FCR Fuel
	Thermal Fuse
	Water
	Graphite
	Lead
	Aluminum
	Steel
	Wood (Pine)
	Polyethylene
	Concrete (Shielding)
	Concrete (Room)

Model and Reality

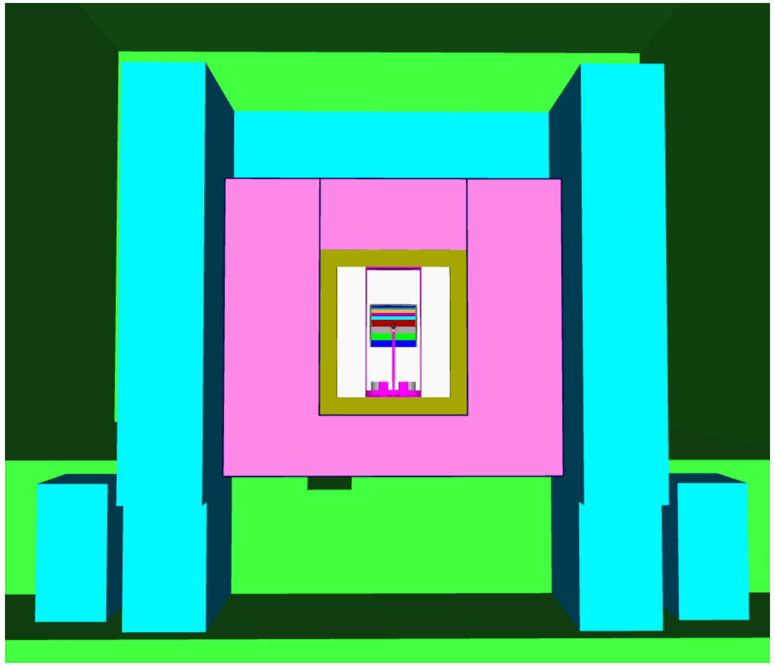
- Rod Positions Corrected for:
  - Limit Switch Offset of 0.46 cm
  - Console Error (0.06 cm for CCR and 0.13 cm for FCR)
- Contains Access Port Loadings
  - No 2-Ci PuBe Startup Source
  - No Cd Shield or Al Container
  - Modeled as Ponderosa Pine
  - Rest match
- Contains Shielding and Reactor Room



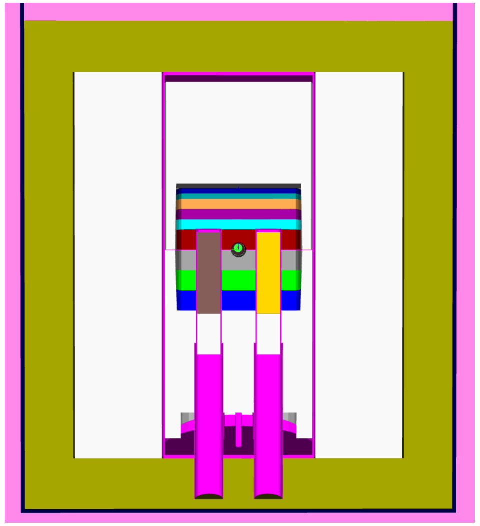
Color	Material
	Fuel Disk 097
	Fuel Disk 098
	Fuel Disk 099
	Fuel Disk 100
	Fuel Disk 101
	Fuel Disk 102
	Fuel Disk 103
	Fuel Disk 104
	Fuel Disk 105
	SR1 Fuel
	SR2 Fuel
	CCR Fuel
	FCR Fuel
	Thermal Fuse
	Water
	Graphite
	Lead
	Aluminum
	Steel
	Wood (Pine)
	Polyethylene
	Concrete (Shielding)
	Concrete (Room)

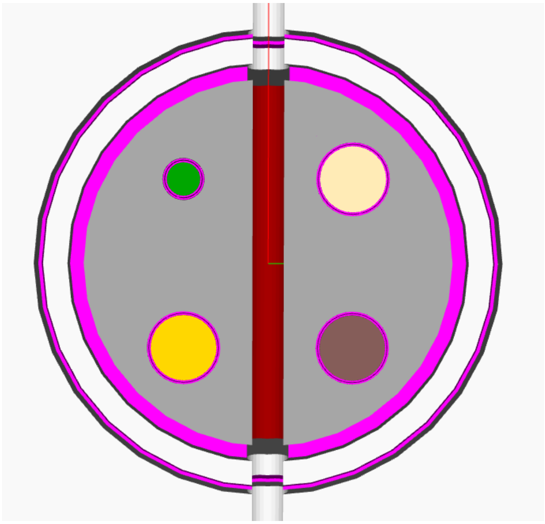
Model and Reality

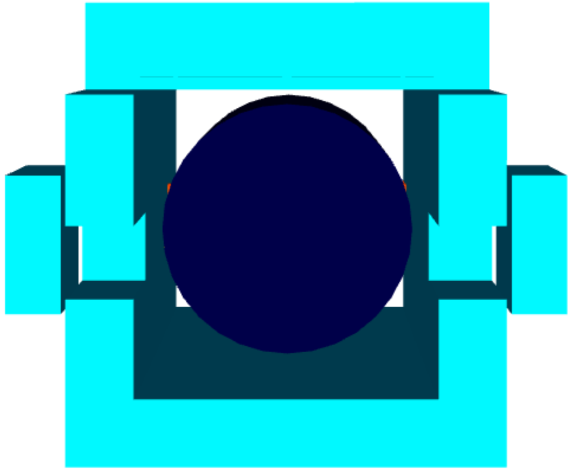
- Rod Positions Corrected for:
  - Limit Switch Offset of 0.46 cm
  - Console Error (0.06 cm for CCR and 0.13 cm for FCR)
- Contains Access Port Loadings
  - No 2-Ci PuBe Startup Source
  - No Cd Shield or Al Container
  - Modeled as Ponderosa Pine
- Contains Shielding and Reactor Room
- Contains material impurities, where known
  - Lead/Graphite: U of Utah
  - Water/Fuel: UNM

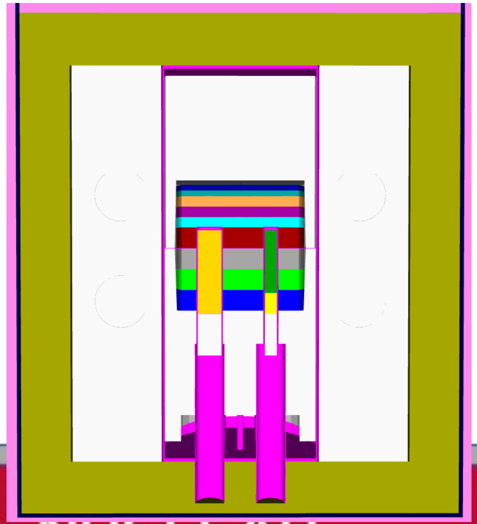


Color	Material
	Fuel Disk 097
	Fuel Disk 098
	Fuel Disk 099
	Fuel Disk 100
	Fuel Disk 101
	Fuel Disk 102
	Fuel Disk 103
	Fuel Disk 104
	Fuel Disk 105
	SR1 Fuel
	SR2 Fuel
	CCR Fuel
	FCR Fuel
	Thermal Fuse
	Water
	Graphite
	Lead
	Aluminum
	Steel
	Wood (Pine)
	Polyethylene
	Concrete (Shielding)
	Concrete (Room)

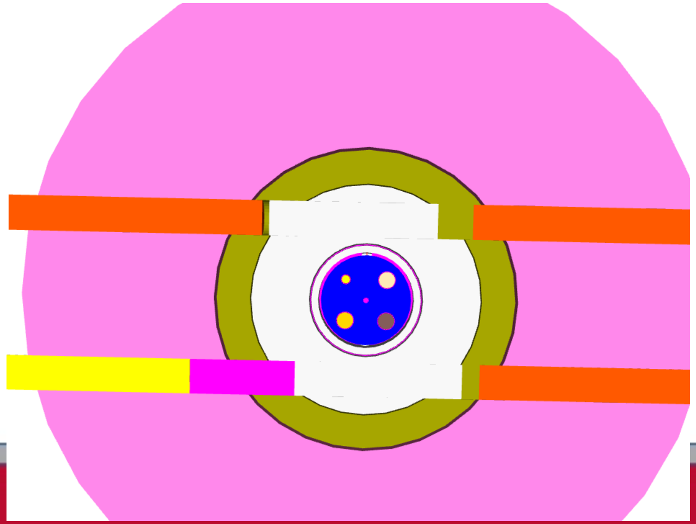








Color	Material
	Fuel Disk 097
	Fuel Disk 098
	Fuel Disk 099
	Fuel Disk 100
	Fuel Disk 101
	Fuel Disk 102
	Fuel Disk 103
	Fuel Disk 104
	Fuel Disk 105
	SR1 Fuel
	SR2 Fuel
	CCR Fuel
	FCR Fuel
	Thermal Fuse
	Water
	Graphite
	Lead
	Aluminum
	Steel
	Wood (Pine)
	Polyethylene
	Concrete (Shielding)
	Concrete (Room)



Total Model Uncertainty

Total Uncertainty Category	Uncertainty Value (PCM)
Bounding Enrichment with Nuclear XS Data	1367.36
Realistic Enrichment with Nuclear XS Data	671.94
Realistic Enrichment w/out Nuclear XS Data	**241.61**

Challenges in the Benchmark

- Fuel Enrichment
  - Said to be within "19.5 wt% +/- 0.5%" but mass must be known to 1 part per thousand

11. MATERIAL: FACILITY HEREBY ORDERS FROM THE AEC, PURSUANT TO THE AGREEMENT REFERRED TO IN ITEM 6 ABOVE, THE FOLLOWING SPECIAL NUCLEAR MATERIAL:

MATERIAL DESCRIPTION TYPE	CHEMICAL FORM	ELEMENT WT. (KILOGRAMS)	WEIGHT % ISOTOPE	SPECIFICATIONS (IF APPLICABLE)
U-235	UO_2	3.51400	19.72	AGN 201 Rx Core
U-235	UO_2	.01372	19.75	AGN 201 Rx fine control rod fuel

Challenges in the Benchmark

- Initial uncertainty was too high for ICSBEP
- Dr. S. LaMont of LANL took swipes of seven (7) different locations of upper fuel.

	234U/238U	Unc (K=2)	235U/238U	Unc (K=2)	236U/238U	Unc (K=2)
100	0.0014855	3.751E-06	0.24996	3.707E-04	0.0026204	4.175E-06
101	0.0014979	3.783E-06	0.24978	3.705E-04	0.0026215	4.177E-06
102	0.0015093	3.811E-06	0.25128	3.727E-04	0.0026300	4.190E-06
103	0.0015036	3.797E-06	0.24970	3.704E-04	0.0026235	4.180E-06
104	0.0014984	3.784E-06	0.25054	3.716E-04	0.0026248	4.182E-06
105	0.0015061	3.803E-06	0.25075	3.719E-04	0.0026266	4.185E-06
Chip	0.0015157	3.828E-06	0.24950	3.701E-04	0.0026351	4.198E-06

Challenges in the Benchmark

	TOTAL	ENRICHMENT	UNC	Rel Uncert (%)
100	0.2540611	0.199316607	1.2360E-04	0.06201062
101	0.2538989	0.199202288	1.2351E-04	0.062002664
102	**0.2554185**	**0.200155776**	**1.2425E-04**	**0.062077794**
103	0.2538293	0.199151661	1.2347E-04	0.06199926
104	0.2546603	0.199685218	1.2389E-04	0.062040284
105	0.2548866	0.199821927	1.2399E-04	0.062051497
Chip	0.2536495	0.199017853	1.2337E-04	0.061990464

Notable Benchmark Findings

- Graphite Impurities offer highest uncertainty
- Water shielding accounts for +0.02 on the eigenvalue
- Upper graphite density has a higher effect on uncertainty than lower graphite density
- Able to lower uncertainty from ISU’s AGN of 846 pcm to 241 pcm

Validation

- How did adding the AGN-201M quantitatively improve benchmark coverage?
  - Is the AGN a better fit than other benchmarks?
  - How does the AGN affect cross section adjustment?
- Using WHISPER, TSUNAMI-IP, and TSURFER to answer these questions

WHISPER

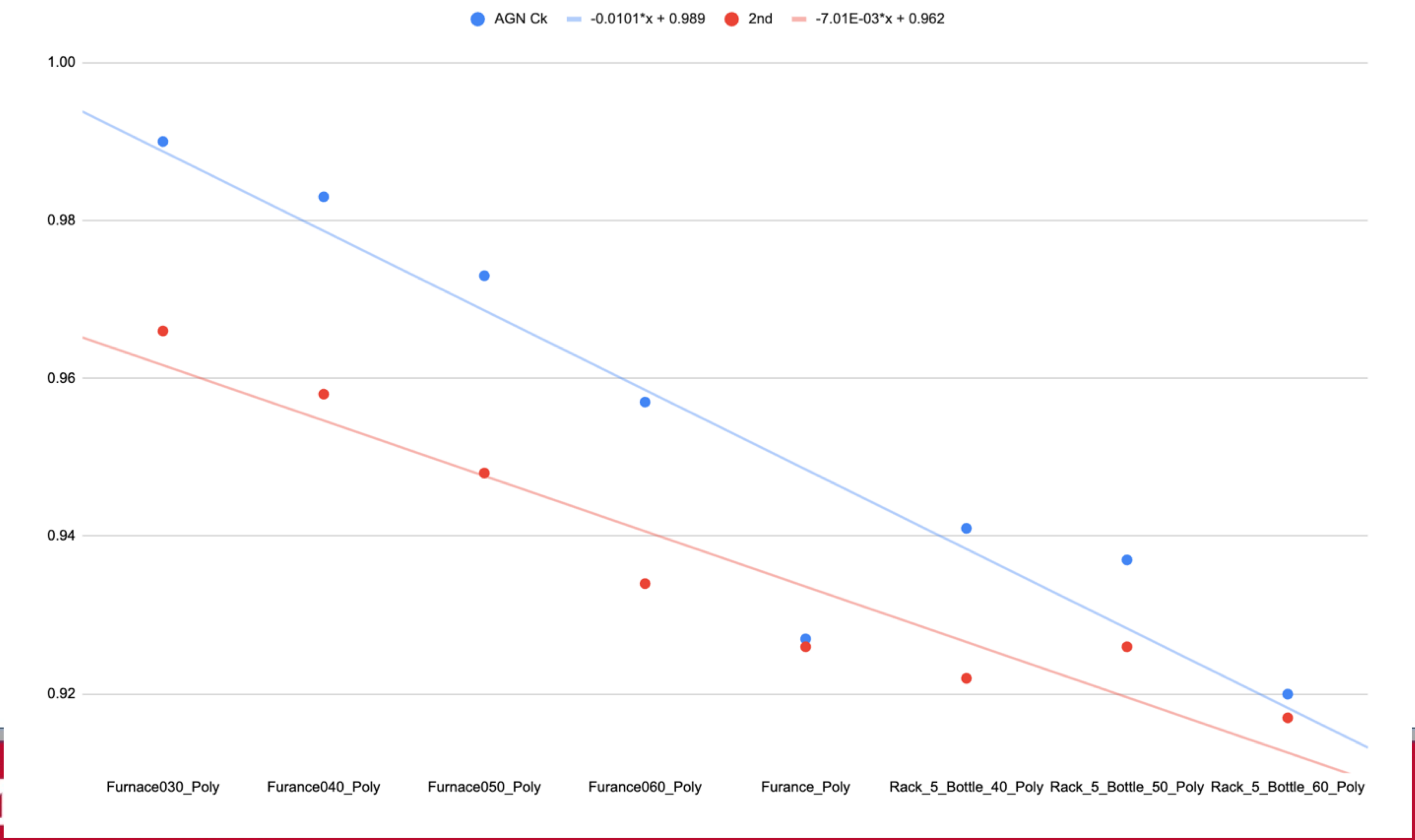
- Used to identify similar experiments to aid in library creation for TSUNAMI and TSURFER
- Uses Extreme Value Theory to estimate worst-case bias based on observed biases in similar experiments
- Identified a nuclear data uncertainty of 670 pcm
- 65 benchmarks were identified to be similar down to a c_k of 0.92
- 52 of 65 were HEU
- All 65 were thermal spectrum

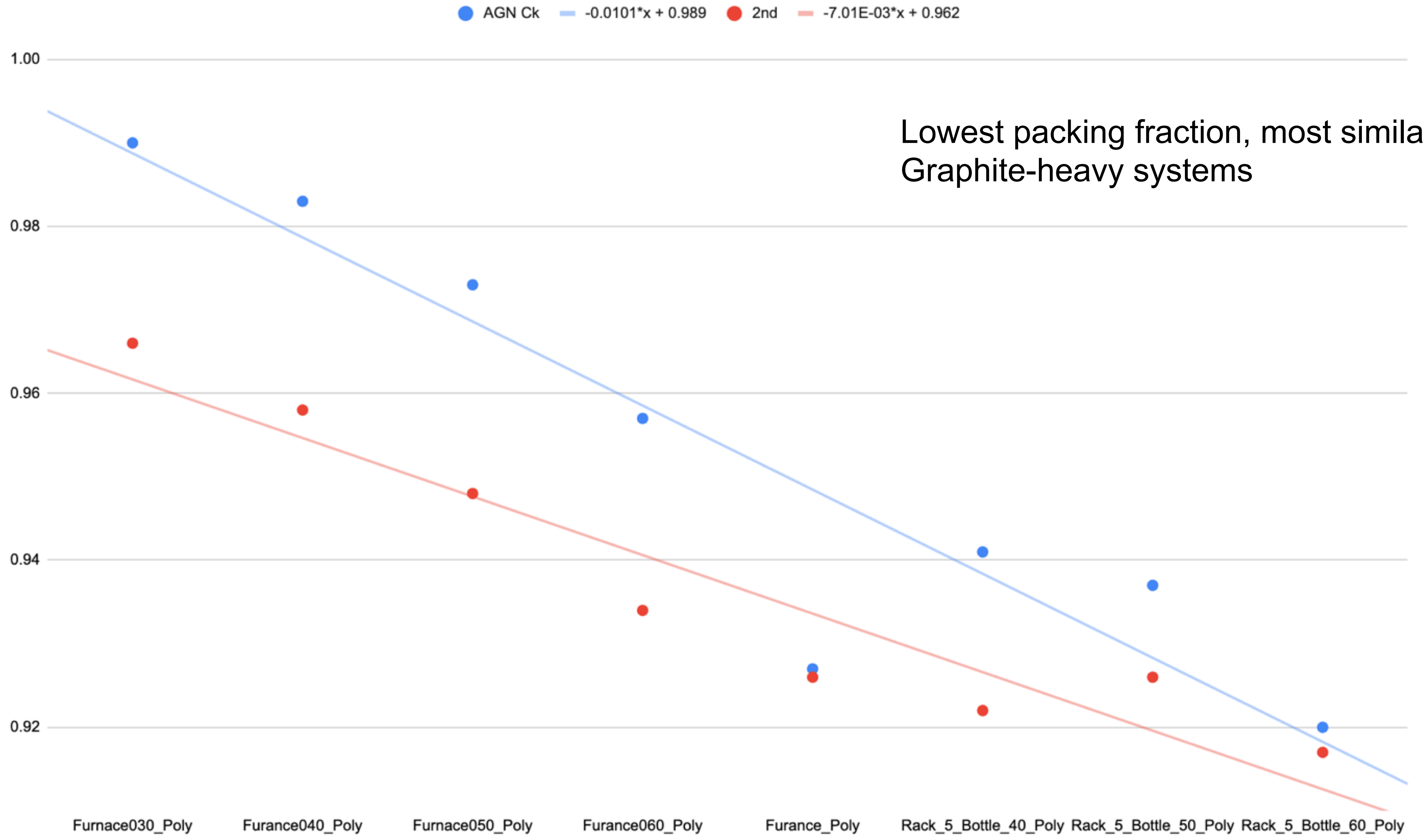
TSUNAMI-IP

- Used to investigate similarity coefficients between the AGN and other experiments and cases
- Estimates similarity coefficients, then uses linear regression to extrapolate bias based on the observed biases from similar experiments
- 2,929 experiments from the NEA
- 36 applications
- AGN-201M as an experiment
- AGN performed better than the 2,929 experiments on 8 of the 36 applications

TSUNAMI-IP

Application ID	AGN-201 C_k	2nd Best Experiment	2nd Best C_k	Delta C_k (AGN – 2nd Best Exp.)
Furnace030_Poly	0.990	ICT-001-027	0.966	0.024
Furnace040_Poly	0.983	ICT-001-025	0.958	0.025
Furnace050_Poly	0.973	ICT-001-025	0.948	0.025
Furnace060_Poly	0.957	ICT-001-025	0.934	0.023
Infinite (Poly)	0.927	ICT-001-013	0.926	0.001
Rack_5_Bottle_40_Poly	0.941	ICT-001-027	0.922	0.019
Rack_5_Bottle_50_Poly	0.937	ICT-001-025	0.926	0.011
Rack_5_Bottle_60_Poly	0.920	HST-005-004	0.917	0.003


AGN Ck
-0.0101*x + 0.989
2nd
-7.01E-03*x + 0.962
1.00
0.98
0.96
0.94
0.92
Furnace030_Poly
Furance040_Poly
Furnace050_Poly
Furance060_Poly
Furance_Poly
Rack_5_Bottle_40_Poly
Rack_5_Bottle_50_Poly
Rack_5_Bottle_60_Poly



Lowest packing fraction, most similar Graphite-heavy systems

C_k Values

Furnace030 Flooded	**Furnace030 Poly**	Furnace040 Flooded	**Furnace040 Poly**	Furnace050 Flooded	**Furnace050 Poly**	Furnace060 Flooded	**Furnace060 Poly**
0.974	**0.99**	0.967	**0.983**	0.963	**0.973**	0.957	**0.975**
579	**1**	546	**1**	445	**1**	434	**1**

Furnace Flooded	**Furnace Poly**	T_Infinite	Infinite_Carbon04	Infinite_Carbon06	Infinite_Carbon08	Infinite_Carbon10	Infinite_Carbon12
0.925	**0.927**	0.935	0.935	0.850	0.875	0.874	0.825
417	**1**	2662	2662	1629	1545	1576	1535

C_k Values

Infinite_Carbon14	Infinite_Carbon16	Infinite Dry	Infinite_Water04	Infinite_Water06	Infinite_Water08	Infinite_Water10	Infinite_Water12
0.768	0.685	0.935	0.935	0.947	0.944	0.919	0.905
1473	1461	2662	2662	1779	1885	1955	1964

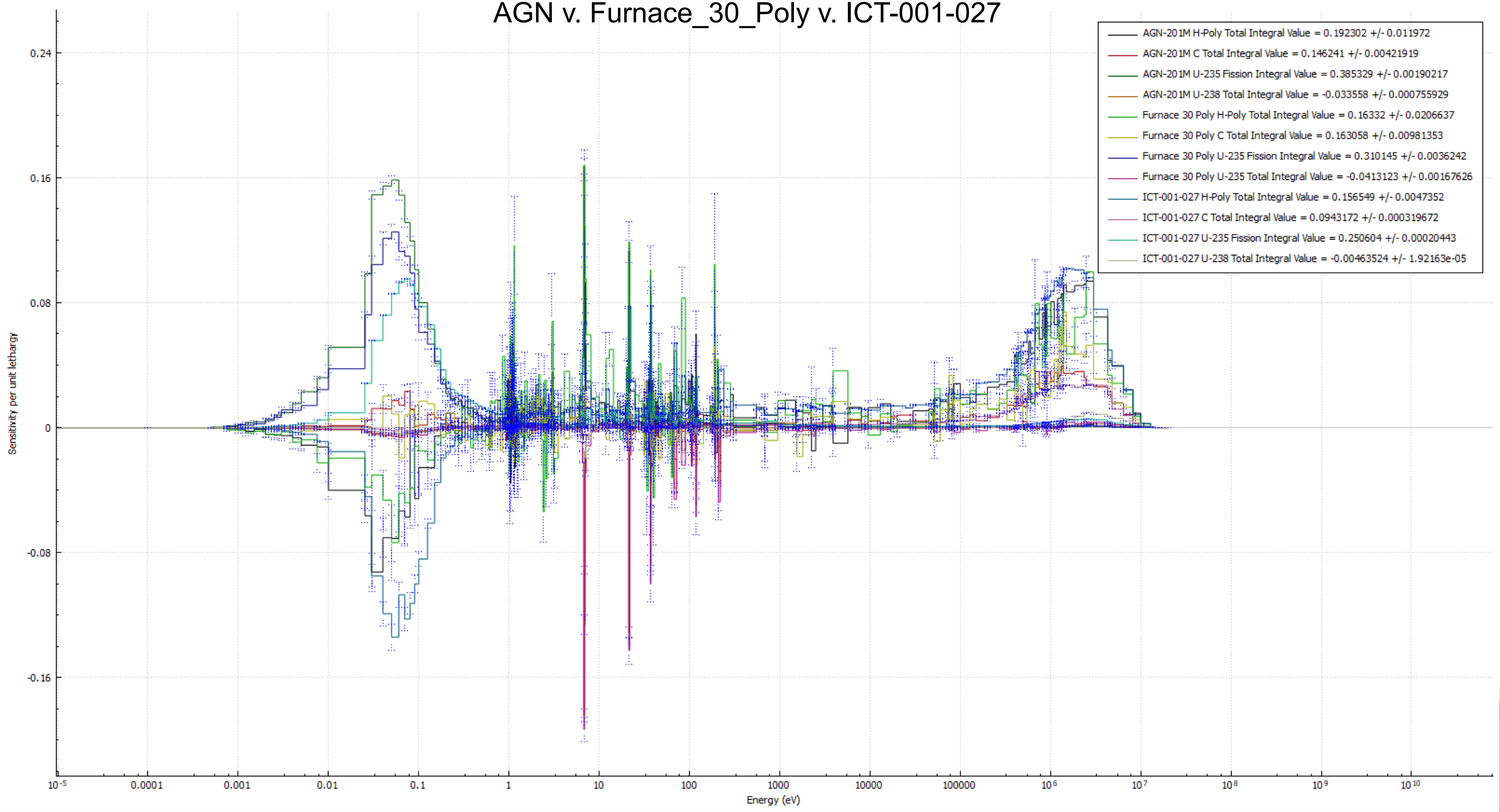
Infinite_Water14	Infinite_Water16	Rack_51	Rack_5_Bottle_40 Flooded	**Rack_5_Bottle_40 Poly**	Rack_5_Bottle_50 Flooded	**Rack_5_Bottle_50 Poly**	Rack_5_Bottle_60 Flooded
0.882	0.877	0.783	0.959	**0.941**	0.950	**0.937**	0.940
2020	2016	998	839	**1**	654	**1**	676

C_k Values

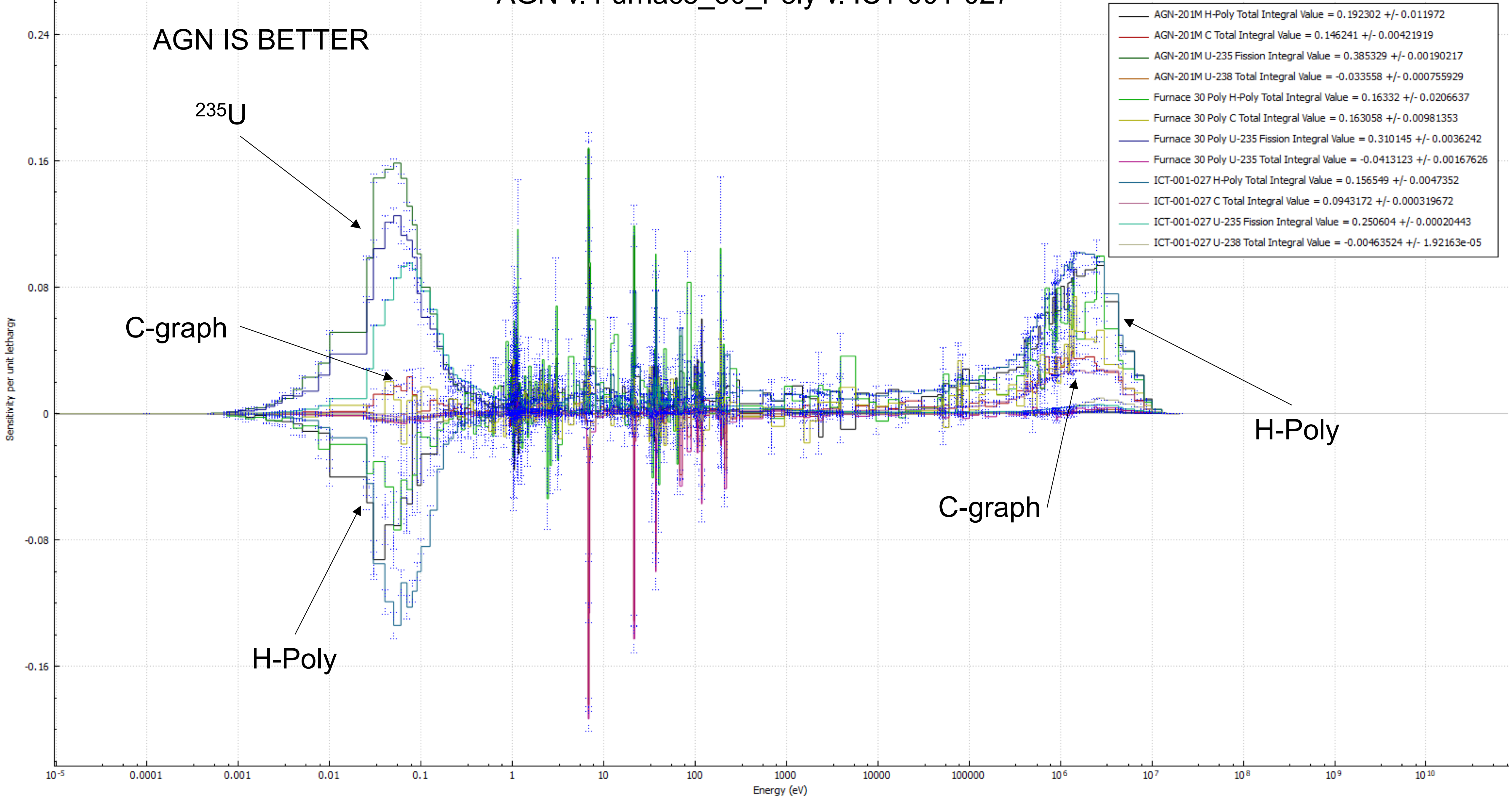
Rack_5_Bottle_60 Poly	Rack_5_Bottle_75 Flooded	Rack_5_Bottle_75 Poly	Rack_5_Flooded_100
0.920	0.906	0.896	0.906
1	936	60	936

Average AGN Rank: 1052
# of Cases Where AGN Ranks above Top 100: 9
# of Cases Where AGN Ranks above avg: 20

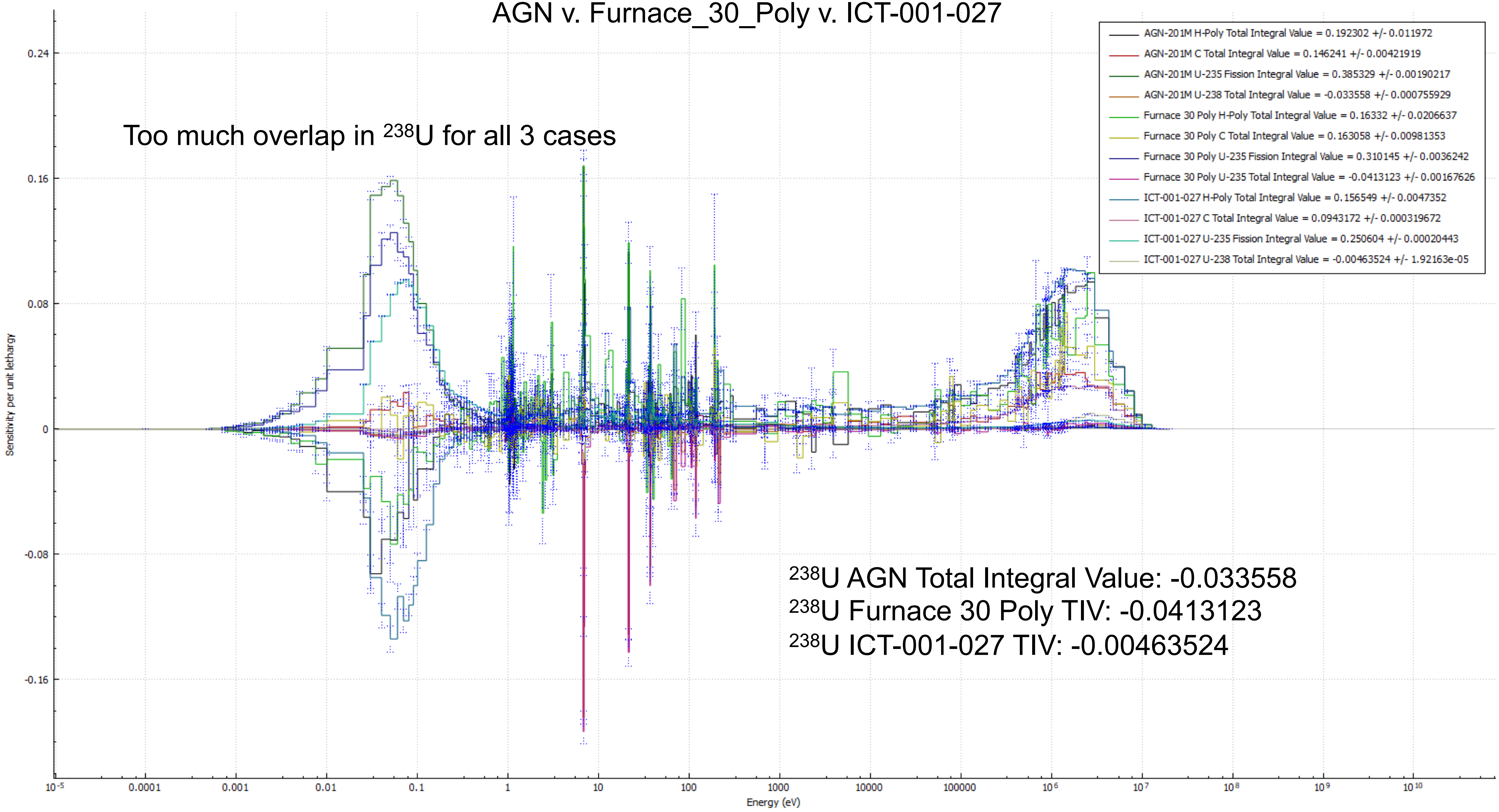
AGN v. Furnace_30_Poly v. ICT-001-027



AGN v. Furnace_30_Poly v. ICT-001-027



AGN v. Furnace_30_Poly v. ICT-001-027

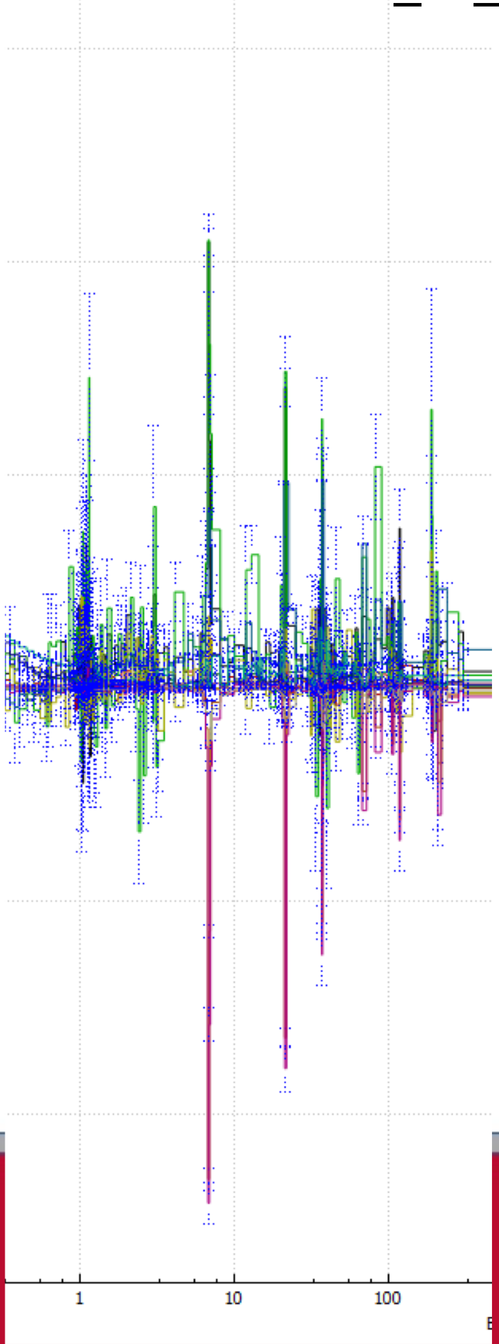


Too much overlap in ^{238}U for all 3 cases

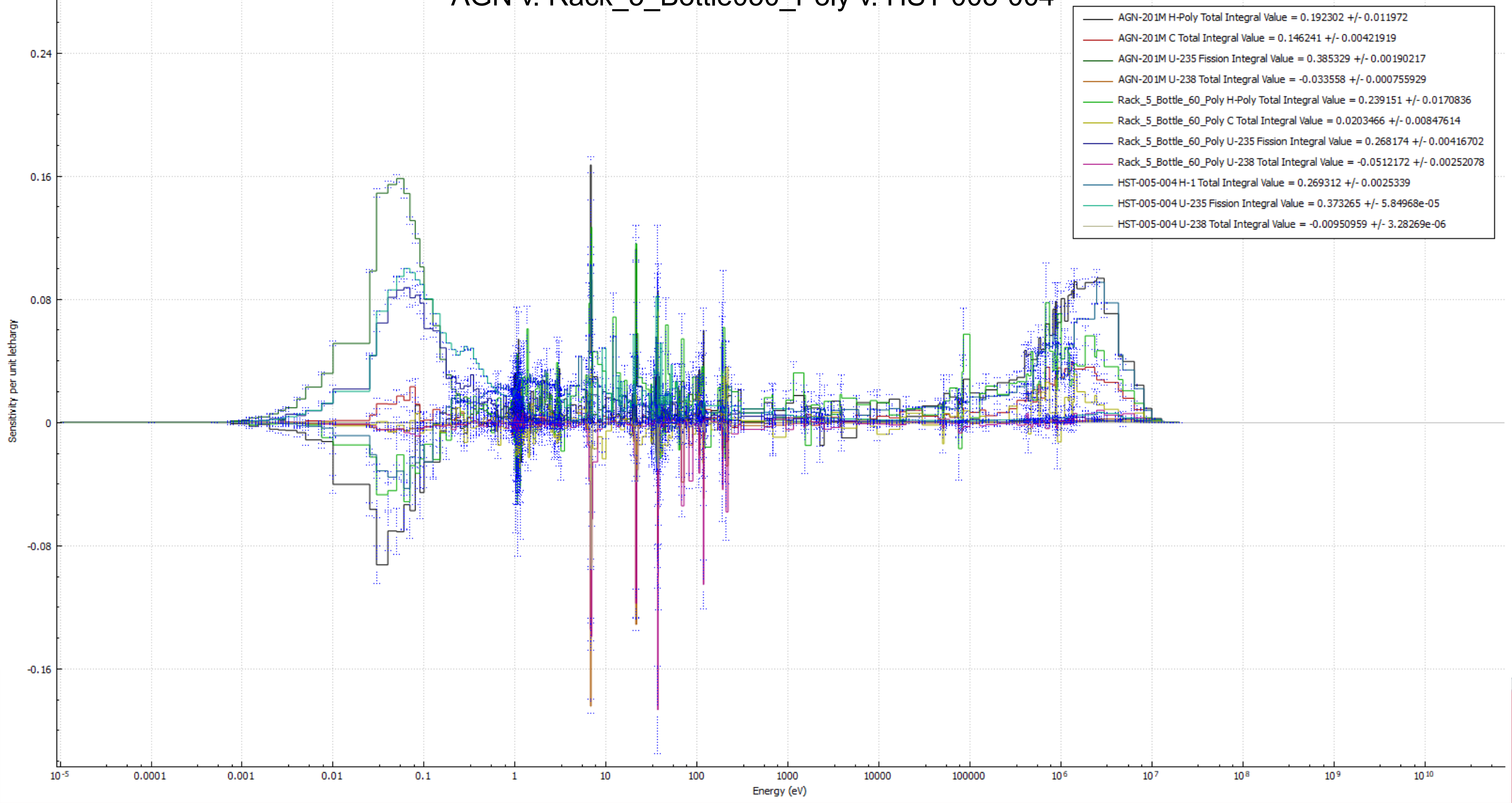
^{238}U AGN Total Integral Value: -0.033558
^{238}U Furnace 30 Poly TIV: -0.0413123
^{238}U ICT-001-027 TIV: -0.00463524

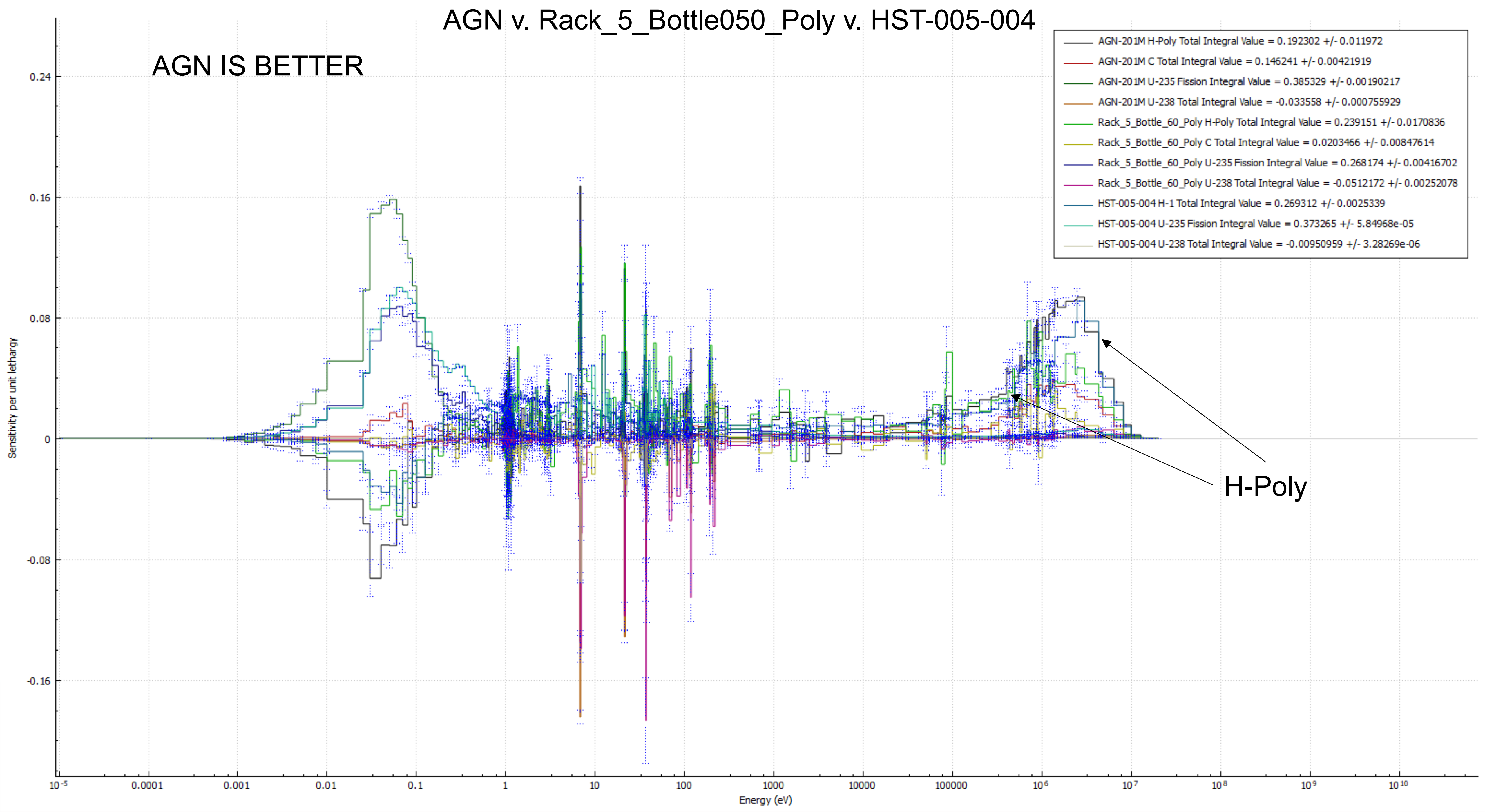
AGN v. Furnace_30_Poly v. ICT-001-027

Too noisy



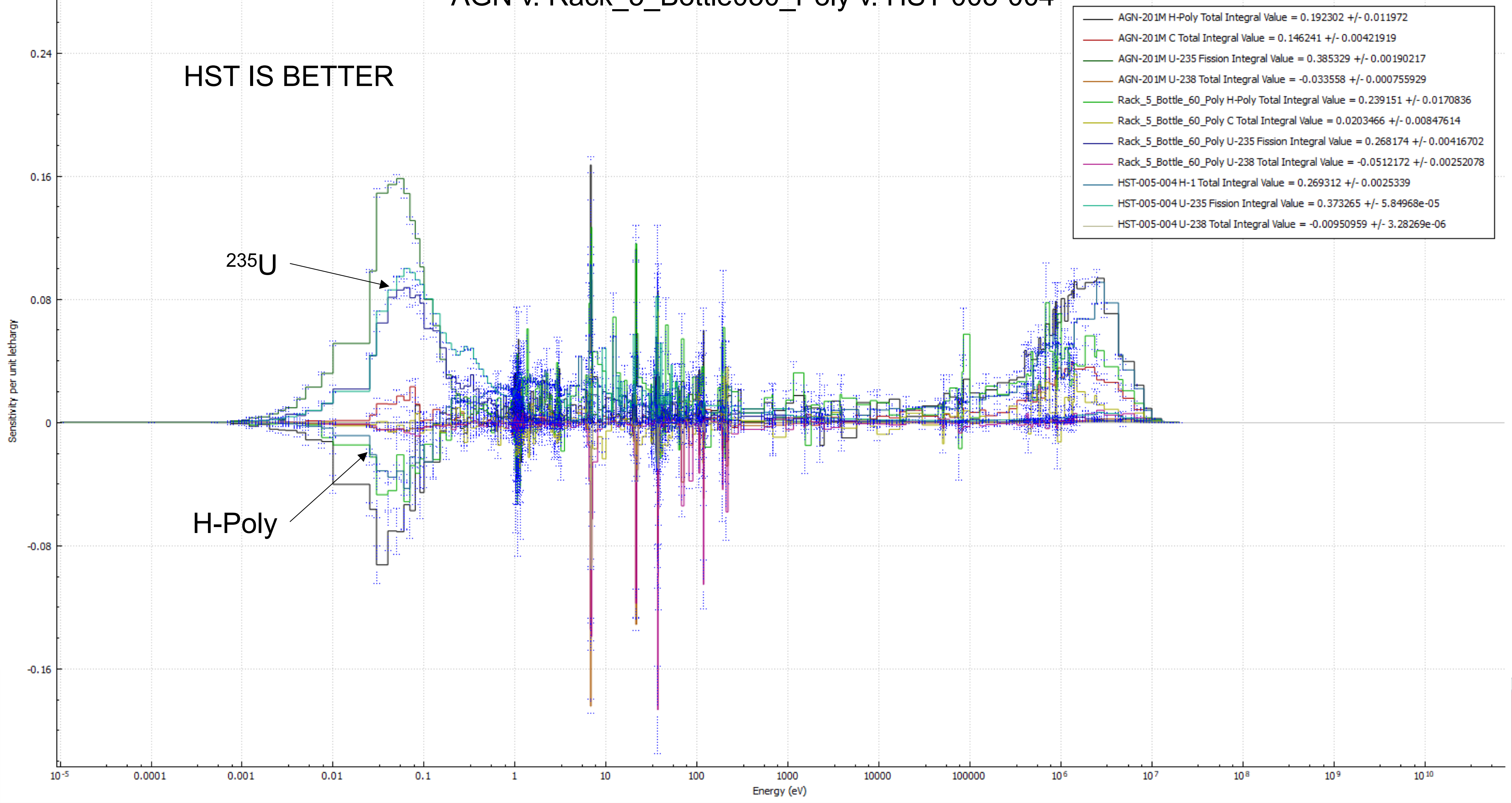
AGN v. Rack_5_Bottle050_Poly v. HST-005-004



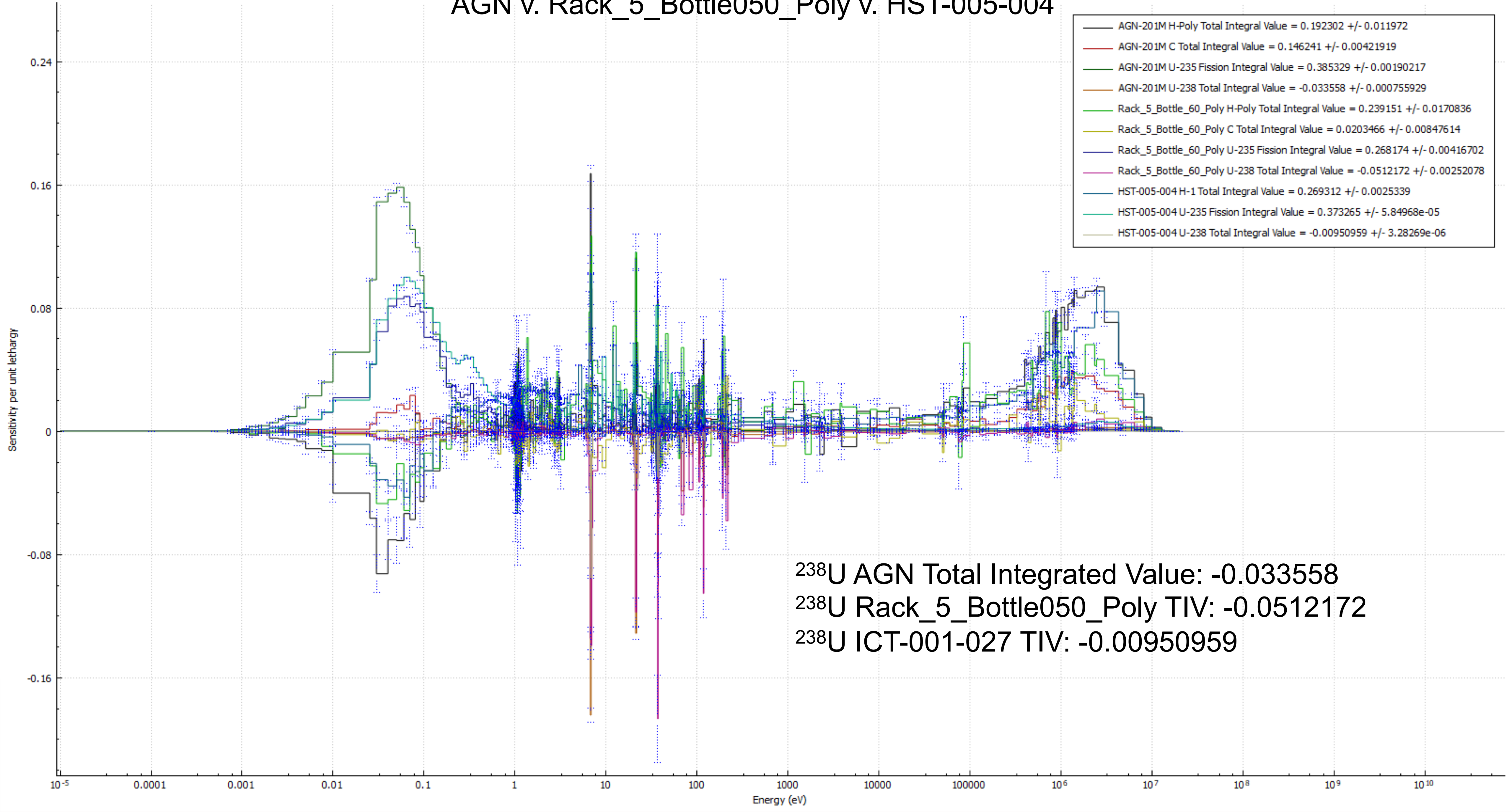


AGN v. Rack_5_Bottle050_Poly v. HST-005-004
AGN IS BETTER
AGN-201M H-Poly Total Integral Value = 0.192302 +/- 0.011972
AGN-201M C Total Integral Value = 0.146241 +/- 0.00421919
AGN-201M U-235 Fission Integral Value = 0.385329 +/- 0.00190217
AGN-201M U-238 Total Integral Value = -0.033558 +/- 0.000755929
Rack_5_Bottle_60_Poly H-Poly Total Integral Value = 0.239151 +/- 0.0170836
Rack_5_Bottle_60_Poly C Total Integral Value = 0.0203466 +/- 0.00847614
Rack_5_Bottle_60_Poly U-235 Fission Integral Value = 0.268174 +/- 0.00416702
Rack_5_Bottle_60_Poly U-238 Total Integral Value = -0.0512172 +/- 0.00252078
HST-005-004 H-1 Total Integral Value = 0.269312 +/- 0.0025339
HST-005-004 U-235 Fission Integral Value = 0.373265 +/- 5.84968e-05
HST-005-004 U-238 Total Integral Value = -0.00950959 +/- 3.28269e-06
H-Poly
Sensitivity per unit lethargy
Energy (eV)

AGN v. Rack_5_Bottle050_Poly v. HST-005-004



AGN v. Rack_5_Bottle050_Poly v. HST-005-004



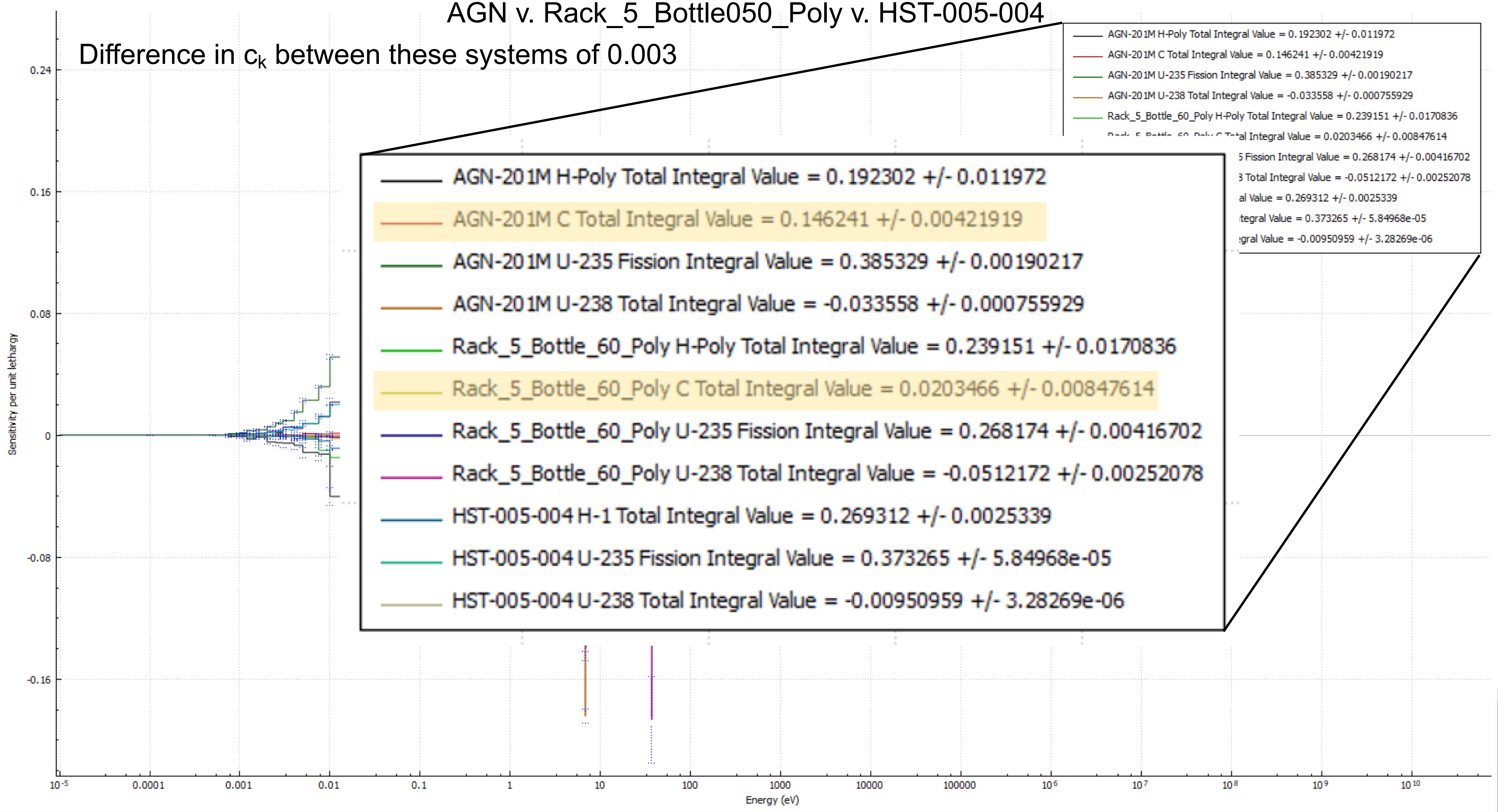
^{238}U AGN Total Integrated Value: -0.033558

^{238}U Rack_5_Bottle050_Poly TIV: -0.0512172

^{238}U ICT-001-027 TIV: -0.00950959

AGN v. Rack_5_Bottle050_Poly v. HST-005-004

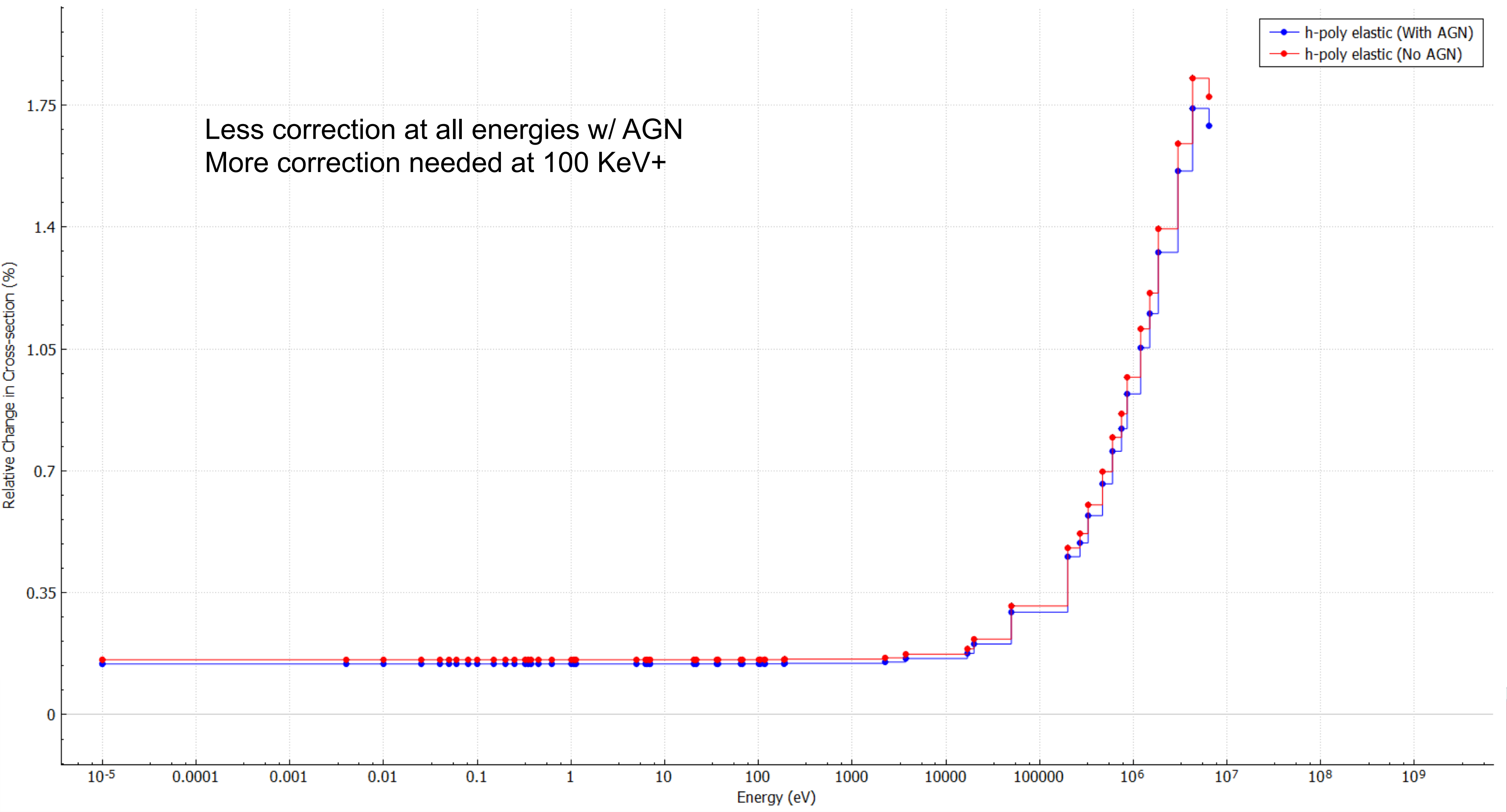
Difference in c_k between these systems of 0.003

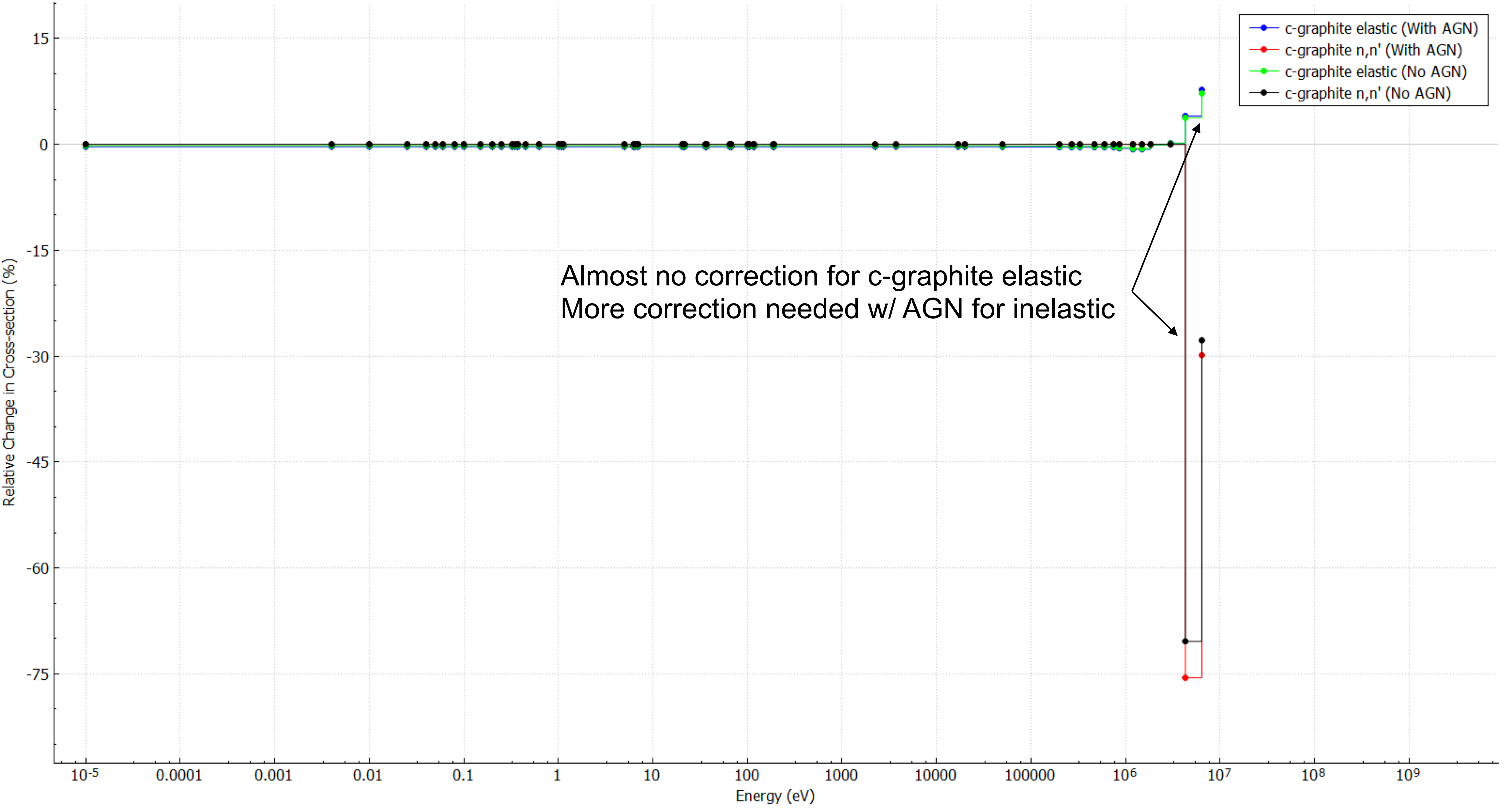


TSURFER

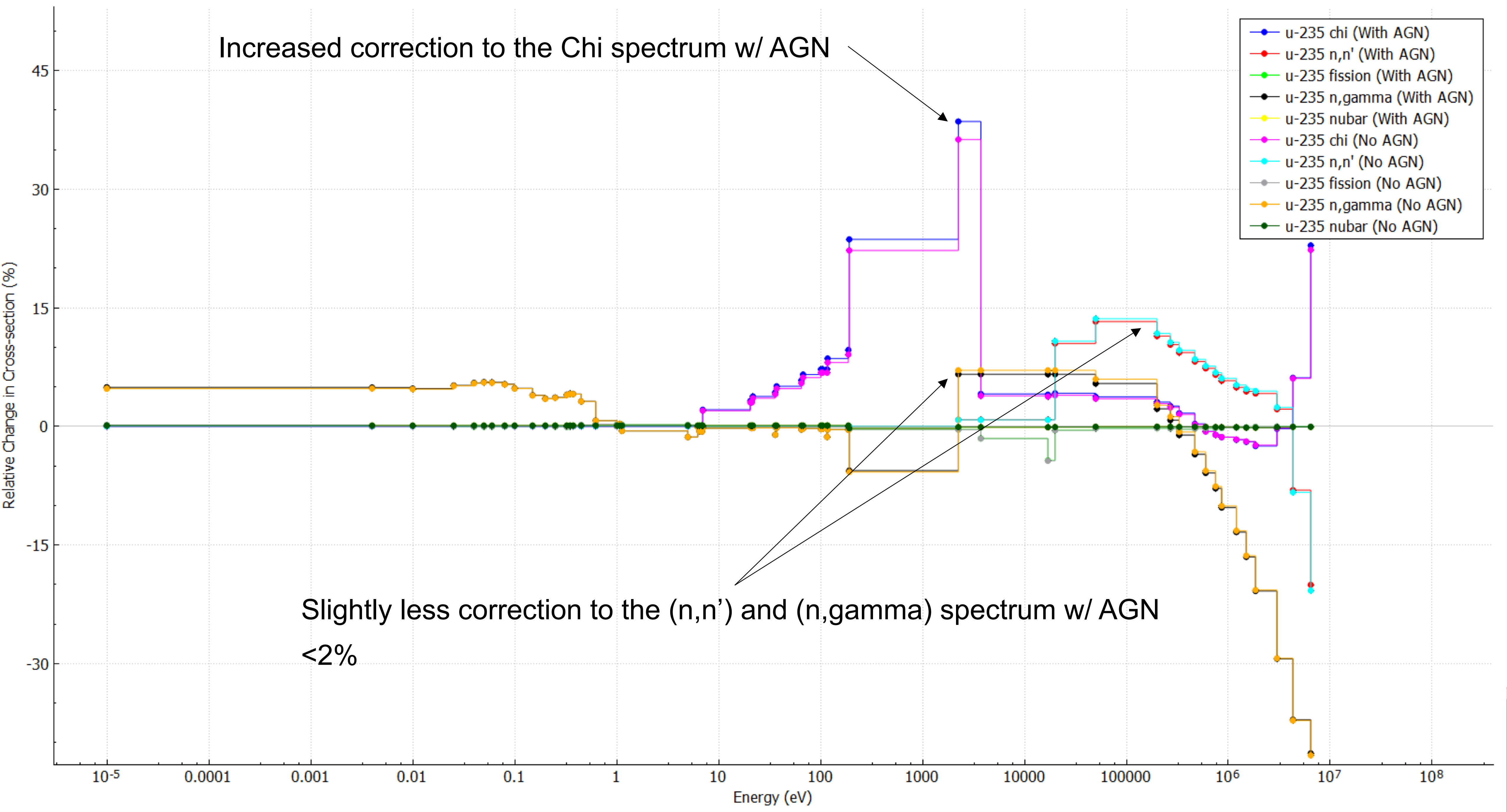
- Quantify XS Adjustment and Error in Adjustment with and without AGN

Metric	Maximum Change (%)	Root Mean Square (%)
Difference in XS Adjustment w/ the inclusion of the AGN	5.043E-02	7.207E-02
Reduction in Uncertainty w/ the inclusion of the AGN	1.786E-02	6.591E-02

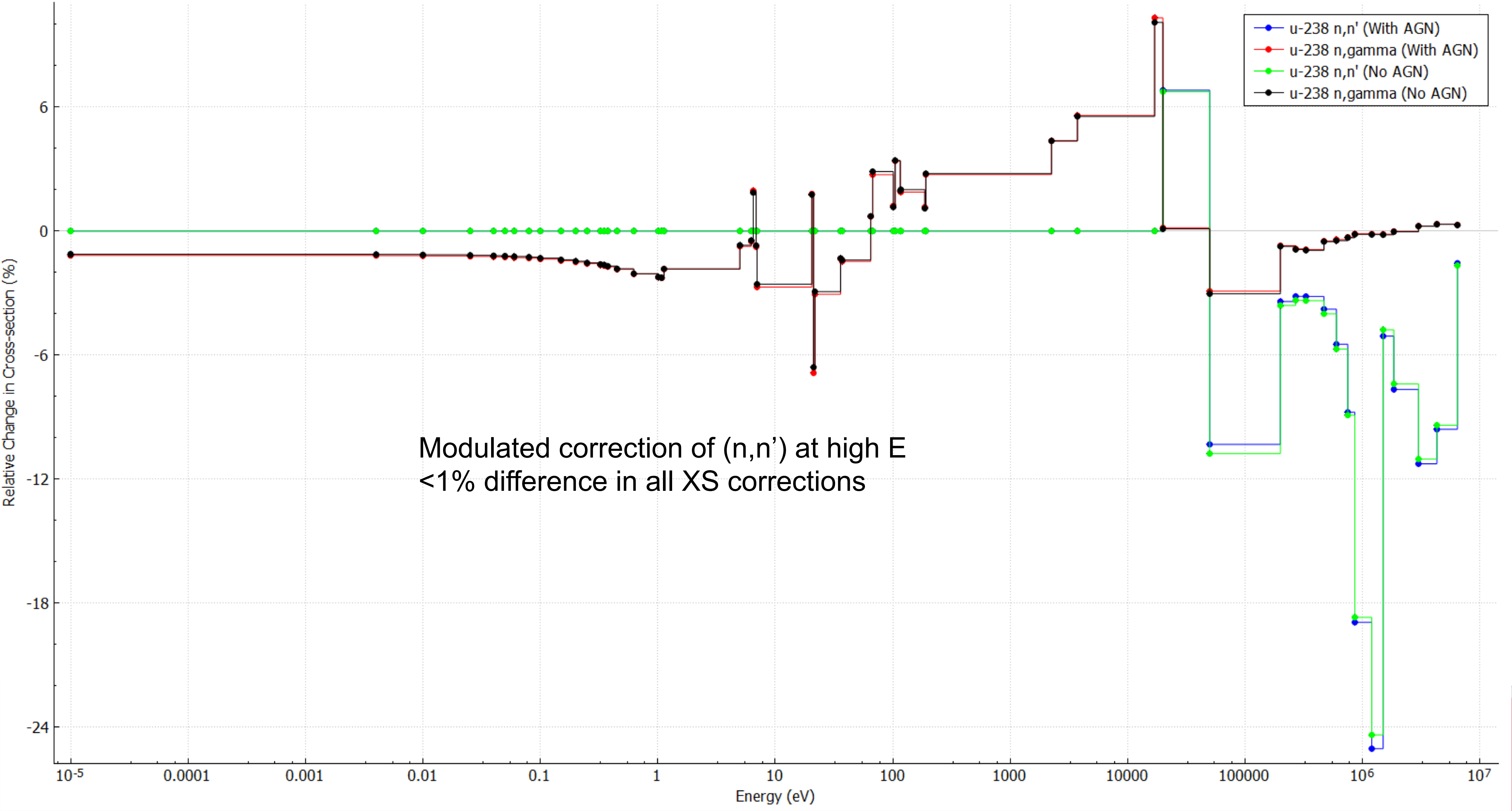

h-poly elastic (With AGN)
h-poly elastic (No AGN)
Less correction at all energies w/ AGN
More correction needed at 100 KeV+
Relative Change in Cross-section (%)
1.75
1.4
1.05
0.7
0.35
0
10-5
0.0001
0.001
0.01
0.1
1
10
100
1000
10000
100000
106
107
108
109
Energy (eV)



c-graphite elastic (With AGN)
c-graphite n,n' (With AGN)
c-graphite elastic (No AGN)
c-graphite n,n' (No AGN)
Almost no correction for c-graphite elastic
More correction needed w/ AGN for inelastic
Relative Change in Cross-section (%)
Energy (eV)
15
0
-15
-30
-45
-60
-75
10-5
0.0001
0.001
0.01
0.1
1
10
100
1000
10000
100000
106
107
108
109



Increased correction to the Chi spectrum w/ AGN
Slightly less correction to the (n,n') and (n,gamma) spectrum w/ AGN
<2%
u-235 chi (With AGN)
u-235 n,n' (With AGN)
u-235 fission (With AGN)
u-235 n,gamma (With AGN)
u-235 nubar (With AGN)
u-235 chi (No AGN)
u-235 n,n' (No AGN)
u-235 fission (No AGN)
u-235 n,gamma (No AGN)
u-235 nubar (No AGN)
Relative Change in Cross-section (%)
Energy (eV)
45
30
15
0
-15
-30
10-5
0.0001
0.001
0.01
0.1
1
10
100
1000
10000
100000
106
107
108



Modulated correction of (n,n’) at high E

<1% difference in all XS corrections

Future Research

- Better fuel qualification
- Better graphite and lead quantification
- Integral experiments for Cu, Cl, Xe, N, and other isotopes of interest

Closing

- Goal: Bridge the gap of the ICSBEP and IRPhEP benchmark handbooks

Closing

- Goal: Bridge the gap of the ICSBEP and IRPhEP benchmark handbooks
- Quantify the improvement

Closing

- Goal: Bridge the gap of the ICSBEP and IRPhEP benchmark handbooks
- Quantify the improvement
- HALEU and TRISO are becoming more present

Closing

- Goal: Bridge the gap of the ICSBEP and IRPhEP benchmark handbooks
- Quantify the improvement
- HALEU and TRISO are becoming more present

Closing

- Goal: Bridge the gap of the ICSBEP and IRPhEP benchmark handbooks
- Quantify the improvement
- HALEU and TRISO are becoming more present
- Benchmark expected to go to review group and get accepted in 7/2024

Closing

- Goal: Bridge the gap of the ICSBEP and IRPhEP benchmark handbooks
- Quantify the improvement
- HALEU and TRISO are becoming more present
- Advanced Reactors need current comparisons
- Benchmark expected to go to review group and get accepted in 7/2024
- AGN most similar to systems with high volumes of moderator
  - ~11 kg of polyethylene compared to 666.76 g of ^{235}U
  - May be useful for NCS upset conditions

Closing

- The AGN benchmark more similar than all of 2,929 cases in benchmark library for 8 of 36 applications
- The AGN produced top 1,000 c_ks for 20/36 applications
- Lowered XS adjustments and uncertainty in those adjustments

Committee Members

Christopher M. Perfetti, Chair (UNM)

Robert D. Busch (UNM)

Forrest B. Brown (UNM)

Douglas G. Bowen (ORNL)

Amir Ali (ISU)

Grant Team

Sans Committee Members

- Larry Wetzel, P.E., LL Wetzel, LLC
- Shawn Henderson, SNL
- Carl Willis, UNM
- Dr. Brad Rearden, ORNL

Special Thanks

- Catherine Percher, ICSBEP / LLNL
- John Bess, JFA
- Nicholas Thompson, LANL
- Jesson Hutchinson, LANL
- Stephen LaMont, LANL / UNM
- Mathew Eden, UNM

Acknowledgement Statement

This research was funded by the United States Department of Energy Nuclear Engineering University Program under DOE NEUP 21-24360.

Any statements or opinions made in this presentation or by the presenter do not reflect the opinion of the University of New Mexico, the Department of Nuclear Engineering at UNM, or the U.S. Department of Energy.

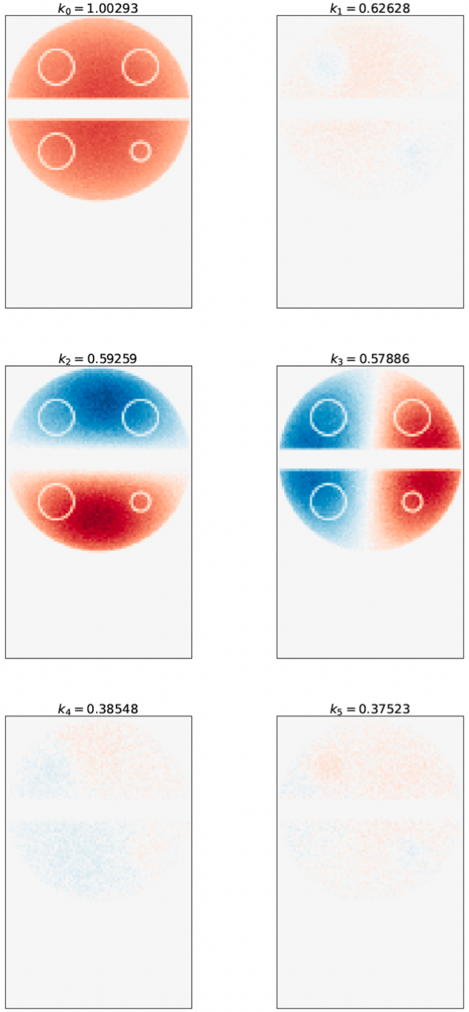
All work herein is derived from the dissertation "Improving Criticality Safety Benchmark Coverage by Developing a Benchmark Evaluation of the UNM AGN-201M Reactor" and its listed references.

Remaining Questions

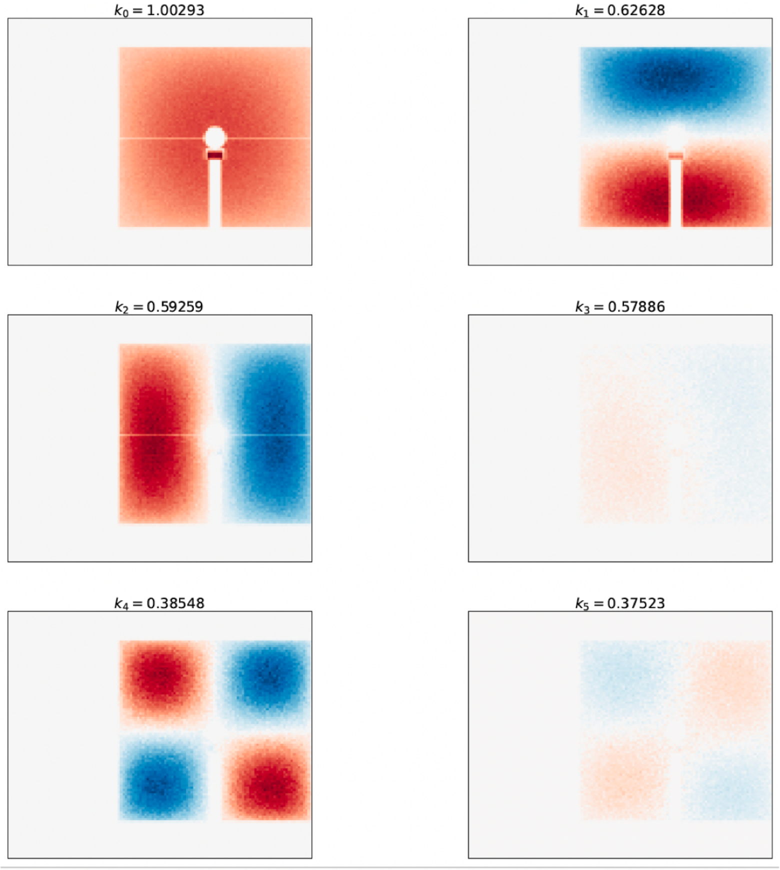
Rowdy Davis
The University of New Mexico
E-mail: davisr760@unm.edu
Office: +1-505-277-2829
Cell: +1-909-890-8966

EXTRA SLIDES

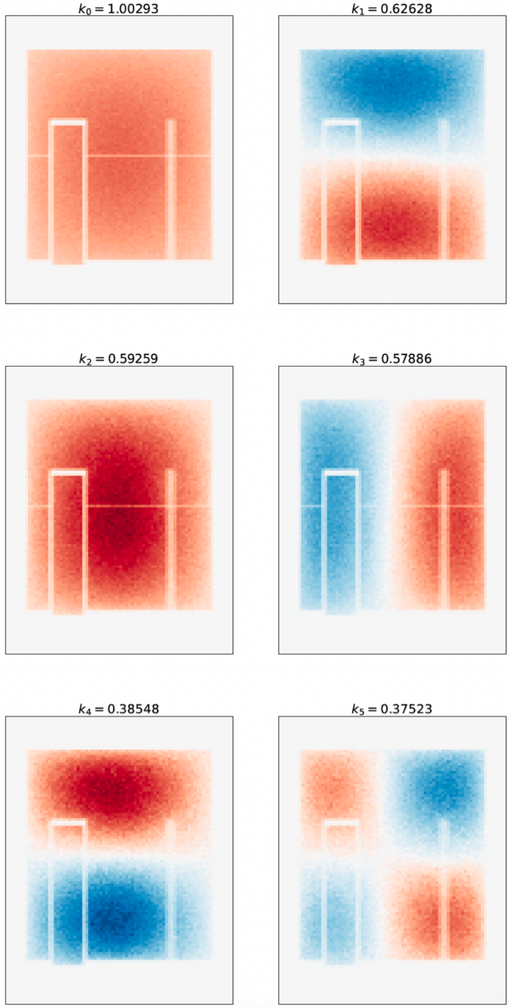
Don’t go past here ☺


$k_0 = 1.00293$
$k_1 = 0.62628$
$k_2 = 0.59259$
$k_3 = 0.57886$
$k_4 = 0.38548$
$k_5 = 0.37523$

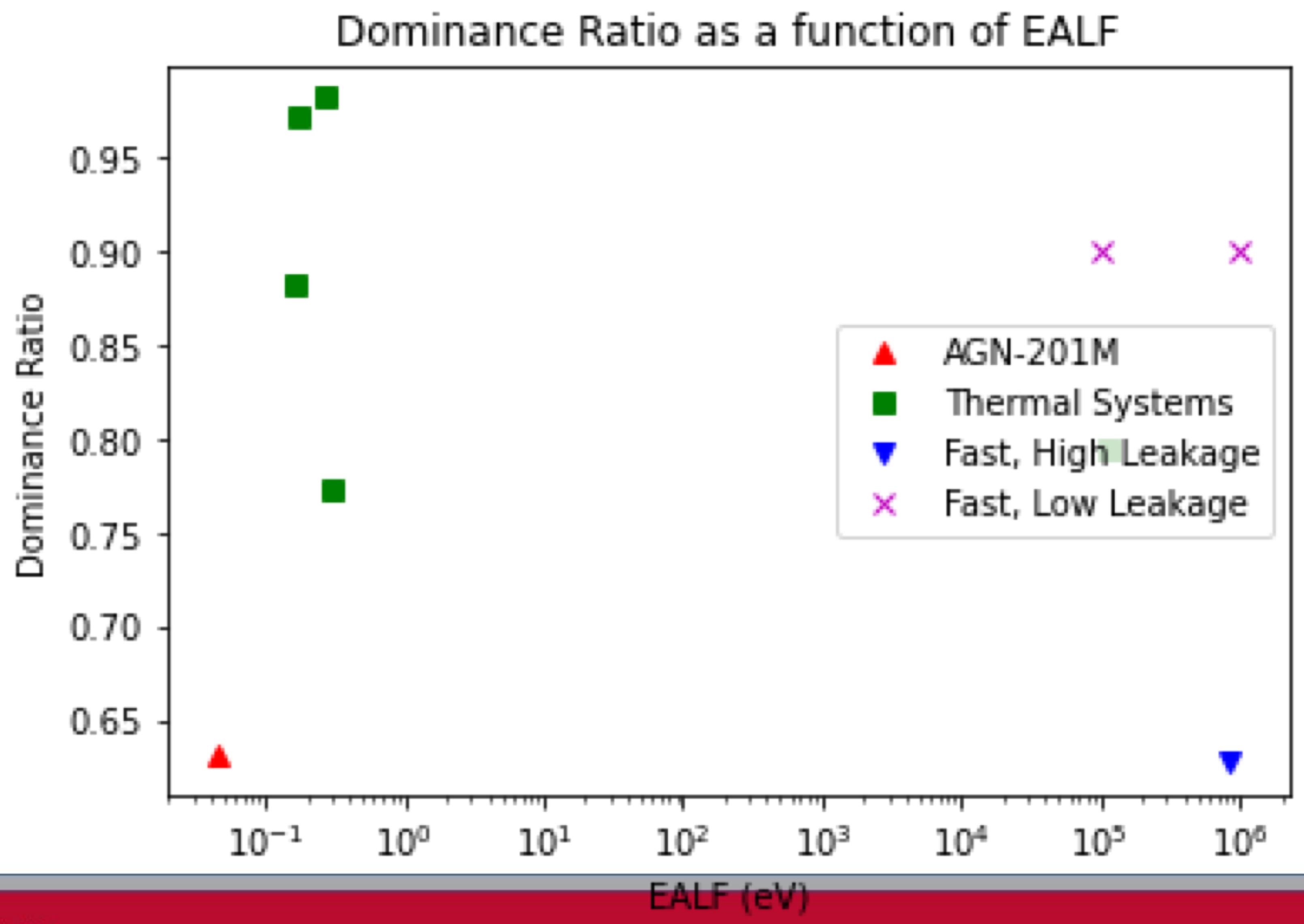
XY


$k_0 = 1.00293$
$k_1 = 0.62628$
$k_2 = 0.59259$
$k_3 = 0.57886$
$k_4 = 0.38548$
$k_5 = 0.37523$

YZ


$k_0 = 1.00293$
$k_1 = 0.62628$
$k_2 = 0.59259$
$k_3 = 0.57886$
$k_4 = 0.38548$
$k_5 = 0.37523$

XZ



Dominance Ratio as a function of EALF
Dominance Ratio
0.95
0.90
0.85
0.80
0.75
0.70
0.65
AGN-201M
Thermal Systems
Fast, High Leakage
Fast, Low Leakage
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
EALF (eV)

Application ID	Packing Fraction (%)	Case Composition
Furnace – Polyethylene Between Particles (Homogenized)		
T_Furnace030_Poly	30	30% particles, 70% poly, graphite reflected
T_Furnace040_Poly	40	40% particles, 60% poly, graphite reflected
T_Furnace050_Poly	50	50% particles, 50% poly, graphite reflected
T_Furnace060_Poly	60	60% particles, 40% poly, graphite reflected
T_Furnace_Poly	75	75% particles, 25% poly, graphite reflected
Furnace - Dry		
T_Infinite (Poly)	-----	Infinite square pitched particles, pitch = 0.083 cm
Furnace – Water Between Particles		
T_Furnace030_Flooded	30	30% particles, 70% water, graphite reflected
T_Furnace040_Flooded	40	40% particles, 60% water, graphite reflected
T_Furnace050_Flooded	50	50% particles, 50% water, graphite reflected
T_Furnace060_Flooded	60	60% particles, 40% water, graphite reflected
T_Furnace_Flooded	75	75% particles, 25% water, graphite reflected
Furnace - Wet		
T_Infinite (Flooded)	-----	Infinite square pitched particles, pitch = 0.083 cm
Furnace – Dry – Graphite Between Particles (Homogenized)		
T_Infinite_Carbon_04	0.04	Infinite square pitched particles, pitch = 0.083 cm
T_Infinite_Carbon_06	0.06	Infinite square pitched particles, pitch = 0.12 cm
T_Infinite_Carbon_08	0.08	Infinite square pitched particles, pitch = 0.16 cm
T_Infinite_Carbon_10	0.10	Infinite square pitched particles, pitch = 0.20 cm
T_Infinite_Carbon_12	0.12	Infinite square pitched particles, pitch = 0.24 cm
T_Infinite_Carbon_14	0.14	Infinite square pitched particles, pitch = 0.28 cm
T_Infinite_Carbon_16	0.16	Infinite square pitched particles, pitch = 0.32 cm
Furnace – Dry – Single Particle in Cube		
T_Infinite_Dry	-----	Infinite square pitched particles, pitch = 0.083 cm
Furnace – Water Between Particles (single particle in cube)		
T_Infinite_Water_04	0.04	Infinite square pitched particles, pitch = 0.083 cm
T_Infinite_Water_06	0.06	Infinite square pitched particles, pitch = 0.12 cm
T_Infinite_Water_08	0.08	Infinite square pitched particles, pitch = 0.16 cm
T_Infinite_Water_10	0.10	Infinite square pitched particles, pitch = 0.20 cm
T_Infinite_Water_12	0.12	Infinite square pitched particles, pitch = 0.24 cm
T_Infinite_Water_14	0.14	Infinite square pitched particles, pitch = 0.28 cm
T_Infinite_Water_16	0.16	Infinite square pitched particles, pitch = 0.32 cm
Storage Rack – Water Between Particles (Homogenized)		
T_Rack_5_Bottle040_Flooded	40	40% particles, 60% water, 5L bottle on rack
T_Rack_5_Bottle050_Flooded	50	50% particles, 50% water, 5L bottle on rack
T_Rack_5_Bottle060_Flooded	60	60% particles, 40% water, 5L bottle on rack
T_Rack_5_Bottle075_Flooded	75	75% particles, 25% water, 5L bottle on rack
Storage Rack – Polyethylene Between Particles (Homogenized)		
T_Rack_5_Bottle040_Poly	40	40% particles, 60% poly, 5L bottle on rack
T_Rack_5_Bottle050_Poly	50	50% particles, 50% poly, 5L bottle on rack
T_Rack_5_Bottle060_Poly	60	60% particles, 40% poly, 5L bottle on rack
T_Rack_5_Bottle075_Poly	75	75% particles, 25% poly, 5L bottle on rack

Fuel Enrichment Measurement Issues

- Broken filaments
- Filaments overloaded
- <20%

Total Uncertainty Category	PCM
Nuclear Data	627
Lower Graphite	5.36
Upper Graphite	35.86
Shielding	0.5
Fuel Plates Enrichment (19) [BOUND]	1151.9
Fuel Plates Enrichment (20) [BOUND]	303
Water	6.7
Lead Impurities	41

Total Uncertainty Category	PCM
Graphite Impurities	232
Fuel Plate Impurities	6.6
CCR Upper Rod Bounds	6
CCR Lower Rod Bounds	7
FCR Upper Bounds	21
FCR Lower Bounds	21
Maximum Fuel Uncertainty	22
Minimum Fuel Uncertainty	4
*Homogeneity	0.5

Benchmark ID	C_k	Weight
HMT-010-001	0.9832	1
HMT-031-001	0.9810	0.962
HCT-002-008	0.9668	0.72
HCT-002-007	0.9661	0.7084
HCT-002-006	0.9652	0.6922
HCT-002-014	0.9649	0.6877
HST-025-003	0.9637	0.6669
HCT-002-025	0.9637	0.6669
HCT-002-005	0.962	0.6386
HCT-002-013	0.9618	0.6352
HST-043-002	0.9617	0.6336
HCT-002-009	0.9605	0.6124
HCT-002-020	0.9594	0.5929
HCT-002-004	0.9588	0.5839
HCT-002-012	0.9583	0.5754
HCT-002-024	0.958	0.569
HCT-002-003	0.9561	0.5364
HST-025-009	0.9548	0.5156
HCT-002-002	0.9531	0.4853
HST-025-004	0.9527	0.4795
HST-025-001	0.9527	0.4789
HCT-002-019	0.9523	0.4718
HST-025-007	0.9523	0.4717
HST-025-010	0.9521	0.4692
HST-013-003	0.952	0.4676
HST-025-002	0.9516	0.4599
HST-013-004	0.9514	0.4574
HCT-002-011	0.9498	0.4303
HST-025-011	0.9498	0.4293
HST-025-006	0.9497	0.4282
HCT-002-010	0.9497	0.4282
HST-011-002	0.9493	0.4212
HST-011-001	0.9492	0.4193
HCT-002-023	0.9488	0.412
HST-025-008	0.9485	0.4074
HST-012-001	0.9481	0.4009
HCT-002-001	0.9464	0.3719
HST-025-012	0.9462	0.3686
HST-013-002	0.9462	0.3683
HST-001-005	0.9457	0.3602
HCT-002-018	0.9452	0.3514
HST-025-014	0.9436	0.3235
HST-025-005	0.9435	0.3213
HST-025-015	0.9431	0.3158
LST-007-014	0.9428	0.3097
LST-001-006	0.9425	0.3054
HST-013-001	0.9414	0.2859
HST-025-018	0.9413	0.2848
HST-025-017	0.9408	0.2756
HST-025-013	0.9407	0.2747
LST-004-001	0.9403	0.2681
HST-043-003	0.9392	0.2493
LST-007-002	0.9381	0.2304
LST-021-001	0.937	0.2115
HST-025-016	0.9369	0.2093
LST-007-030	0.9369	0.2088
LST-007-032	0.9337	0.1548
LST-004-002	0.9335	0.1509
LST-002-002	0.9324	0.1326
HST-010-001	0.9323	0.1301
LST-020-001	0.9309	0.1071
LST-004-003	0.9281	0.0595
LST-007-004	0.926	0.0228
LST-007-036	0.9254	0.012
HST-038-009	0.9249	0.0042

Link to Data Sheets

https://docs.google.com/spreadsheets/d/1bA0FLGg6fAoi04CeXAgMk4Bpt9z-J2FVgHc0KQZFogs/edit#gid=1298495195