Data Testing with Zero Power Reactor (ZPR), Zero Power Physics Reactor (ZPPR), and New Thermal Epithermal eXperiments (TEX) Plutonium Benchmarks

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Cross Section Evaluation Working Group (CSEWG) Virtual Meeting
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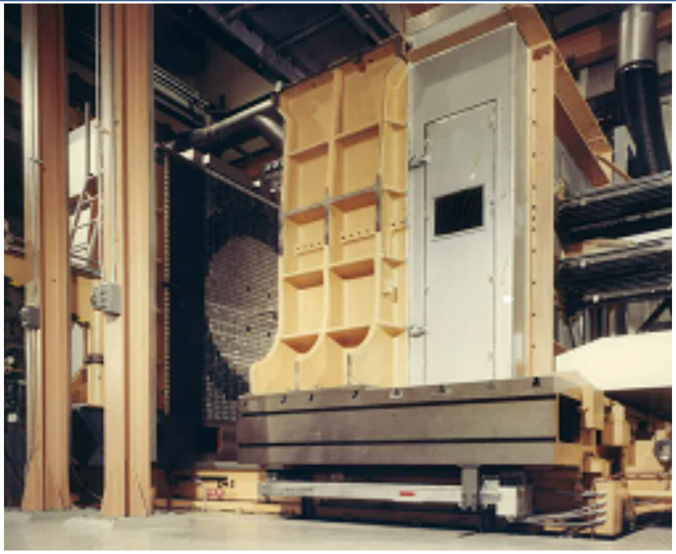
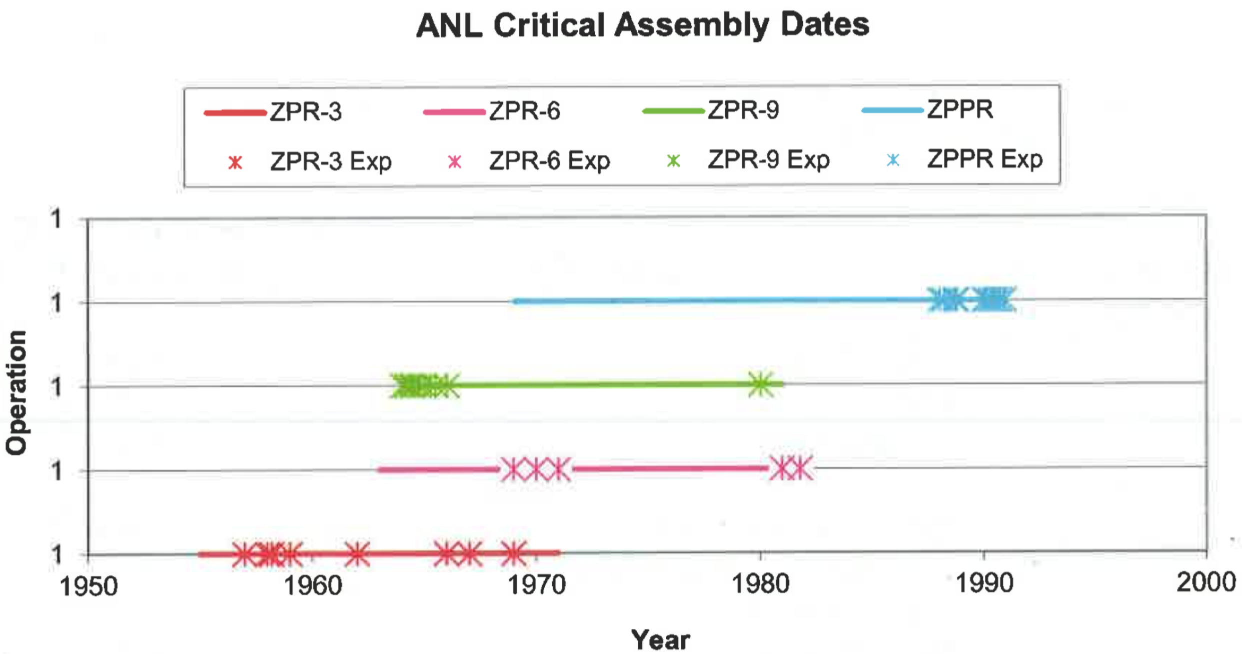
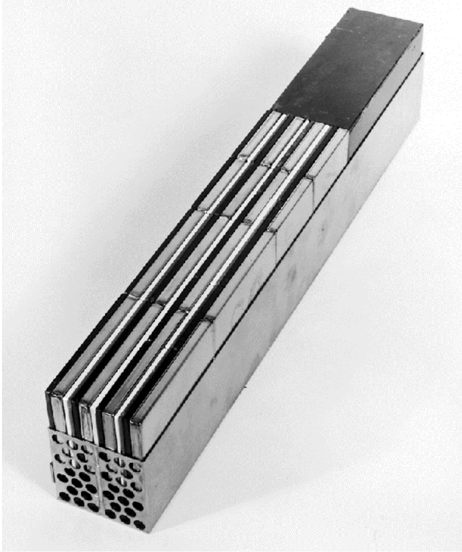
Four Critical Facilities Operated by Argonne National Laboratory

- Zero Power Reactors (ZPR)
  - ZPR-3, ZPR-6, ZPR-9
- Zero Power Physics Reactor (ZPPR)
- Very complicated honeycomb drawer configurations comprising thousands of fissile, diluent, and reflector plates







ZPR-3 Benchmarks- 9 Evaluations

IEU-MET-FAST-015	ZPR-3 ASSEMBLY 6F: A SPHERICAL ASSEMBLY OF HIGHLY ENRICHED URANIUM, DEPLETED URANIUM, ALUMINUM AND STEEL WITH AN AVERAGE 235U ENRICHMENT OF 47 ATOM %
IEU-MET-FAST-016	ZPR-3 ASSEMBLY 11: A CYLINDRICAL ASSEMBLY OF HIGHLY ENRICHED URANIUM AND DEPLETED URANIUM WITH AN AVERAGE 235U ENRICHMENT OF 12 ATOM % AND A DEPLETED URANIUM REFLECTOR
IEU-COMP-FAST-004	ZPR-3 ASSEMBLY 12: A CYLINDRICAL ASSEMBLY OF HIGHLY ENRICHED URANIUM, DEPLETED URANIUM AND GRAPHITE WITH AN AVERAGE 235U ENRICHMENT OF 21 ATOM %
HEU-MET-FAST-055	ZPR-3 ASSEMBLY 23: A CYLINDRICAL ASSEMBLY OF U METAL (93% 235U) AND ALUMINUM REFLECTED BY DEPLETED-URANIUM
IEU-MET-FAST-012	ZPR-3 ASSEMBLY 41: A CYLINDRICAL ASSEMBLY OF U METAL (16% 235U), ALUMINUM, AND STEEL, REFLECTED BY DEPLETED-URANIUM
MIX-COMP-FAST-003	ZPR-3 ASSEMBLIES 48 AND 48B: CYLINDRICAL ASSEMBLIES OF MIXED (PU,U), GRAPHITE AND SODIUM WITH A DEPLETED URANIUM BLANKET
MIX-COMP-FAST-004	ZPR-3 ASSEMBLY 56B: A CYLINDRICAL ASSEMBLY OF MIXED (PU,U), OXIDE AND SODIUM WITH A NICKEL-SODIUM REFLECTOR
PU-MET-INTER-003	ZPR-3 ASSEMBLY 58: A CYLINDRICAL ASSEMBLY OF PLUTONIUM METAL AND GRAPHITE WITH A THICK DEPLETED URANIUM REFLECTOR
PU-MET-INTER-004	ZPR-3 ASSEMBLY 59: A CYLINDRICAL ASSEMBLY OF PLUTONIUM METAL AND GRAPHITE WITH A THICK LEAD REFLECTOR

ZPR-6 Benchmarks, 4 Evaluations

IEU-COMP-INTER-005	ZPR-6 ASSEMBLY 6A: A CYLINDRICAL ASSEMBLY WITH URANIUM OXIDE FUEL AND SODIUM WITH A THICK DEPLETED-URANIUM BLANKET
MIX-COMP-FAST-001	ZPR-6 ASSEMBLY 7: A CYLINDRICAL ASSEMBLY WITH MIXED (PU,U)-OXIDE FUEL AND SODIUM WITH A THICK DEPLETED-URANIUM REFLECTOR
MIX-COMP-FAST-002	ZPR-6 ASSEMBLY 7 HIGH 240PU CORE: A CYLINDRICAL ASSEMBLY WITH MIXED (PU,U)-OXIDE FUEL AND A CENTRAL HIGH 240PU ZONE
PU-MET-INTER-002	**ZPR-6 ASSEMBLY 10: A CYLINDRICAL PLUTONIUM/CARBON/STAINLESS STEEL ASSEMBLY WITH STAINLESS STEEL AND IRON REFLECTORS**

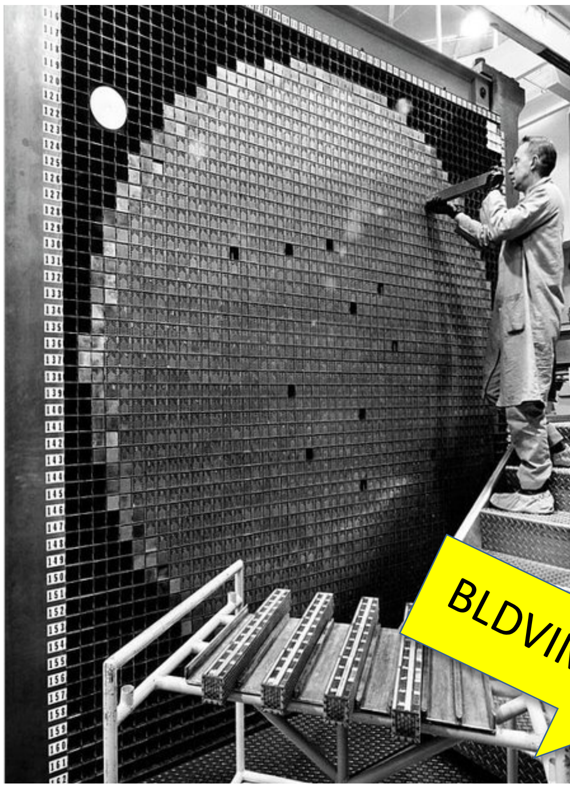
ZPR-9 Benchmarks- 8 Evaluations

IEU-MET-FAST-013	ZPR-9 ASSEMBLY 1: A CYLINDRICAL ASSEMBLY OF U METAL (93% 235U) AND DEPLETED URANIUM WITH ALUMINUM REFLECTORS
IEU-MET-FAST-014	ZPR-9 ASSEMBLIES 2 AND 3: CYLINDRICAL ASSEMBLIES OF U METAL AND TUNGSTEN WITH ALUMINUM REFLECTORS
HEU-MET-FAST-060	ZPR-9 ASSEMBLY 4: A CYLINDRICAL ASSEMBLY OF U METAL (93% 235U) AND TUNGSTEN WITH ALUMINUM REFLECTORS
HEU-MET-FAST-067	ZPR-9 ASSEMBLIES 5 AND 6: HEU (93% 235U) CYLINDRICAL CORES WITH TUNGSTEN, GRAPHITE, AND ALUMINUM DILUENTS WITH A DENSE ALUMINUM REFLECTOR
HEU-MET-FAST-070	ZPR-9 ASSEMBLIES 7, 8 AND 9: CYLINDRICAL CORES WITH HEU (93% 235U), TUNGSTEN, AND ALUMINUM OR ALUMINUM OXIDE WITH A DENSE ALUMINUM, ALUMINUM OXIDE, OR BERYLLIUM OXIDE REFLECTOR
MIX-COMP-FAST-005	ZPR-9 ASSEMBLY 31: A CYLINDRICAL ASSEMBLY WITH MIXED (PU,U)-CARBIDE FUEL AND DEPLETED URANIUM CARBIDE BLANKET
IEU-MET-FAST-010	THE U9 BENCHMARK ASSEMBLY: A CYLINDRICAL ASSEMBLY OF U METAL (9% 235U) WITH A THICK DEPLETED-URANIUM REFLECTOR (ASSEMBLY 34)
HEU-MET-INTER-001	THE URANIUM/IRON BENCHMARK ASSEMBLY: A 235U(93%)/IRON CYLINDER REFLECTED BY STAINLESS STEEL (ASSEMBLY 34)

ZPPR Benchmarks- 8 Evaluations

PU-MET-FAST-033	ZPPR-21 PHASE A: A CYLINDRICAL ASSEMBLY OF PU METAL REFLECTED BY GRAPHITE
HEU-MET-FAST-061	ZPPR-21 PHASE F: A CYLINDRICAL ASSEMBLY OF U METAL REFLECTED BY GRAPHITE
HEU-MET-FAST-075	ZPPR-20 PHASE C: A CYLINDRICAL ASSEMBLY OF U METAL REFLECTED BY BERYLLIUM OXIDE
HEU-MET-MIXED-012	ZPPR-20 PHASE D: A CYLINDRICAL ASSEMBLY OF POLYETHYLENE-MODERATED U METAL REFLECTED BY BERYLLIUM OXIDE AND POLYETHYLENE
MIX-MET-FAST-011	ZPPR-21 PHASES B THROUGH E: CYLINDRICAL ASSEMBLIES OF MIXED FISSILE PU AND U METAL REFLECTED BY GRAPHITE
MIX-COMP-FAST-006	ZPPR-2: A CYLINDRICAL ASSEMBLY WITH MIXED (PU,U)-OXIDE FUEL AND SODIUM REFLECTED BY DU, SODIUM AND STEEL
SUB-HEU-MET-FAST-001	ZPPR-20 PHASE E: A CYLINDRICAL ASSEMBLY OF U METAL REFLECTED BY BERYLLIUM OXIDE AND SAND
SUB-HEU-MET-MIXED-001	ZPPR-20 PHASE D: A CYLINDRICAL ASSEMBLY OF POLYETHYLENE-MODERATED U METAL REFLECTED BY BERYLLIUM OXIDE AND POLYETHYLENE

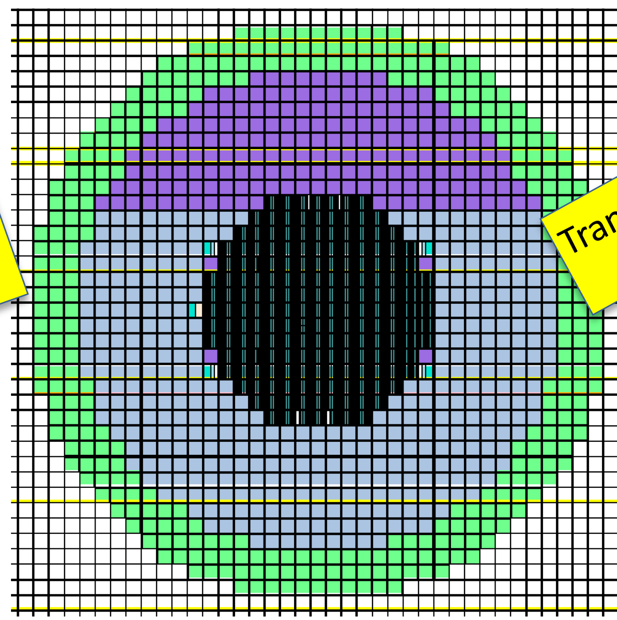
ZPR/ZPPR Benchmarking Process



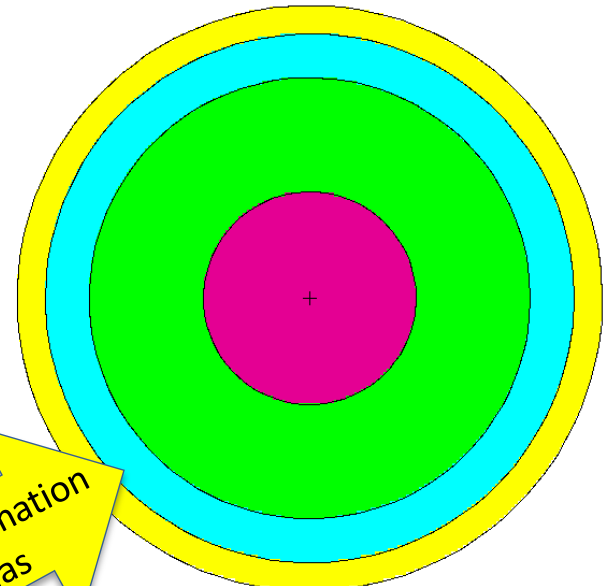
Real ZPR/ZPPR Geometry

BLDVIM

Nominal Plate-by-Plate Detailed Model



Transformation Bias



Benchmark Homogenized RZ Model of Major Core Regions and Materials, Conserving Mass and Volume

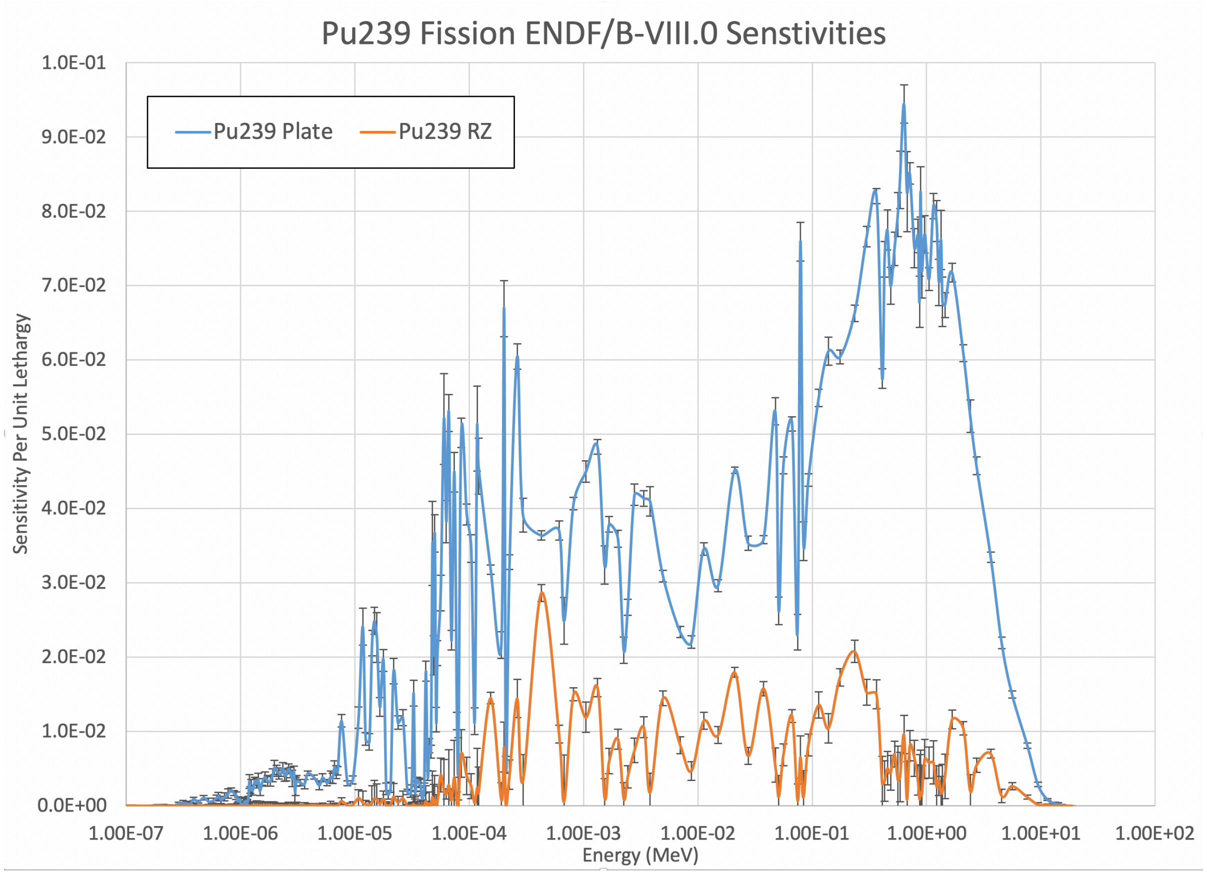
Transformation Bias Can Vary with Data Library

PU-MET-INTER-002, ZPR-6 Assembly 10: A Cylindrical Plutonium/Carbon/Stainless Steel Assembly with Stainless Steel and Iron Reflectors

Library	Code, Reference	Transformation Bias (pcm)
ENDF/B-V	VIM, PMI-002	1470 ± 90
ENDF/B-VII.1	MCNP5, PMI-002	1280 ± 11
ENDF/B-VII.1	MCNP6.1, this work	1311 ± 25
ENDF/B-VIII.0	MCNP6.1, this work	1571 ± 26

PMI-002 total benchmark uncertainty is **230 pcm**

RZ Models are THE Benchmarks, but can have Marked Physics Differences from Detailed



Sensitivities calculated using MCNP6.1 with ENDF/B-VIII.0 cross sections for both detailed plate and homogenized RZ models

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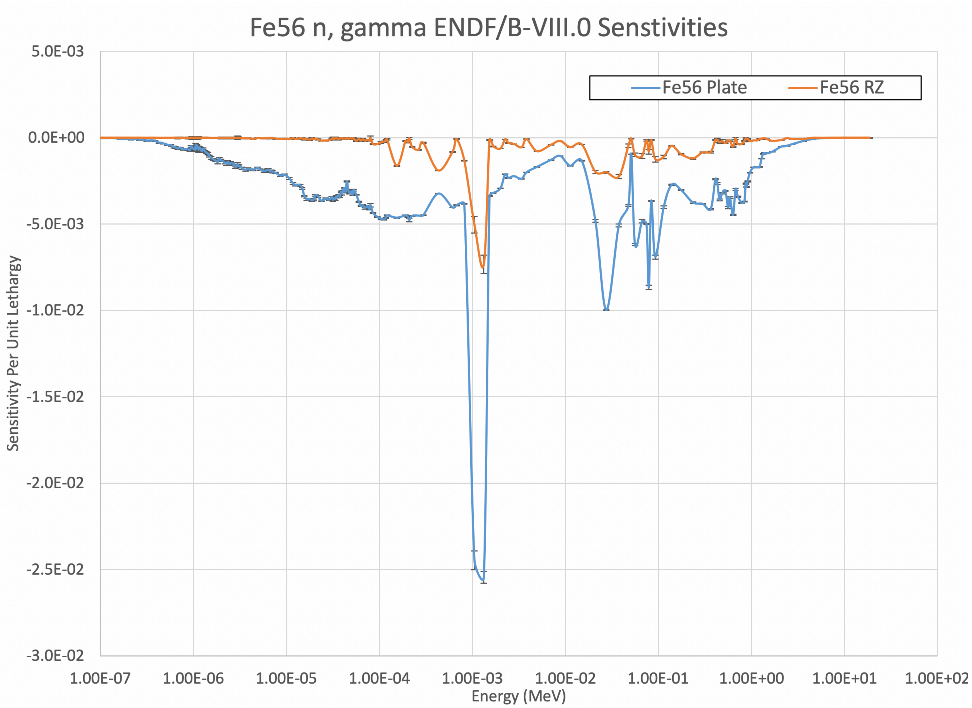

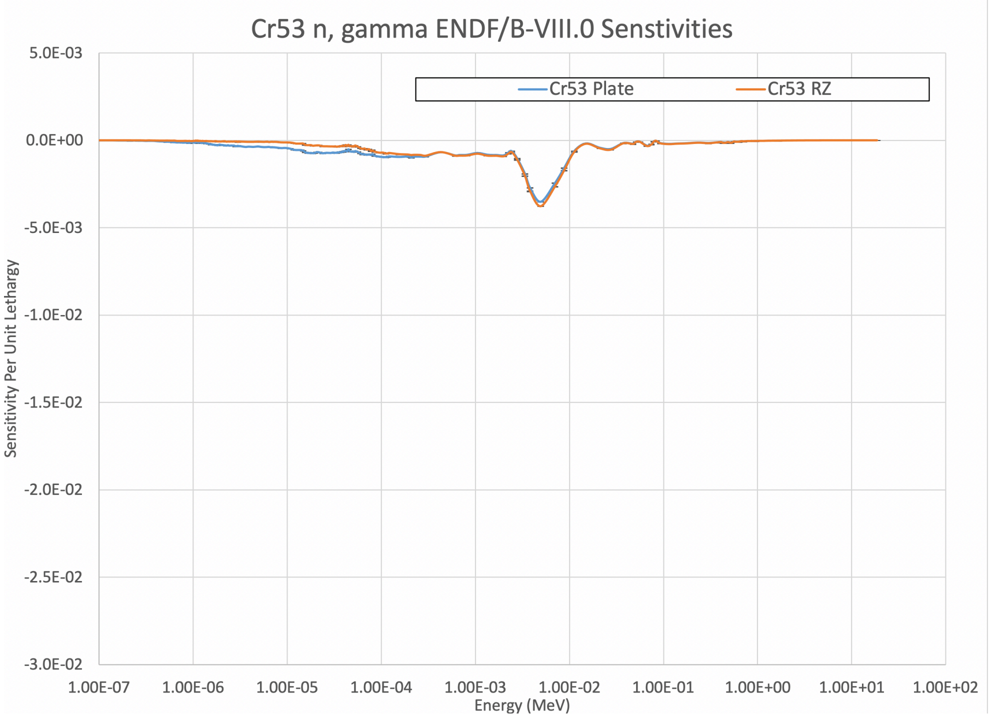

Sensitivities calculated using MCNP6.1 with ENDF/B-VIII.0 cross sections for both detailed plate and homogenized RZ models

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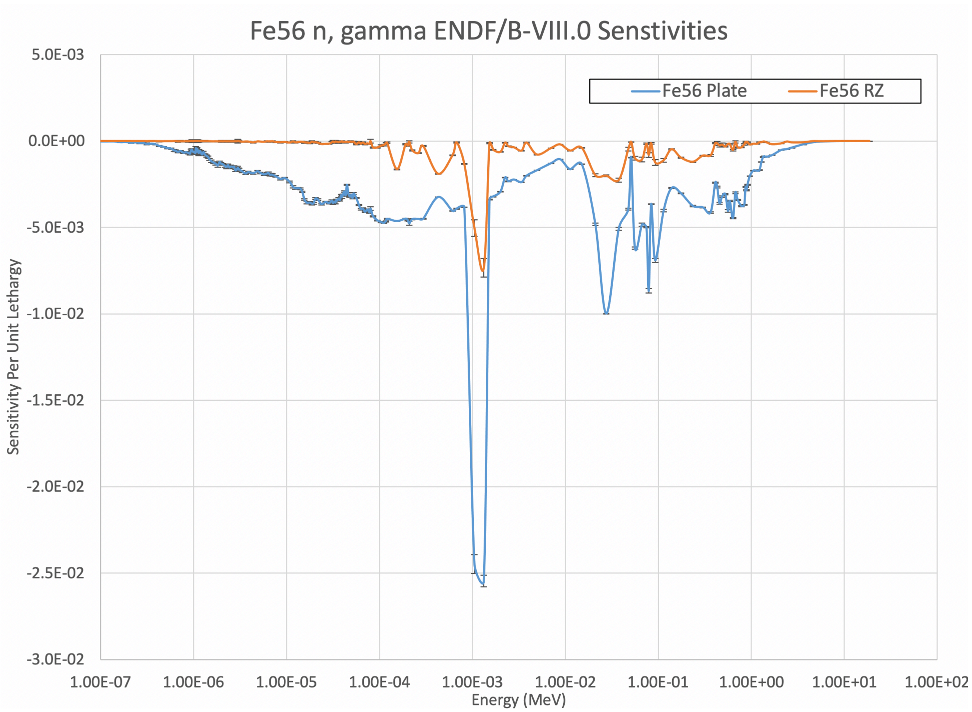
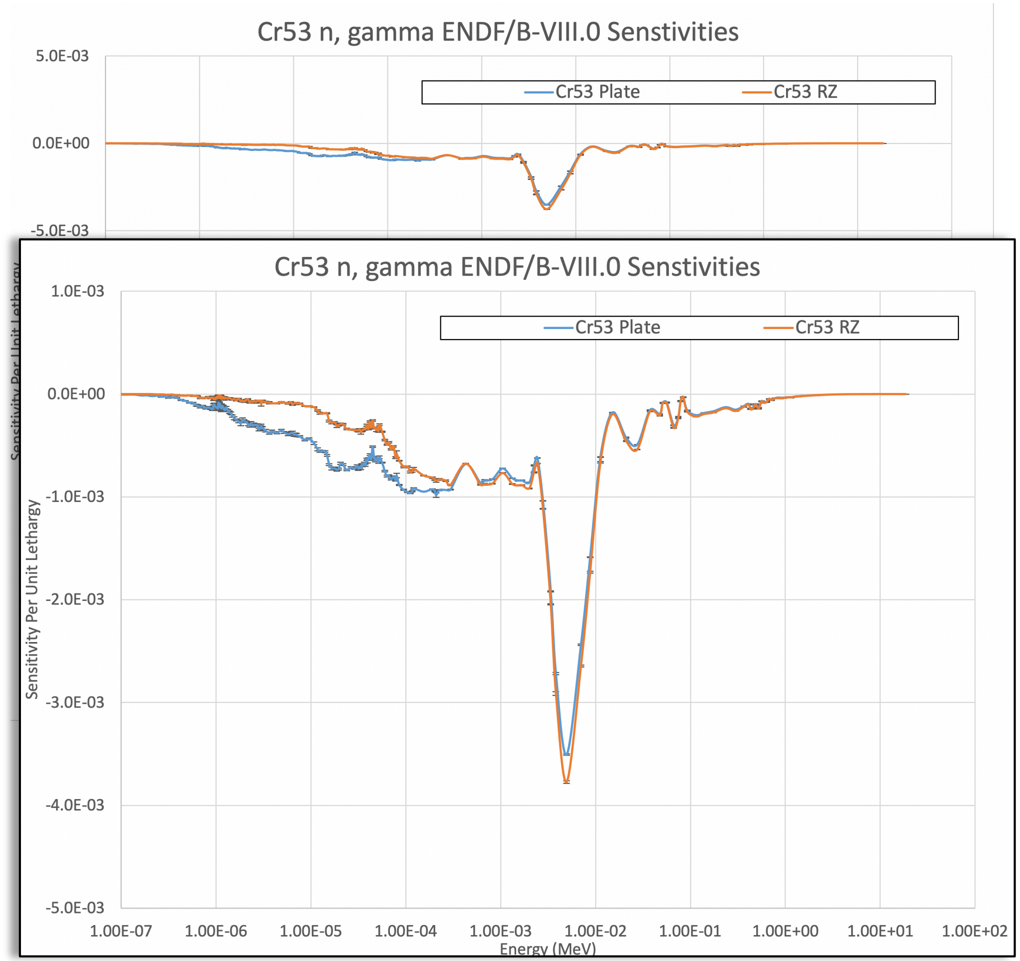
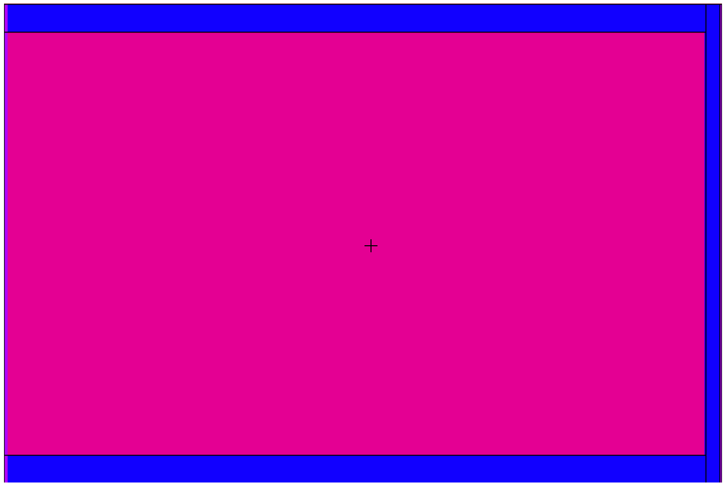


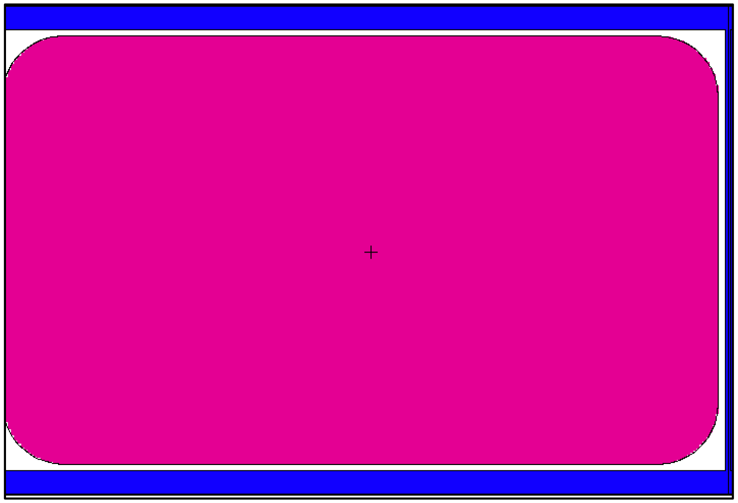


Sensitivities calculated using MCNP6.1 with ENDF/B-VIII.0 cross sections for both detailed plate and homogenized RZ models

Example: Plutonium Aluminum No Nickel (PANN) Plates VIM Models Simplifications



Variable	Value from PMI-002 (Nominal Measurements)
Length of PANN	3.00 in
Width of PANN	2.00 in
Height of PANN	0.125 in
Pu/Al Density	14.61 g/cm^3
SS304 Clad Dens	3.88, 5.89, 4.47, 7.16 g/cm^3



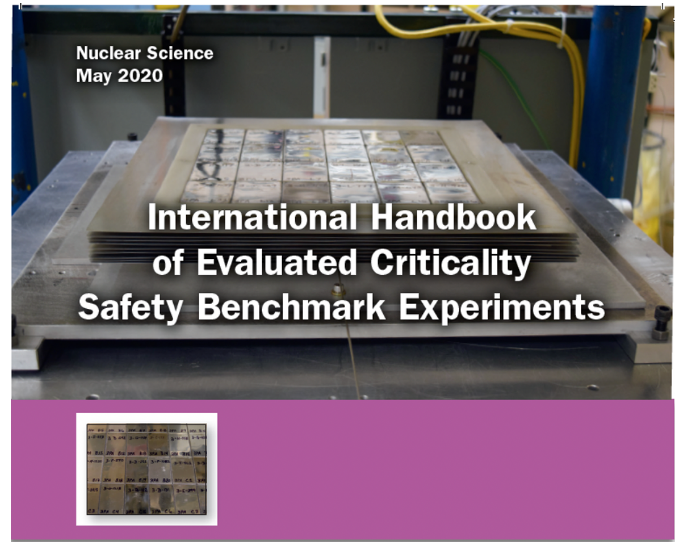
Variable	Value from PMM-002 (Actual Measurements)
Length of PANN	3.002 ± 0.003 in
Width of PANN	1.993 ± 0.004 in
Height of PANN	0.117 ± 0.002 in
Pu/Al Density	15.13 g/cm^3
SS304 Clad Dens	7.9 g/cm^3

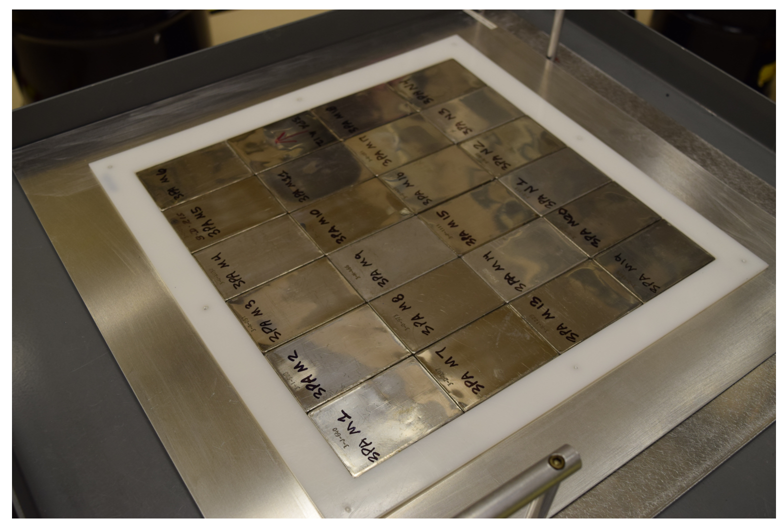
Words of Caution for Using ZPPR Benchmarks, Particularly for Nuclear Data Adjustments

- Large physics differences can be seen between heterogeneous plate-by-plate models versus homogenous RZ models
  - Especially for softer-spectrum experiments
- Plate-by-plate models **are not benchmarked**, nor is enough information provided in Section 1 to allow independent model generation
  - Use nominal plate sizes- uncertainty effects of which are NOT quantified
  - Have non-physical densities
- Uncertainties are almost assuredly underestimated for all ZPPR benchmarks
  - No assessment of geometry uncertainties due to real plate sizes, including overall core size

PU-MET-MIXED-002

- New plutonium-fueled benchmark accepted into the International Criticality Safety Benchmark Evaluation Project (ICSBEP) Handbook
  - Fuel was plutonium/aluminum Zero Power Physics Reactor (ZPPR) plates
  - Pu plates arranged in 12” x 12” layers (6 plates by 4 plates)
- First Benchmark for the Thermal/ Epithermal eXperiments (TEX) Project
  - Minimum of materials
  - Designed to span multiple neutron fission energy spectra (fast through thermal) using polyethylene moderator
  - Assembly designed to be easily modified to test materials of interest





PU-MET-MIXED-002 Configurations

Picture of TEX-Pu Configuration on Planet Vertical Lift Machine at the National Criticality Experiments Research Center (NCERC), Photo credit Los Alamos National Laboratory

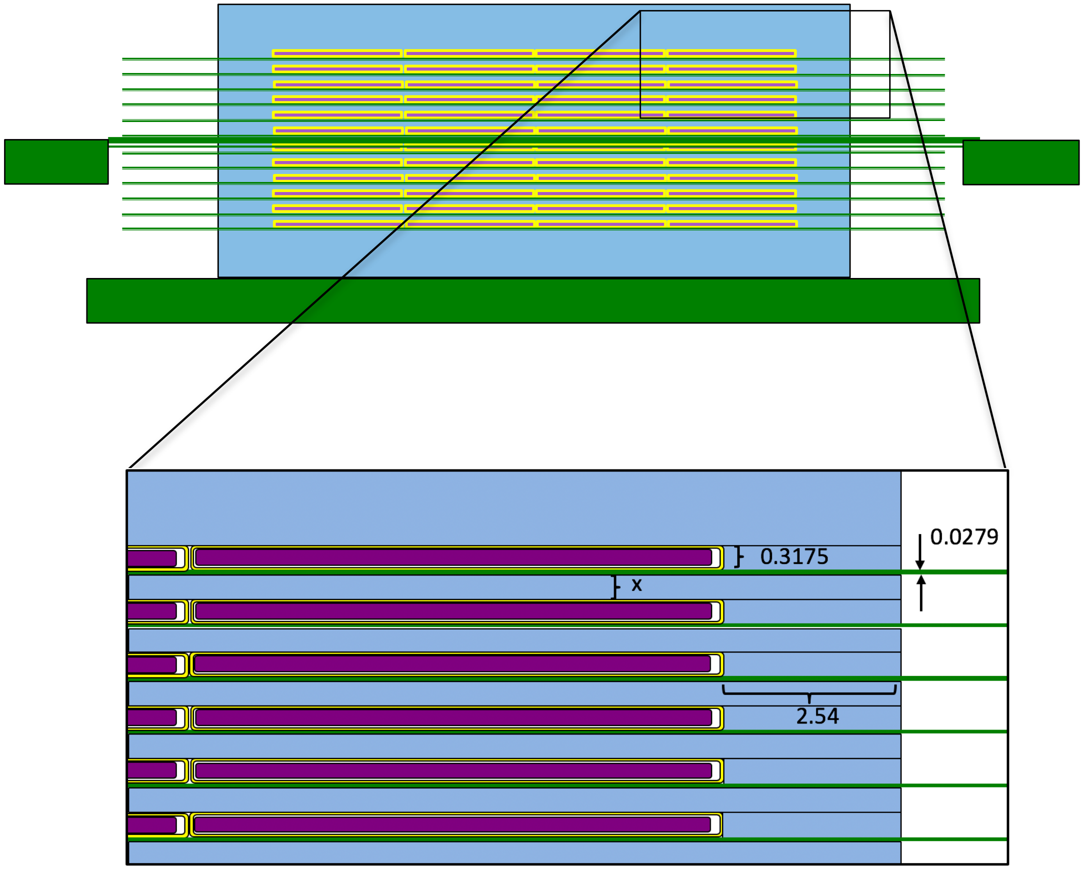
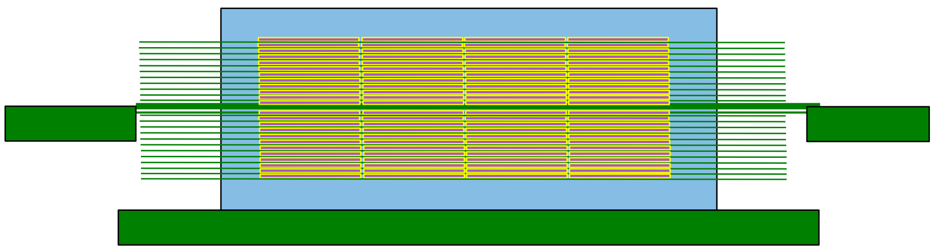
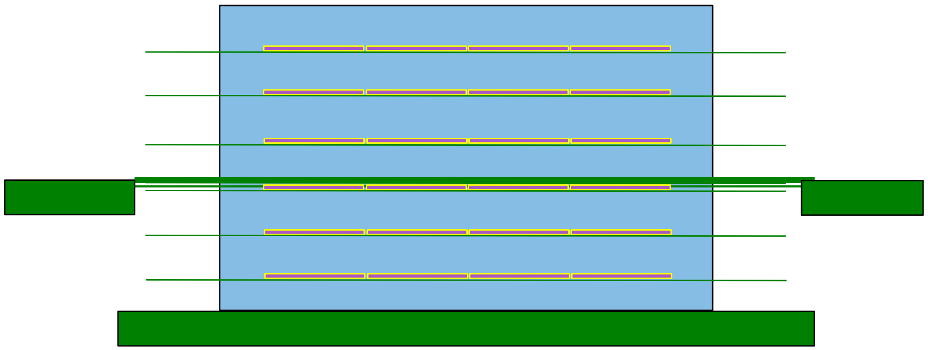


Diagram showing the Plutonium TEX configurations and the variable thickness, x, of polyethylene moderator between each layer

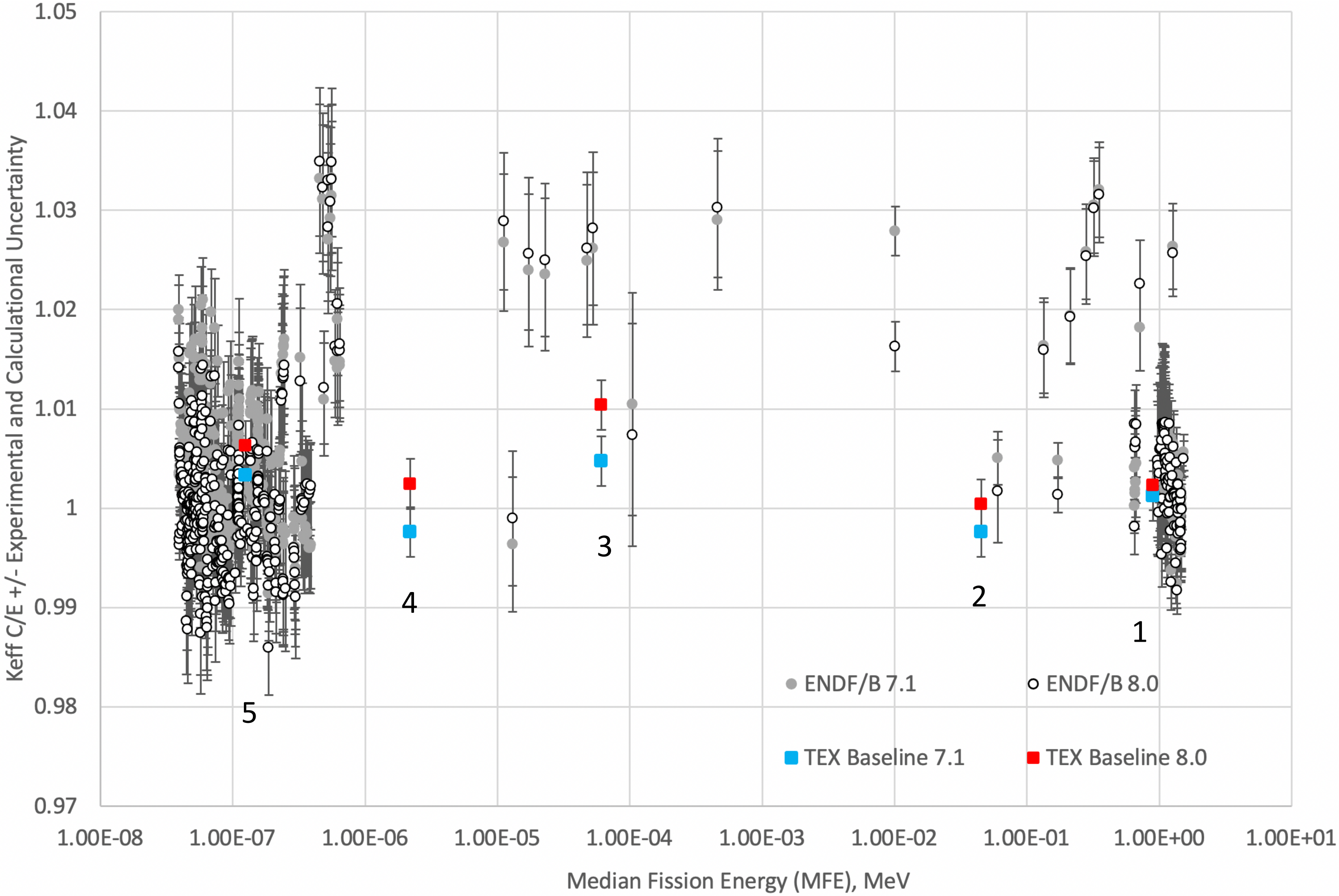
PU-MET-MIXED-002 Characteristics by Case

Case Number	Thickness of PE Moderator (in)	Thermal Fission Fraction (<0.625 eV)	Intermediate Fission Fraction (0.625 eV-100 KeV)	Fast Fission Fraction (>100 KeV)
1	0 (no PE)	0.09	0.18	0.73
2	1/16	0.14	0.38	0.48
3	3/16	0.28	0.43	0.29
4	7/16	0.50	0.32	0.18
5	1	0.66	0.21	0.13

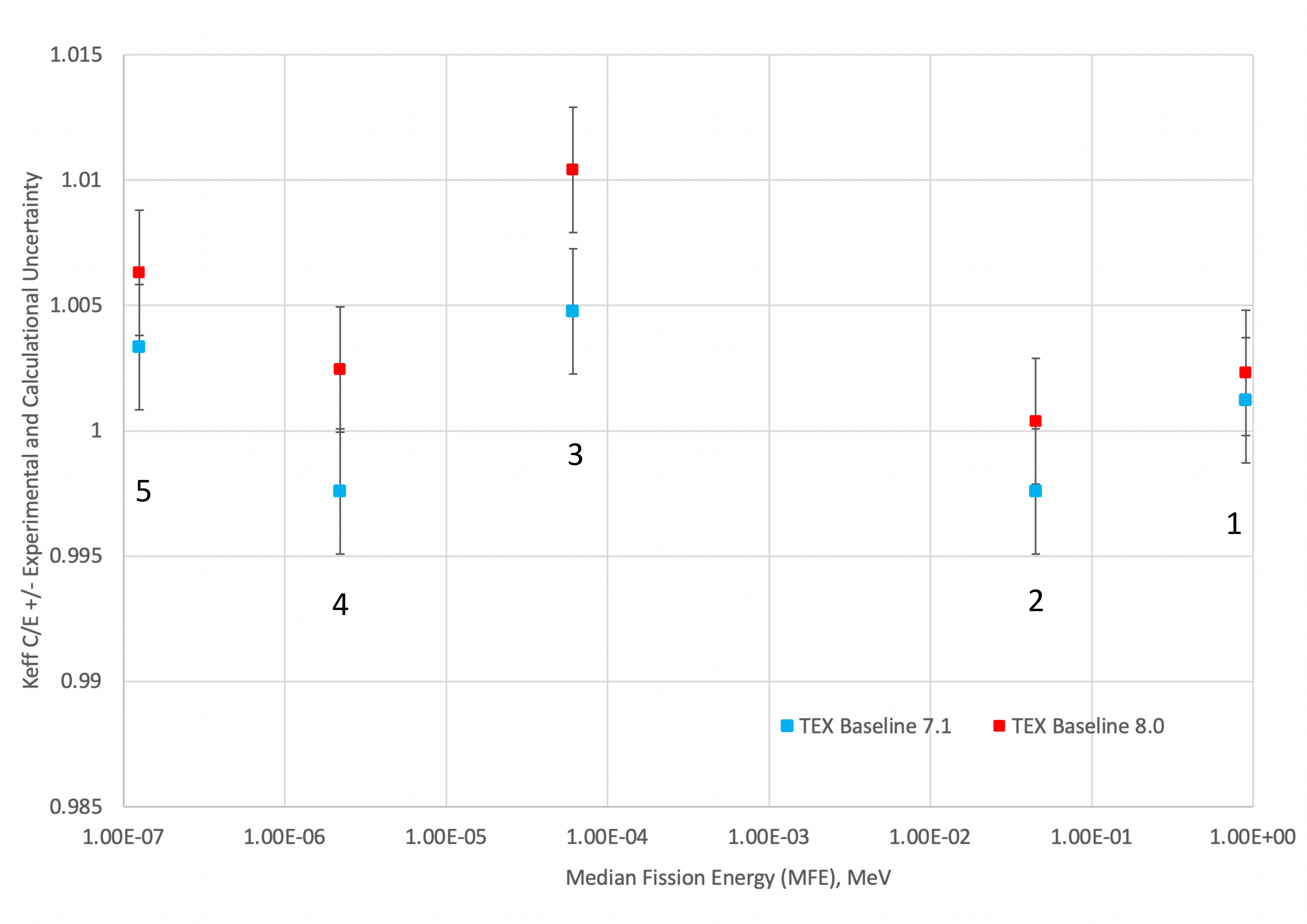




PMM-002 Results- MCNP6.1



PU-MET-MIXED Results



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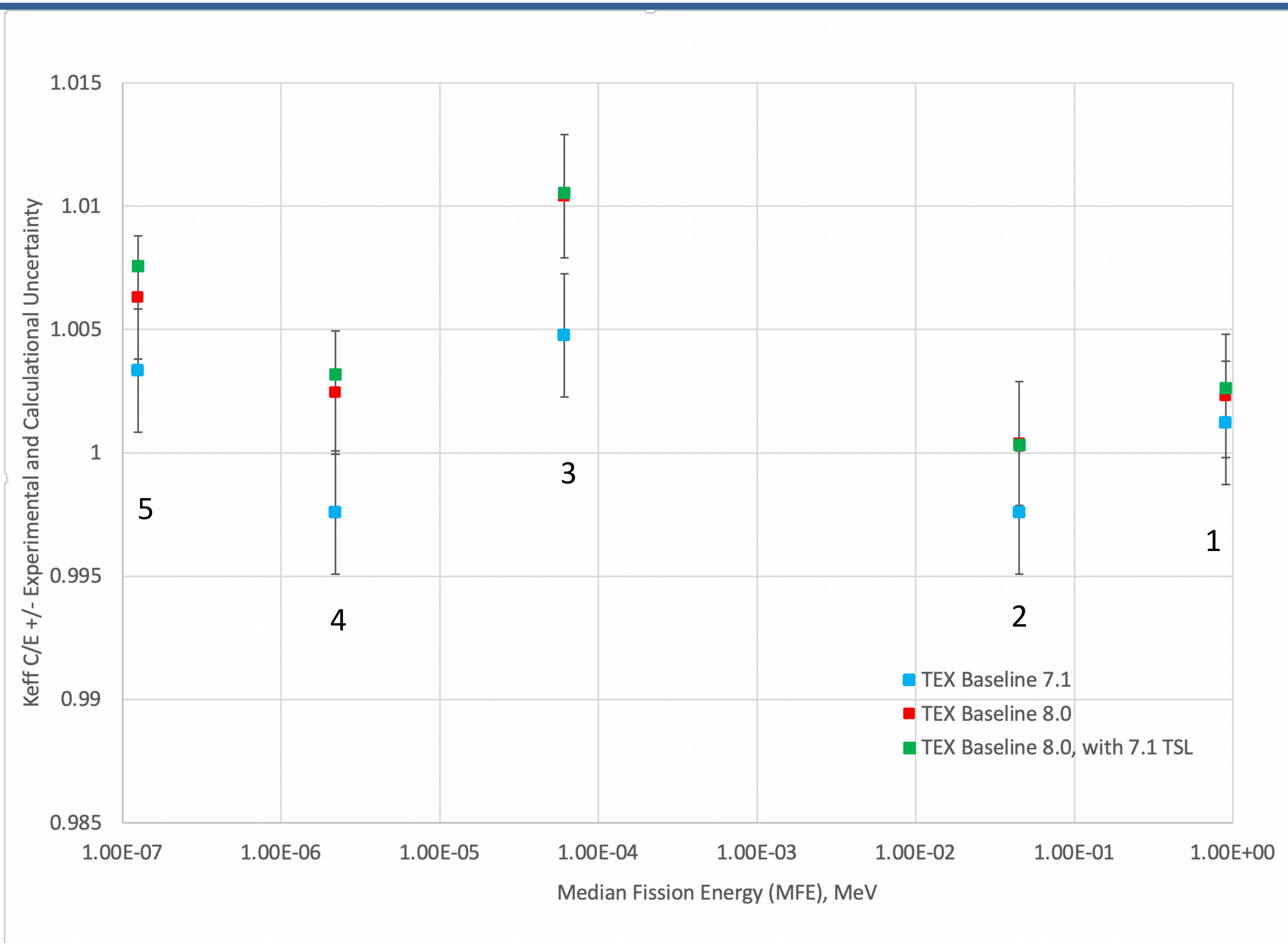
New TSL is Mitigating ENDF/B-VIII.0 Overprediction



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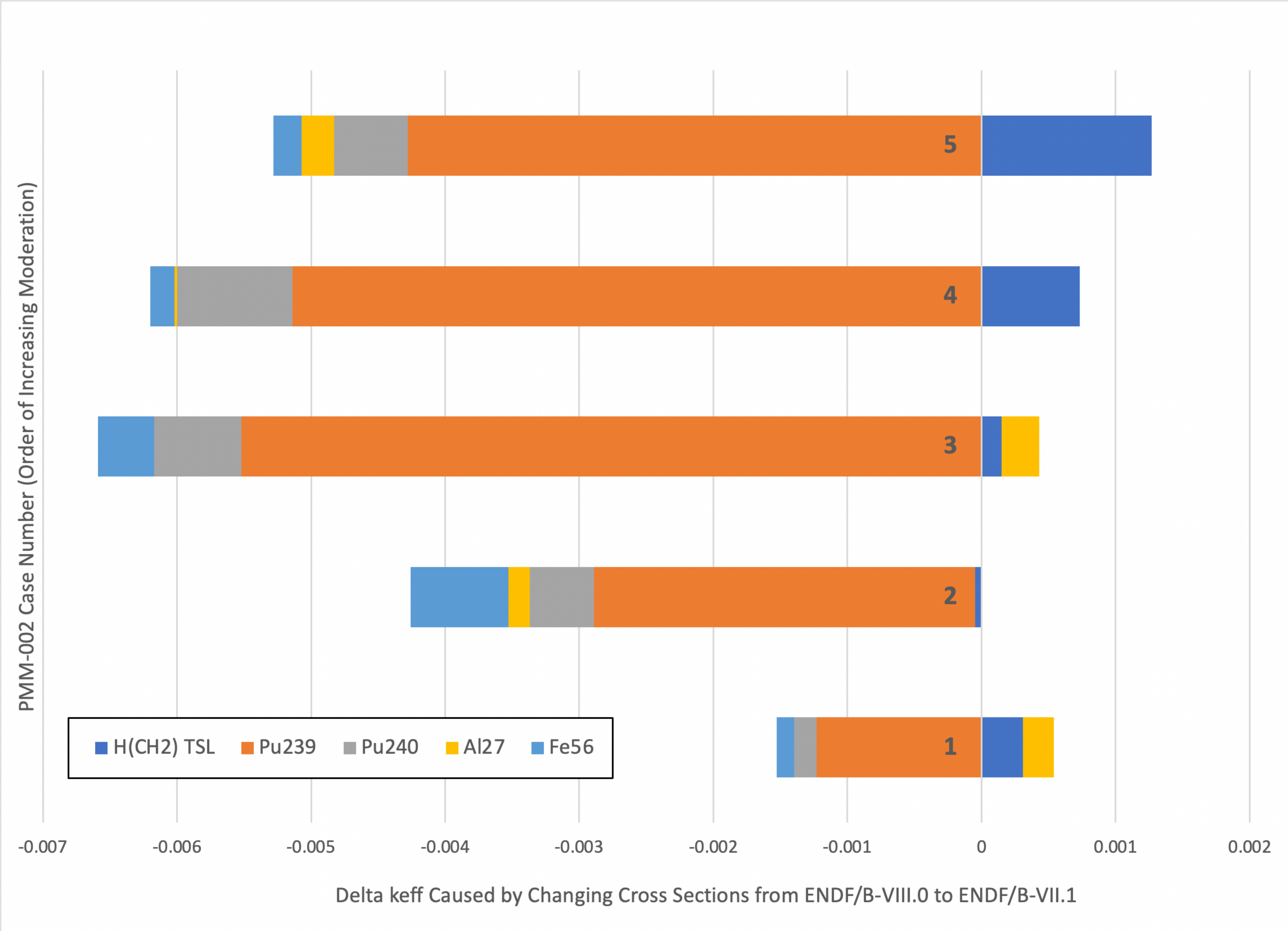
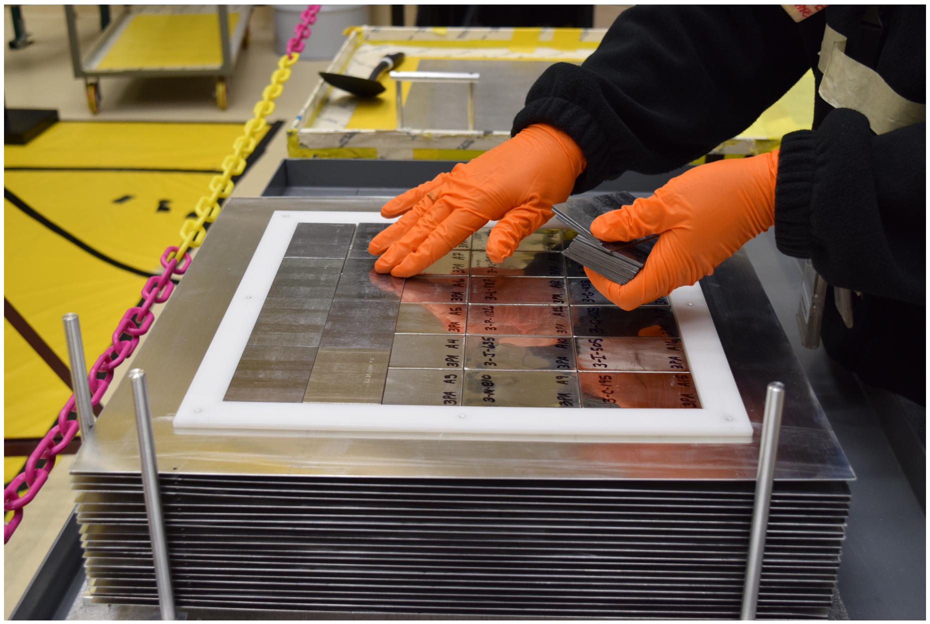
^{239}Pu Changes are Driving the Differences



PMM-002 Data Testing Conclusions

- New TSLs in ENDF/B-VIII.0 reduce the overprediction of the library for the most moderated cases
- The differences between VII.1 and VIII.0 are driven by the ^{239}Pu changes, and are consistently higher for all configurations
  - The VIII.0 ^{239}Pu thermal cross sections were specifically adjusted lower to better predict plutonium thermal solutions criticality benchmarks, yet they overpredict the TEX thermal configurations, moderated by PE
- Other, smaller differences seen for ^{240}Pu and ^{56}Fe
- PMM-002 has shown utility in testing cross sections over a wide range of neutron energies

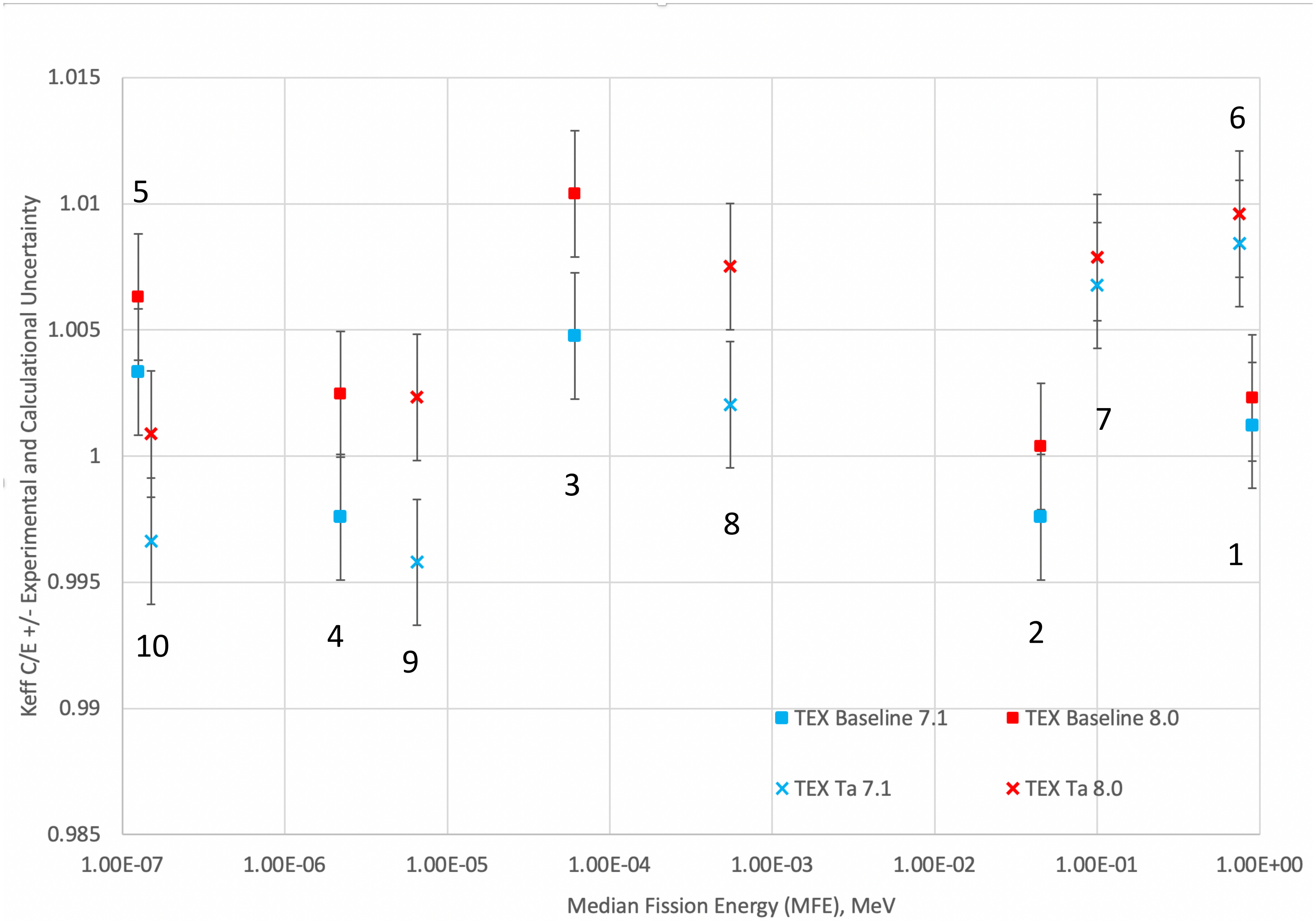
PU-MET-MIXED-003, TEX-Pu with Tantalum



- TEX was designed to easily accommodate test materials of interest
- First test material was Tantalum, due to lack of integral benchmarks

- ZPPR Inventory included 15,000 very pure tantalum plates
  — Nominal outer dimensions of 2" by 3" by 0.0625"
- Five configurations benchmarked as PU-MET-MIXED-003, approved by ICSBEP pending comment resolution

PMM-002 (1-5) and PMM-003 (6-10, with Ta) Results, MCNP6.1



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