Critical Experiments and Their Important Role in Nuclear Data and Code Validation

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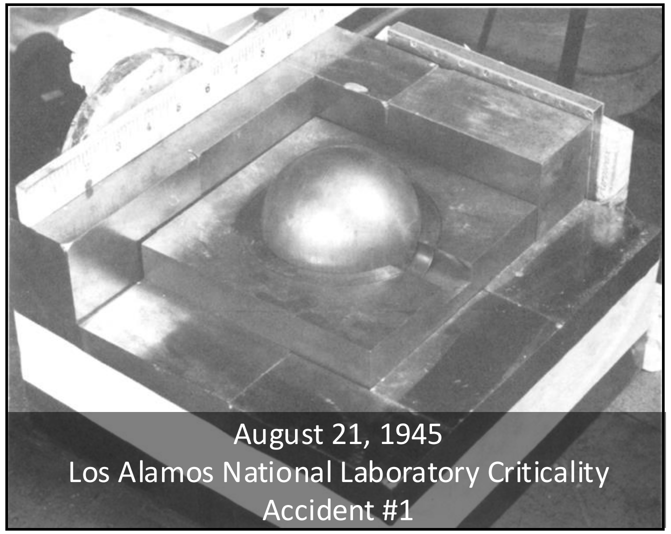
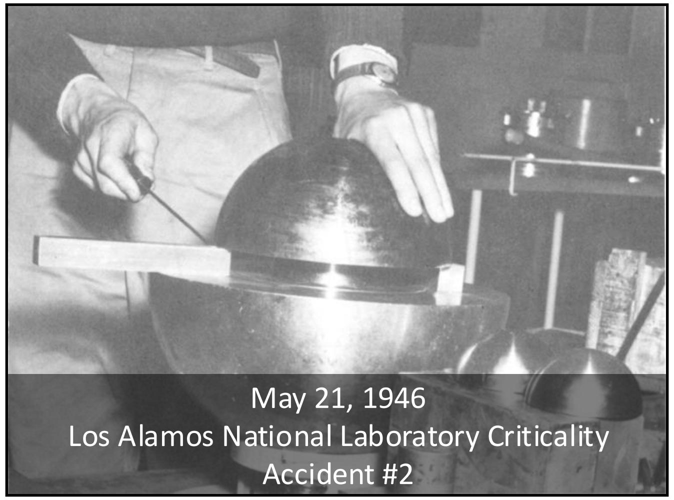
Nuclear Criticality Safety

- Criticality Accidents: Self-sustaining chain reactions that occur during the handling (transport, processing, storage) of fissionable materials

- Nuclear Criticality Safety: the art and science of preventing self-sustaining chain reactions during nuclear material operations
  - Before starting work, analyze expected operating conditions and credible abnormal conditions to ensure subcriticality

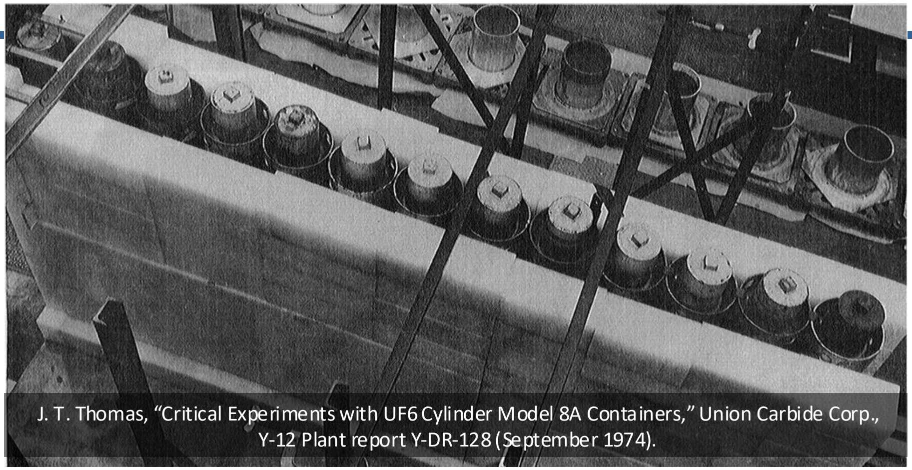
- Even before the first accidents, the need for ensuring the subcriticality of operations was recognized from the very beginning of the nuclear age


August 21, 1945
Los Alamos National Laboratory Criticality Accident #1

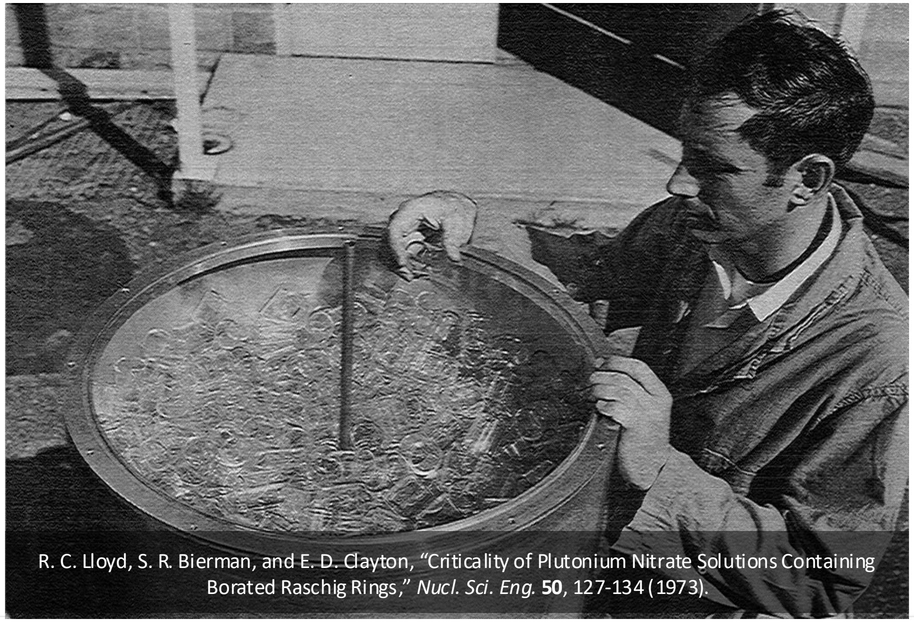

May 21, 1946
Los Alamos National Laboratory Criticality Accident #2

Criticality Safety Was Historically Experimentally Based

R. C. Lloyd, E. D. Clayton, and J. H. Chalmers, "Criticality of Arrays of ^{233}U Solution," *Nucl. Appl.* **4**, 136-141 (1968).



J. T. Thomas, "Critical Experiments with UF6 Cylinder Model 8A Containers," Union Carbide Corp., Y-12 Plant report Y-DR-128 (September 1974).

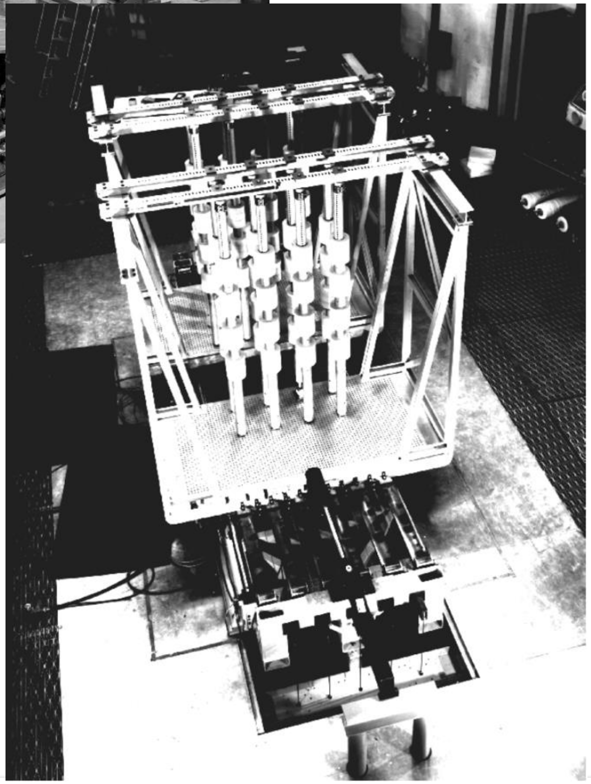


R. C. Lloyd, S. R. Bierman, and E. D. Clayton, "Criticality of Plutonium Nitrate Solutions Containing Borated Raschig Rings," *Nucl. Sci. Eng.* **50**, 127-134 (1973).

What are Critical Experiments?

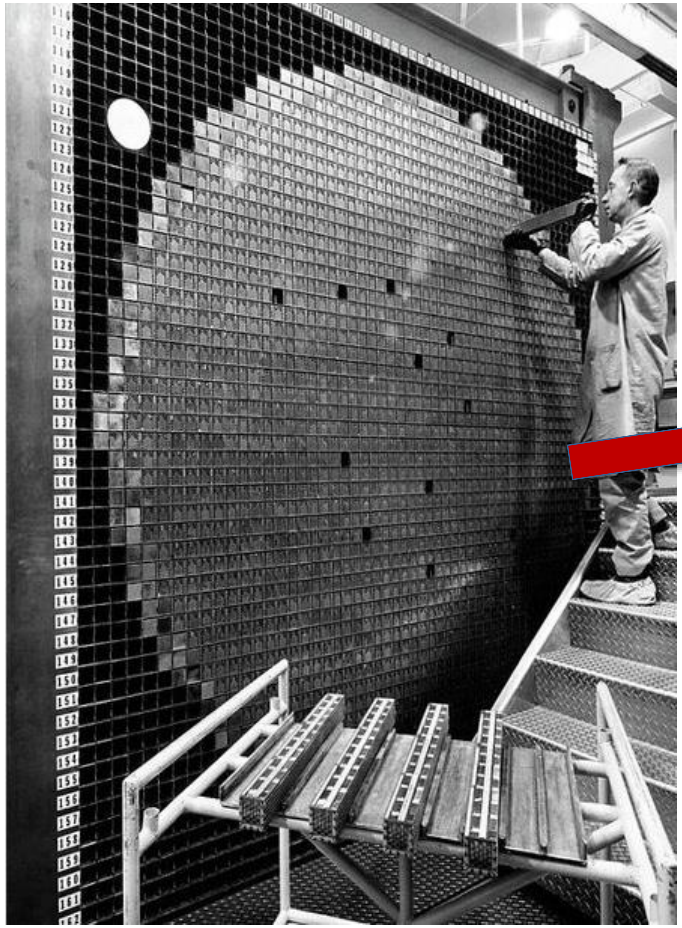
- Controlled assemblies of nuclear material designed to just achieve the critical point (or slightly lower/higher)
  - Critical point: neutrons have self-sustaining chain reaction within the assembly
  - Neutron production (mainly through fission) balance losses (through absorption and leakage)
  - Integral experiments in that they depend on multiple nuclear data (isotopes, energy ranges, reaction types)

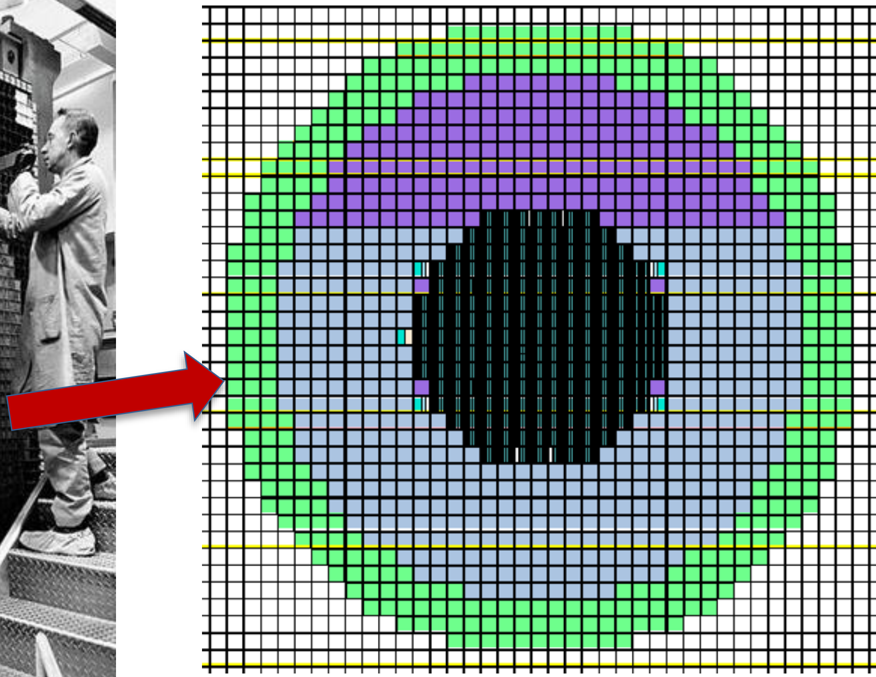
- Critical Experiment Measured Quantity (Effective Multiplication Factor, k_{eff})
  - Not actually directly measurable
  - Infer from subcritical configurations (extrapolate to critical, k_{eff} = 1.0)
  - Calculate from reactor period measurement (depends on other nuclear data like delayed neutron fraction/effectiveness)
  - Uncertainties in k_{eff} measurement usually very low (hundredths of a percent)



Benchmarks Are Evaluated Integral Experiments

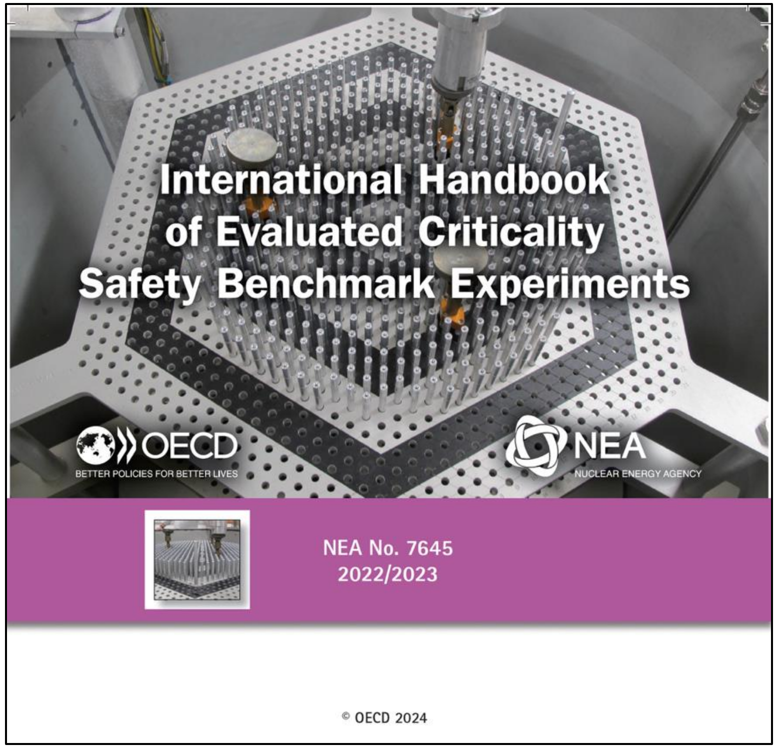
- Well characterized experiments
- Evaluate all experimental uncertainties
- Bias and uncertainty for model simplifications
  - Geometry simplifications
  - Room return
  - Material impurities
- Describe benchmark model
- Sample calculation results
- Disseminate for broader use





International Criticality Safety Benchmark Evaluation Project (ICSBEP)

- Official activity of the Organization for Economic Cooperation and Development’s (OECD) Nuclear Energy Agency since 1995
- Main Goal: Provide standardized benchmarks for **criticality safety validation**
- Updated handbook with new evaluations released regularly- most recently this week (2022/2023 Edition)!

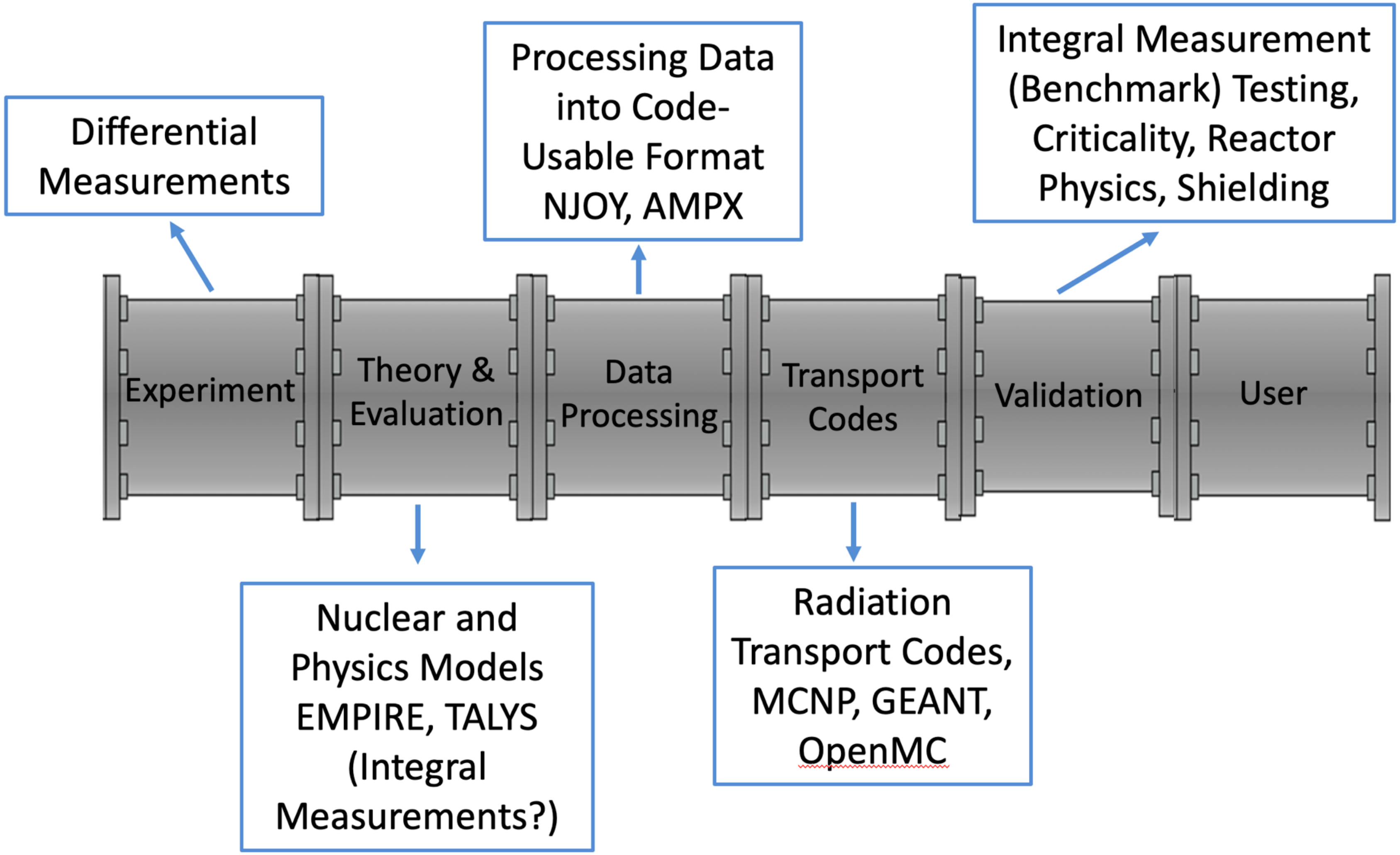


ICSBEP Type	Description	Configurations
PU	Plutonium	801
HEU	Highly Enriched Uranium	1455
IEU	Intermediate Enriched Uranium	278
LEU	Low Enriched Uranium	1827
U233	Uranium 233	244
MIX	Mixed Material Systems	536
SPEC	Other Actinides	20
ALARM	Shielding and Criticality Accident Alarm Placement	51
FUND	Fundamental Physics Measurements	246
	Handbook Total	5458

Extensive International Review Process

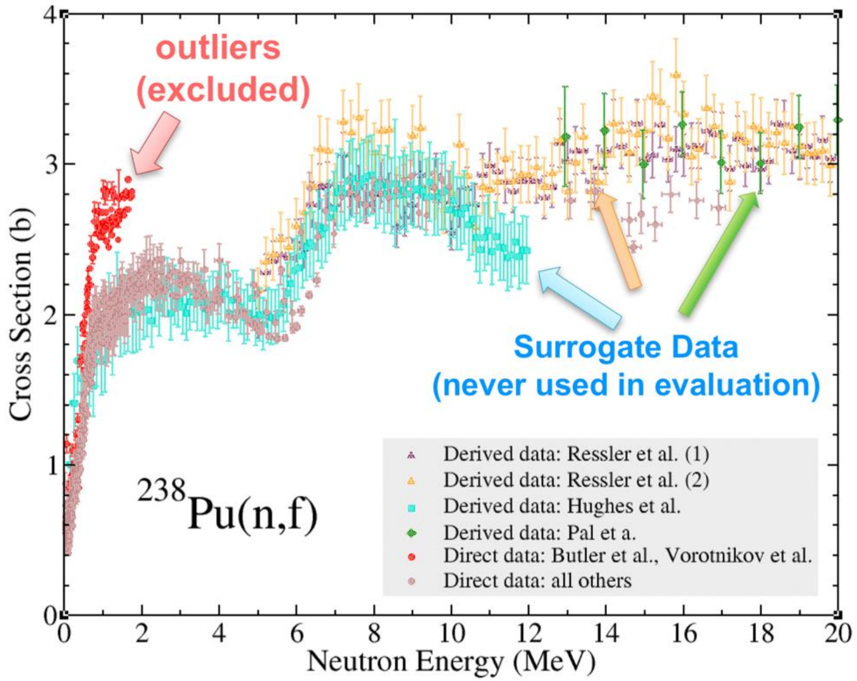
- Benchmark Standardized Format
  - Section 1: Experiment Description
  - Section 2: Uncertainty Analysis
  - Section 3: Benchmark Model Description
  - Section 4: Sample Calculations
- Many Experts Involved
  - Evaluator(s) – primary assessment of the benchmark
  - Internal Reviewer(s) – in-house verification of the analysis and adherence to procedure
  - Independent Reviewer(s) – external verification of the analysis
  - Technical Working Group Meeting – annual international effort and panel review

The Nuclear Data Pipeline



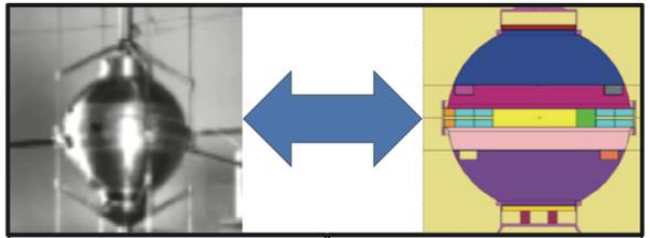
Data Adjustment: When Integral Experiments Are Used During Nuclear Data Evaluation

Differential data often disagrees, so evaluators use integral data (how well the cross section predicts integral experiments) to determine which data to believe



Quaglioni, S., Nuclear Data Week 2017

Major cross sections are “tuned” to certain critical experiments



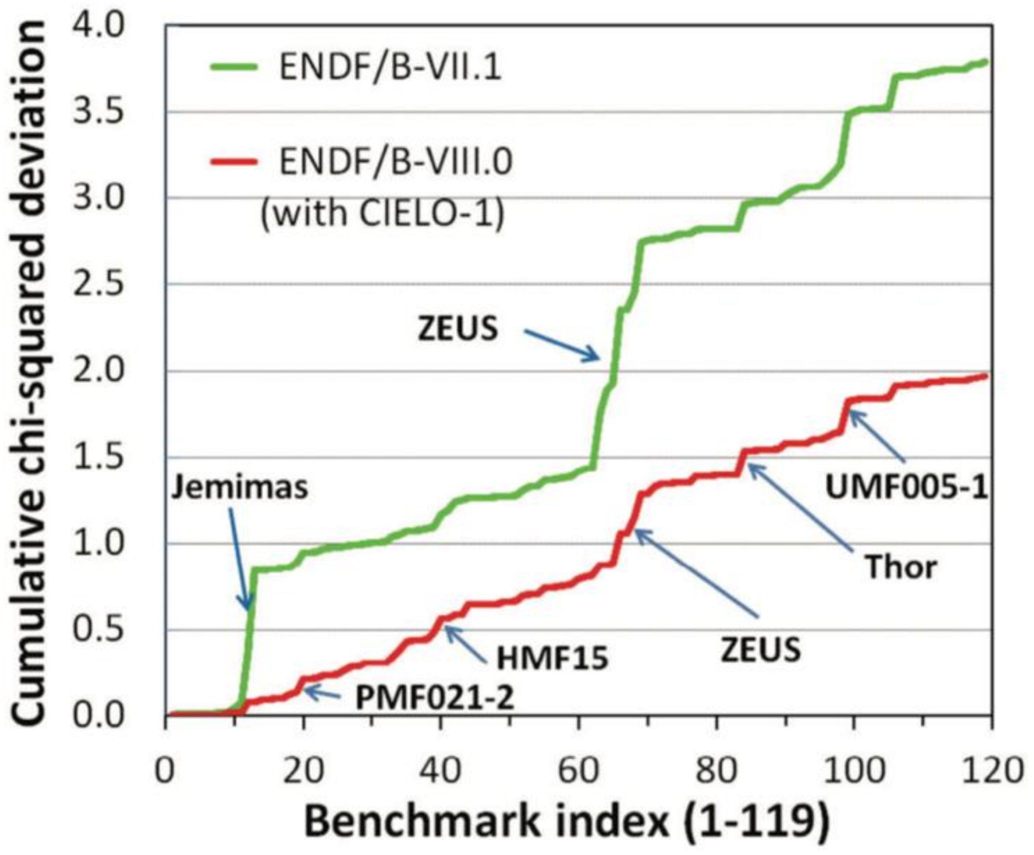
BRC09 (CEA) k_{eff}=1.00082(11)	ENDF-VII.1 k_{eff}=1.00060(12)
How does k_{eff} change when a BRC09 value is replaced by one from ENDF-VII.1?	
Quantity	**Δk_{eff} (1000th's of %)**
Fission	-138
Capture	+269
Elastic Scattering	**-638**
Inelastic Scattering	**+522**

The end result is a lack of confidence in modeling systems that significantly differ from the integral benchmark

Work by E. Bauge, et al. (CEA-DAM)
L. Bernstein, Nuclear Data Week 2016

Data Validation: Nuclear Data Libraries are Judged by How Well They Predict Integral Experiments

- **Ultimate goal is to improve evaluated nuclear data for applications**
- Suite of benchmarks to validate evaluated nuclear data
  - Example shows improvement in fast metal systems for ENDF/B-VIII.0
- Provides feedback to measurement and evaluation community
  - **Currently dominated by critical benchmarks**, NEED representation from other applications
- Drives improvements in evaluated nuclear data
- Provides end-users confidence they can use codes and nuclear data for their applications



M.B. Chadwick et al, Nuclear Data Sheets 148, 189 (2018)

ENDF/B-VIII.0 Library Validation

Available online at www.sciencedirect.com
ScienceDirect
Nuclear Data Sheets 148 (2018) 1–142
Nuclear Data Sheets
www.elsevier.com/locate/nds

ENDF/B-VIII.0: The 8^{th} Major Release of the Nuclear Reaction Data Library with CIELO-project Cross Sections, New Standards and Thermal Scattering Data

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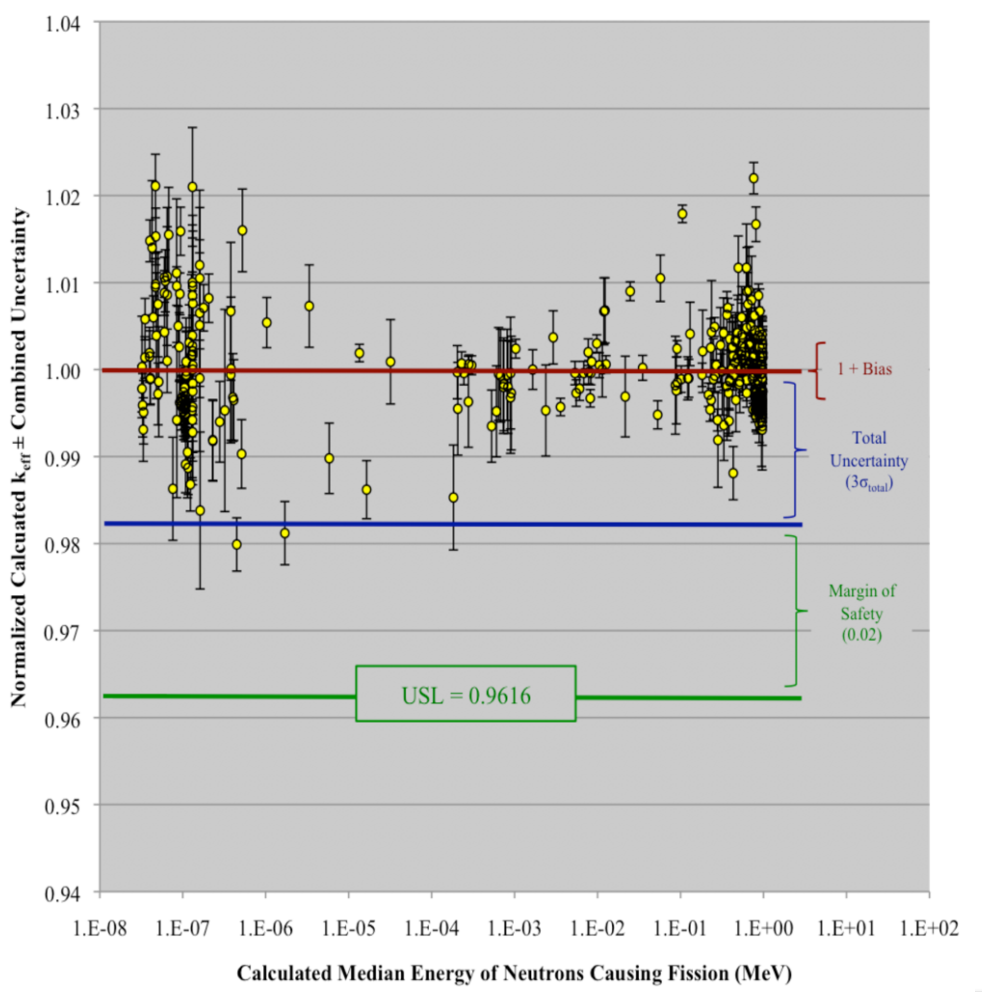
Pages 81-99 Detail Integral Testing of the ENDF/B-VIII.0 Library

Usage of Benchmarks for Nuclear Criticality Safety

- Ensure subcriticality of operations
  - Radiation transport codes calculate k_{eff}
  - Perfect codes, data, and benchmarks should result in k_{eff} of 1.00000 for all critical configurations
- Validation is required
  - Regulatory driven
  - Many benchmarks needed
  - Provide coverage for all important reactions
- Set an Upper Subcritical Limit (USL) for operations

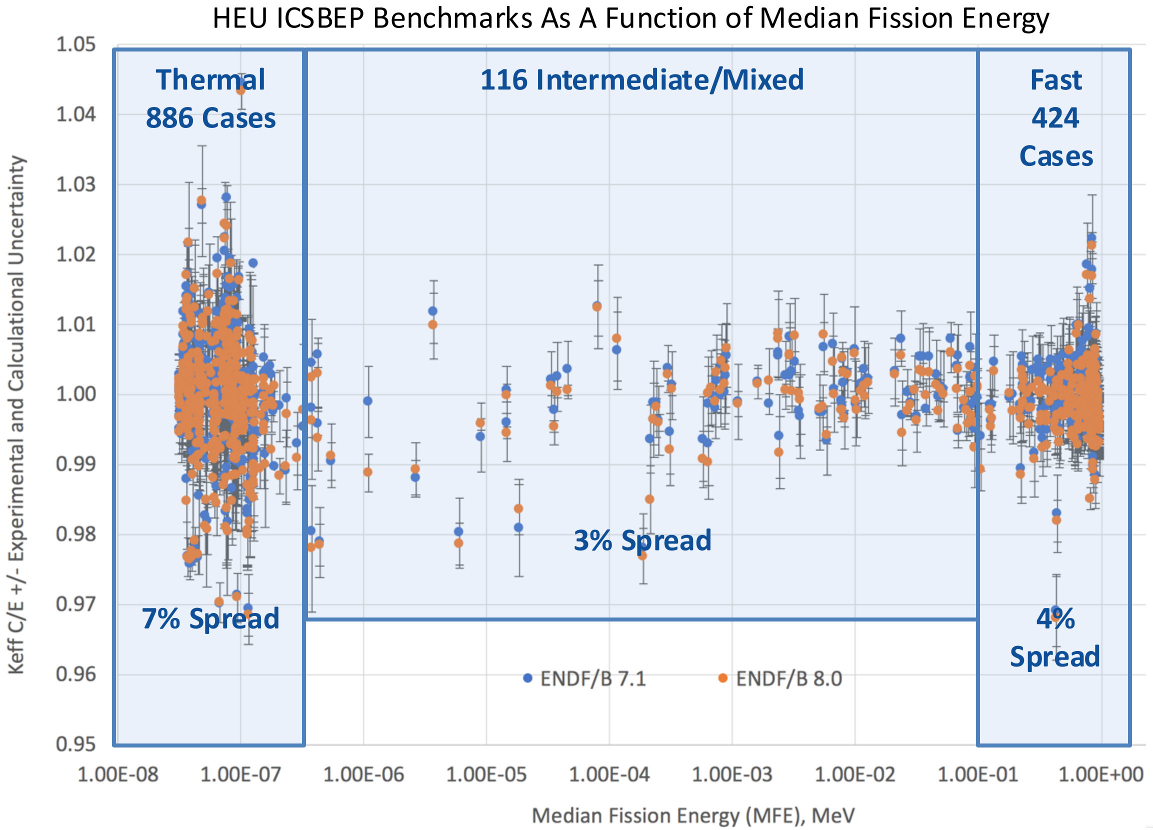
Example NCS Validation Graph



Even with >5,000 Benchmarks, the Test Set is Not Comprehensive

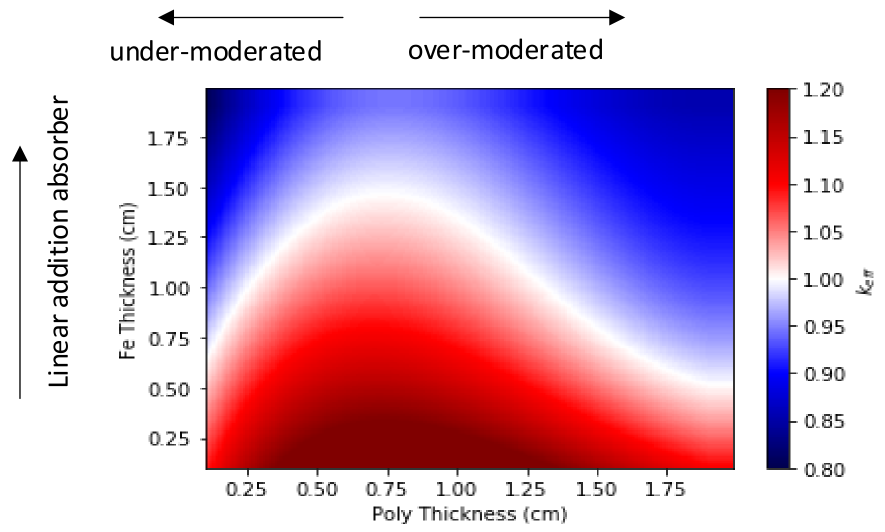
- Major Isotopes (^{235}U and ^{239}Pu)
  - Not all energy regimes covered (most notably missing are intermediate/resonance energy systems)
  - Lots of LEU and HEU, not as much intermediate or HALEU-type enrichments

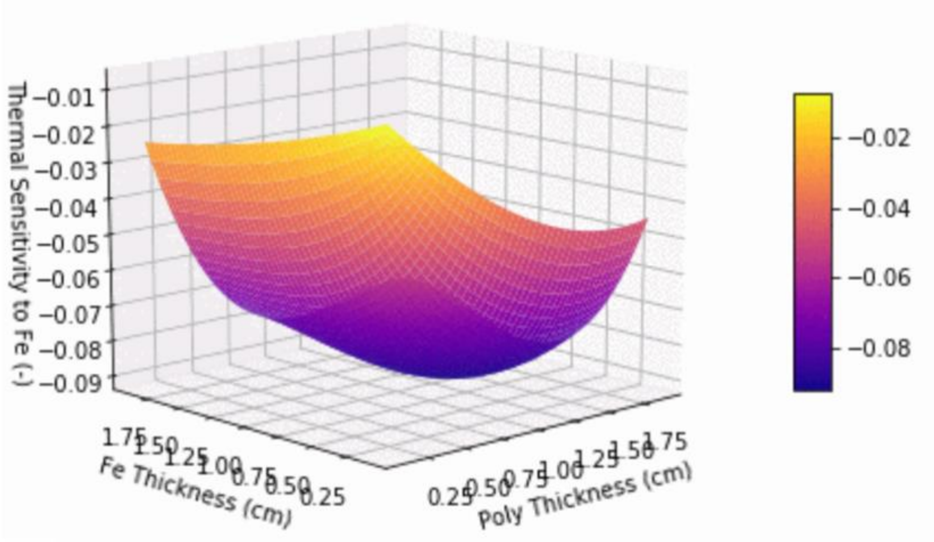
- Other Isotopes
  - Many materials are missing from ICSBEP or existing benchmarks have inadequate sensitivity to included materials, such as:
    - Angular scattering sensitivity
    - Absorption sensitivity
    - Thermal scattering sensitivity to moderators that are not water
  - Known gaps for many basic structural materials (Fe, Cr, Mo, Mn, Ni etc) and advanced reactor materials



Designing Modern Critical Experiments for Benchmarks

- Optimize experiment design to provide the best possible test of some variable
  - Targeting averaging neutron energy of a system
  - Sensitivity to specific reaction of specific nuclide at a specific energy
  - Representativity of criticality safety application

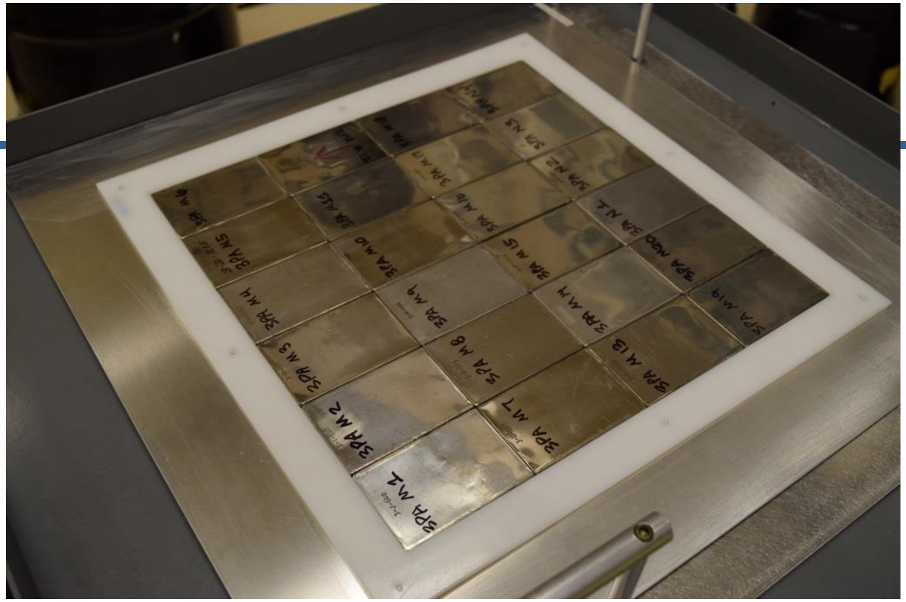


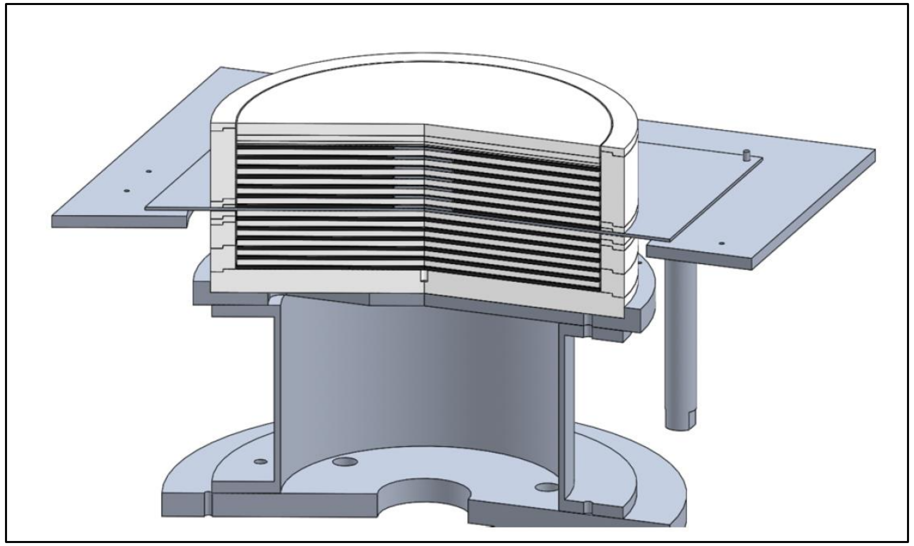


Thermal/Epithermal eXperiments (TEX)

- LLNL/LANL collaboration funded by the DOE Nuclear Criticality Safety Program (NCSP) to produce new critical benchmarks to address the nuclear data and validation needs for criticality safety

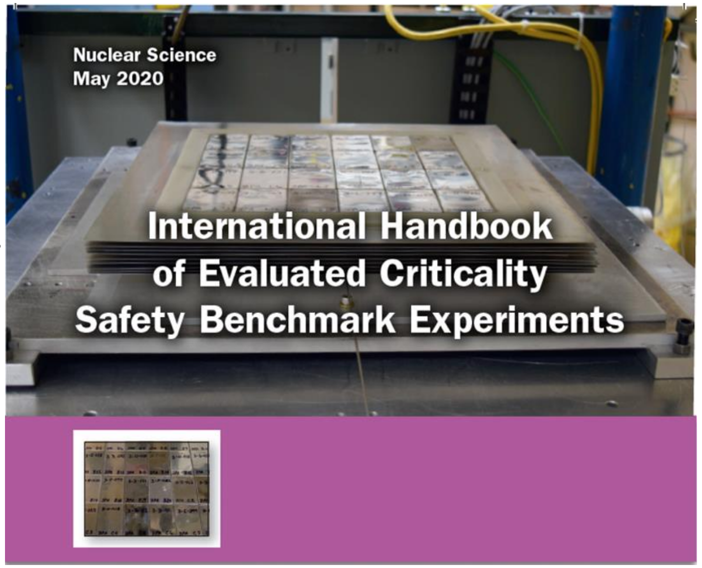
- Two test bed assemblies (Pu and HEU)
  - Plutonium fueled with plutonium/aluminum Zero Power Physics Reactor (ZPPR) plates arranged in 12” by 12” layers
  - HEU fueled with Jemima plates (15” OD)
  - Minimum of materials
  - Designed to span multiple neutron fission energy spectra (fast through thermal) using polyethylene moderator
  - Assembly designed to be easily modified to test materials of interest





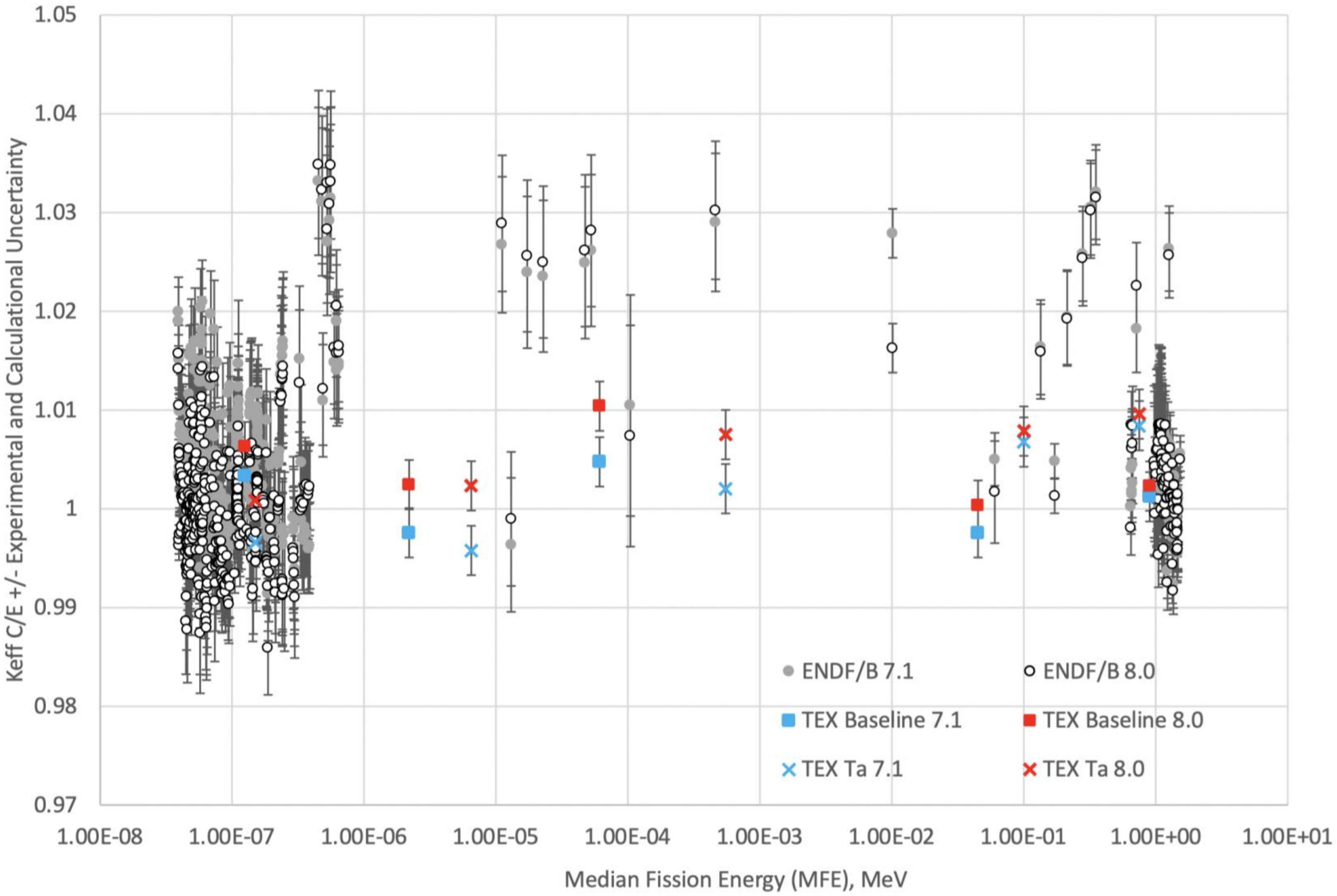
Five TEX Benchmarks Complete

- TEX-PU
  - **PU-MET-MIXED-002-** TEX Plutonium Baseline Assemblies: Plutonium-Aluminum Metal Alloy Plates with Varying Thicknesses of Polyethylene Moderator and a Thin Polyethylene Reflector
  - **PU-MET-MIXED-003-** TEX Plutonium Assemblies with Tantalum: Plutonium-Aluminum Metal Alloy Plates with Varying Thicknesses of Polyethylene Moderator, Interstitial Tantalum, and a Thin Polyethylene Reflector
  - **PU-MET-THERM-004-** TEX Plutonium Thermal Assemblies: Plutonium-Aluminum Metal Alloy Plates with Thick Polyethylene or Polymethyl Methacrylate (Lucite) Moderators



- TEX-HEU
  - **HEU-MET-MIXED-021-** TEX-HEU Baseline Assemblies: Highly Enriched Uranium Plates with Polyethylene Moderator and Polyethylene Reflector
  - **HEU-MET-INTER-013-** TEX-Hf Assemblies: Highly Enriched Uranium Plates with Hafnium Using Polyethylene Moderator and Polyethylene Reflector

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



Planned Work for TEX

TEX-Pu

- Experimental campaign planned for 2025 for configurations using an iron diluent to address criticality safety validation needs at US Hanford Tank Farm Facility
- Additional variants designed to investigate ^{240}Pu and Mn
- Additional baseline experiments targeting intermediate energy regime

TEX-HEU

- Chlorine diluted thermal experiments conducted in FY24 to address validation need from Y-12 (electrorefining) and LANL (solutions), benchmark evaluation underway
- Additional, intermediate and fast configurations with chlorine, more targeted at molten salt reactors, planned for execution in FY25
- Low Temperature experiments at -40 °C (-40 °F) with HEU to address transportation and unheated facility validation needs with the UK’s NNL, planned for FY26
- ^{6}Li diluted experiment design underway, address validation need from Y-12 (electrorefining)

Lawrence Livermore National Laboratory

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