



Integral Perspectives on Nuclear Data for the Next Decade

Presented at the 3rd P(ND)² Meeting
March 13, 2026

Catherine Percher
ICSBEP Chair

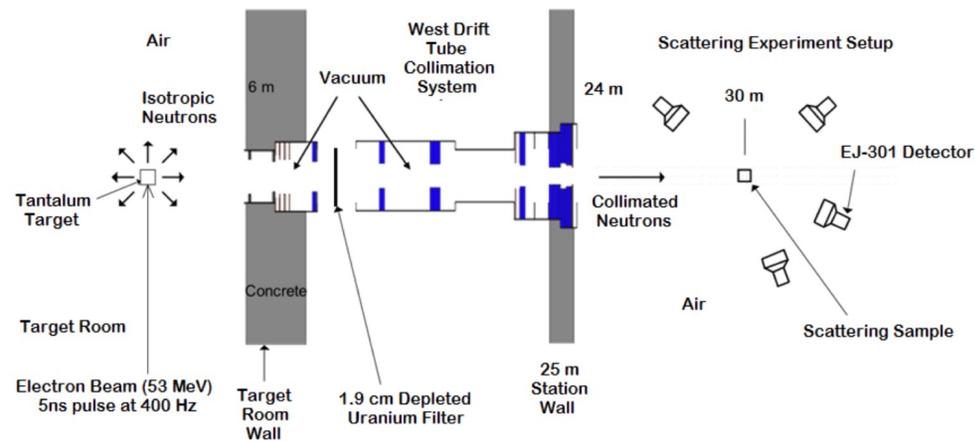
Lawrence Livermore National Laboratory, USA

Prepared by LLNL under Contract DE-AC52-07NA27344.

Measurements Form the Basis for Nuclear Data

- **Differential Measurements**

- Measurements of a single (ideally) reaction of a particle and a nucleus at a specific energy
- Example: Neutron Scattering Experiments



Picture from D. Smith, *NNL Measurements at the RPI LINAC*, National Nuclear Data Week 2018, New York.



Measurements Form the Basis for Nuclear Data

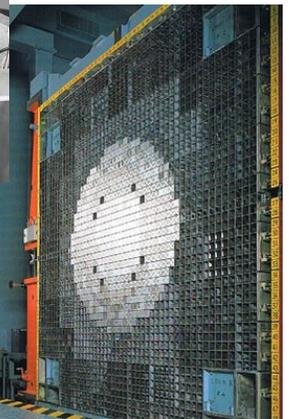
■ Integral Measurements

- Measurements of a system that is dependent on multiple data (isotopes, reactions, energies) at once
- May be designed to be particularly sensitive to one piece of data



Examples:

- Critical assemblies
- Subcritical assemblies
- Reactor startup experiments
- Reactor operation data
- Shielding Experiments
- Transmission Experiments
- Activation Experiments
- Post Irradiation Examination



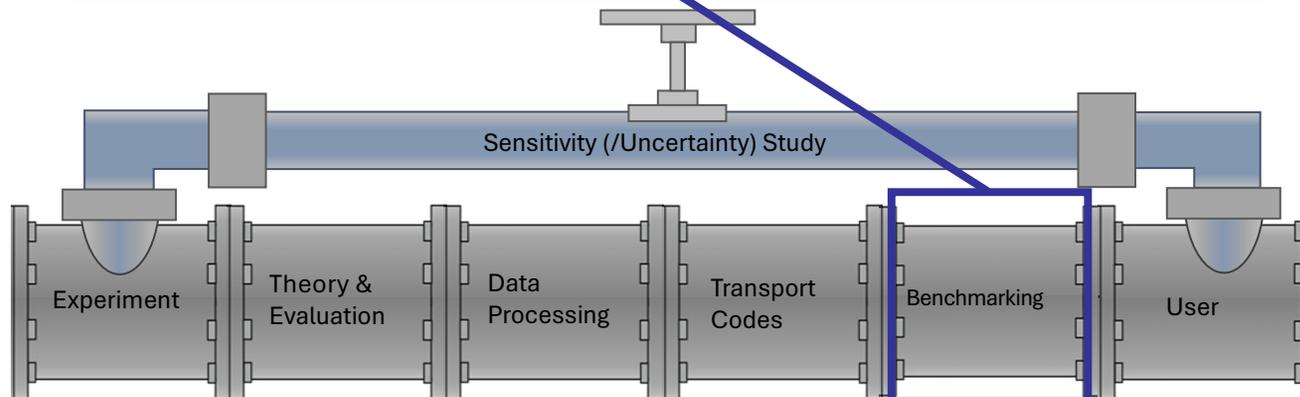
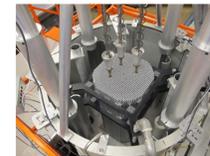


Benchmarking: Comparison to Experimental Truth

Validation that analytical method adequately represents reality for a given application

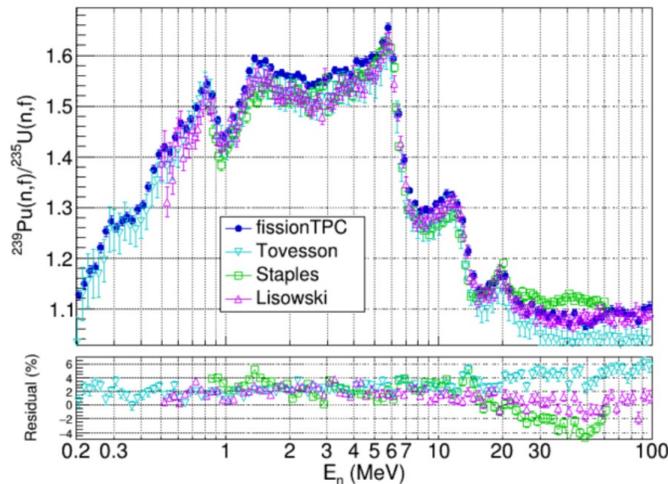
Integrated test of:

- Evaluated nuclear data
- Nuclear data processing codes
- Transport codes



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



L. Snyder, et al, Nuclear Data Sheets **178**, 2021

Major cross sections are “tuned” to certain critical experiments

BRC09 (CEA) $k_{eff}=1.00082(11)$	ENDF-VII.1 $k_{eff}=1.00060(12)$
<i>How does k_{eff} change when a BRC09 value is replaced by one from ENDF-VII.1?</i>	
Quantity	Δk_{eff} (1000th's of %)
Fission	-138
Capture	+269
Elastic Scattering	-638
Inelastic Scattering	+522
<i>The end result is a lack of confidence in modeling systems that significantly differ from the integral benchmark</i>	

E. Bauge, et al, Eur. Phys. J. A **48**, 113, 2012

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
- 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

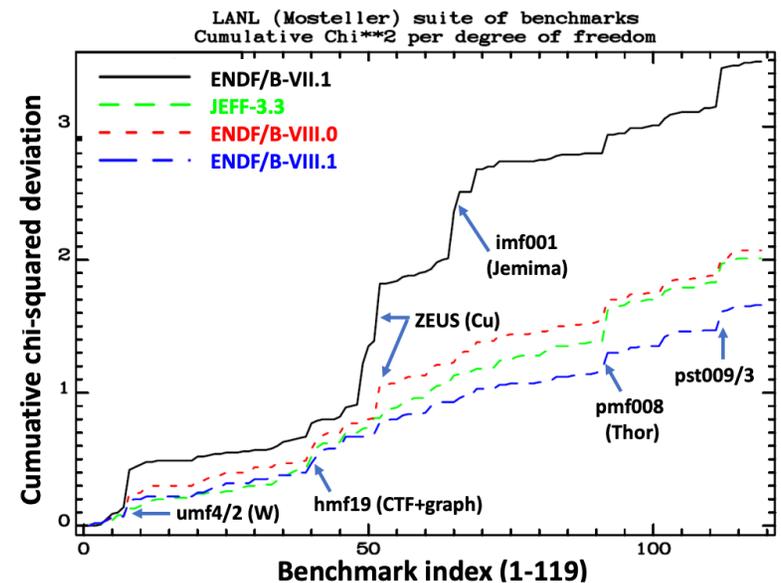
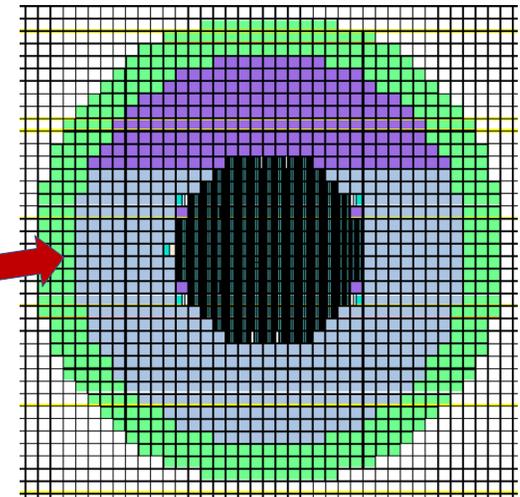
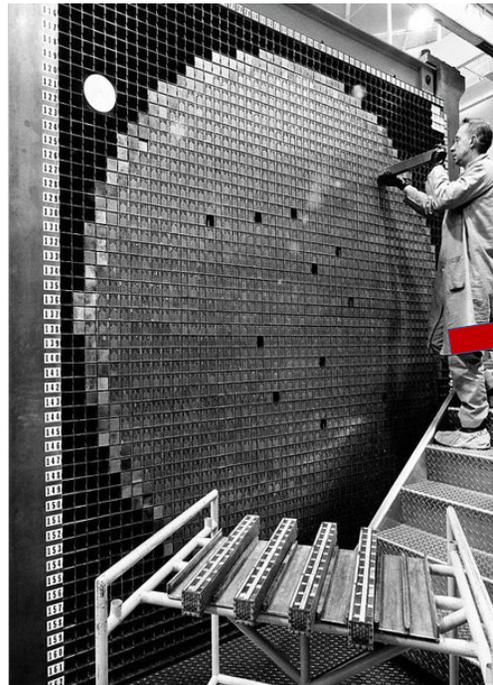


Figure from Nobre, et al. ENDF/B-VIII.1: Updated Nuclear Reaction Data Library for Science and Applications. 5 Nov 2025. [arXiv:2511.03564](https://arxiv.org/abs/2511.03564)

Benchmarks Are Evaluated Integral Experiments

- Well characterized experiments
- Evaluate all benchmark uncertainty effects on measured quantity, driven by:
 - Uncertain measurements
 - Missing data
- Bias and uncertainty for model simplifications
 - Geometry simplifications
 - Room return
 - Material impurities
- Describe benchmark model
- Sample calculation results
- Disseminate for broader use



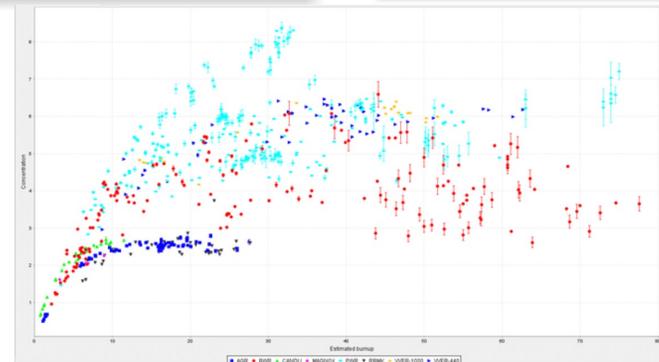
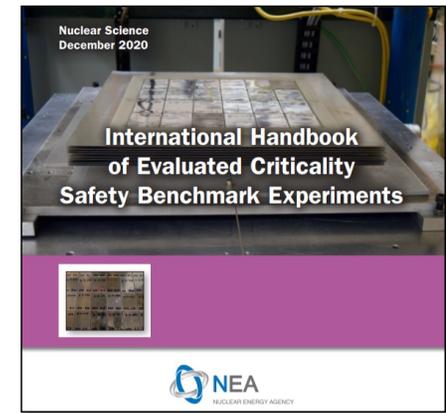
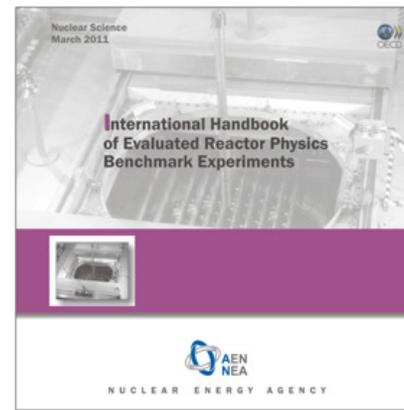


Sources of Benchmark Uncertainty

- **Experimental:** How certain are the experimenters of the data reported?
 - Uncertainty in measurement technique, reproducibility measurements, etc
 - Small contribution for k_{eff} and reactivity worth
 - Larger contribution for direct radiation measurements
- **Benchmark Model Uncertainties:** How certain are the evaluators of the benchmark model? Model vs. Reality
 - Mass (are all masses or densities well known?)
 - Dimensions (were all parts measured? How do they fit together?)
 - Composition (what are the constituents of all parts, including impurities?)
 - Other Factors (Temperature, irradiation history, etc)

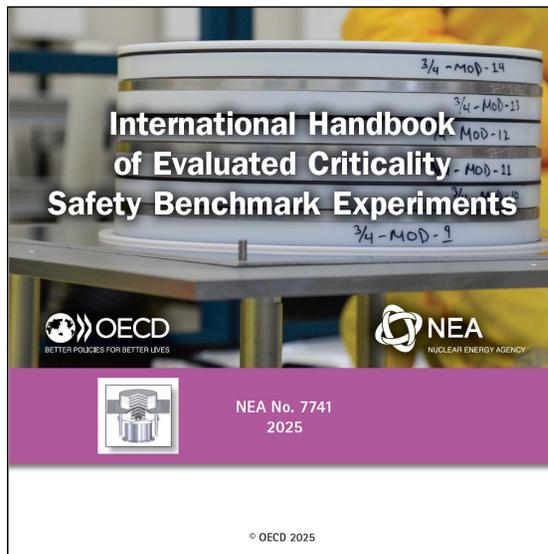
Established Integral Benchmark Handbooks and Databases

- **International Criticality Safety Benchmark Evaluation Project (ICSBEP)**
 - >5000 Critical, subcritical, shielding and physics configurations
- **International Reactor Physics Evaluation Project (IRPhEP)**
 - 200 Reactor benchmarks
 - 200 Spectra benchmarks
- **Shielding Integral Benchmark Database (SINBAD)**
 - Reactor shielding (46)
 - Fusion neutronics shielding (31)
 - Accelerator shielding (23)
- **Spent Fuel Composition (SFCompo)**
 - 700 Samples



International Criticality Safety Benchmark Evaluation Project (ICSBEP)

- Official activity of the Organization for Economic Cooperation and Development's (OECD) Nuclear Energy Agency since 1995 under Working Party for Nuclear Criticality Safety (WPNCS)
- Main Goal: Provide standardized benchmarks for **criticality safety validation**
- Updated handbook with new evaluations released regularly- 2025 edition released Feb 2026



ICSBEP Type	Description	Configurations
PU	Plutonium	810
HEU	Highly Enriched Uranium	1461
IEU	Intermediate Enriched Uranium	278
LEU	Low Enriched Uranium	1829
U233	Uranium 233	244
MIX	Mixed Material Systems	536
SPEC	Other Actinides	20
ALARM	Shielding and Criticality Accident Alarm Placement	53
FUND	Fundamental Physics Measurements	250
	Handbook Total	5481

Extensive International Review Process

Many Experts Involved

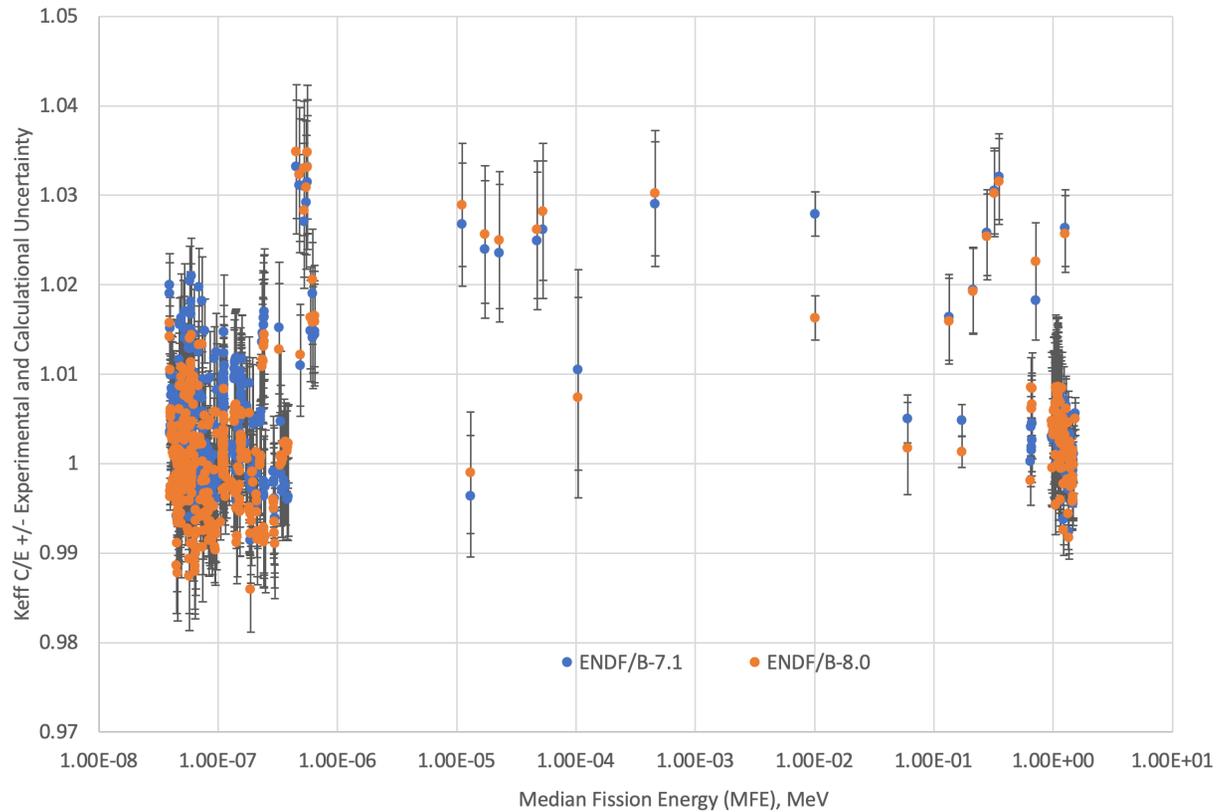
- Evaluator(s) – primary assessment of the benchmark
- Internal Reviewer(s) – in-house verification of the analysis, same access to information
- Independent Reviewer(s) – external verification of the analysis and modeling
- Technical Review Group (TRG) Meeting – annual international effort and panel review

ICSBEP is the “Gold Standard” of Integral Data

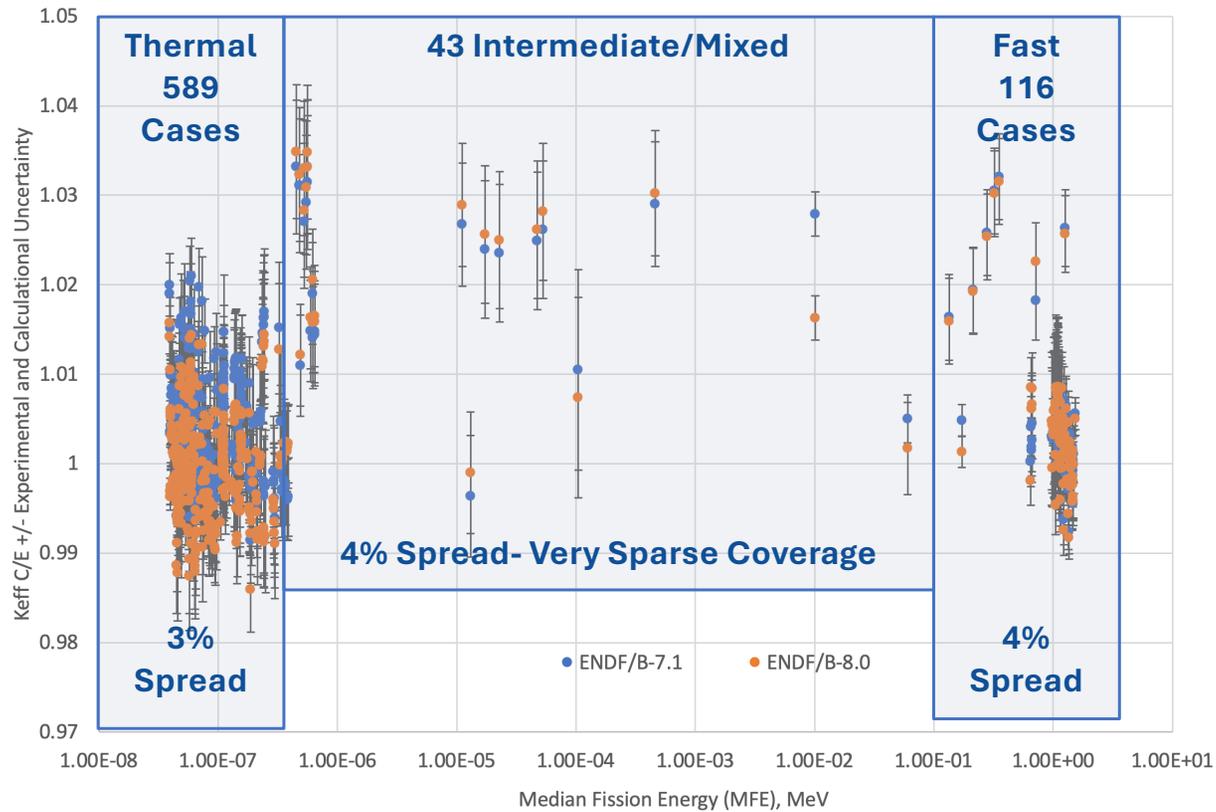
- Used by the nuclear data, code developer, and nuclear criticality safety communities
- Critical benchmarks do not provide a good test of all parts of an isotope’s nuclear data
- One number (k_{eff}) is susceptible to compensating errors
- ICSBEP standards and rigor have evolved over time



ICSBEP- Plutonium Benchmarks Circa 2015 (748 Cases)

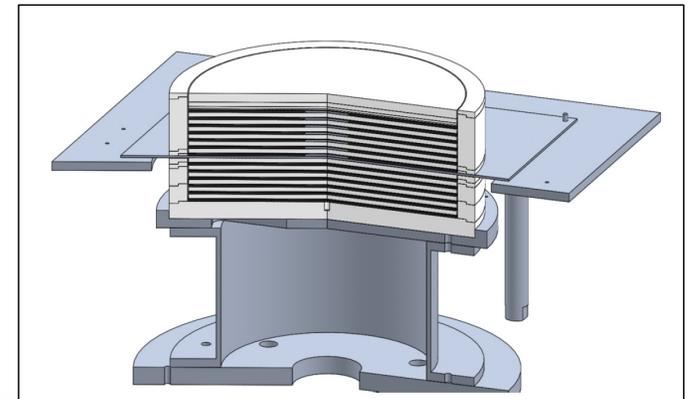
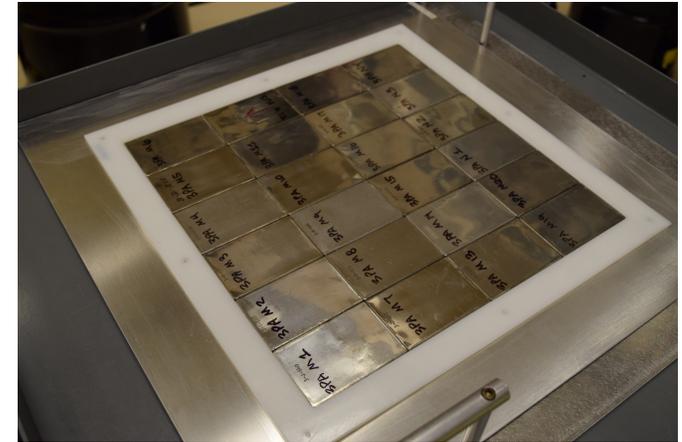


ICSBEP- Plutonium Benchmarks Circa 2015 (748 Cases)



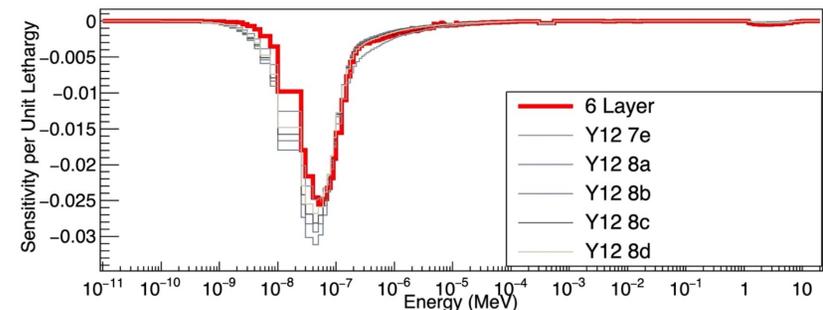
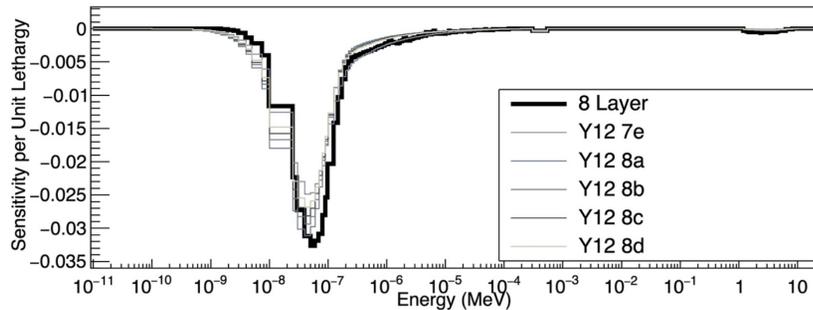
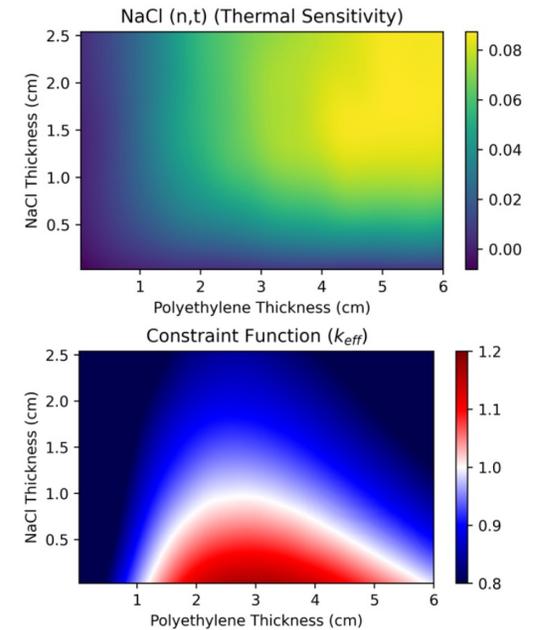
Thermal/Epithermal eXperiments (TEX)

- LLNL/LANL collaboration funded by the US 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 30 cm by 30 cm layers
 - HEU fueled with Jemima plates (48 cm 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



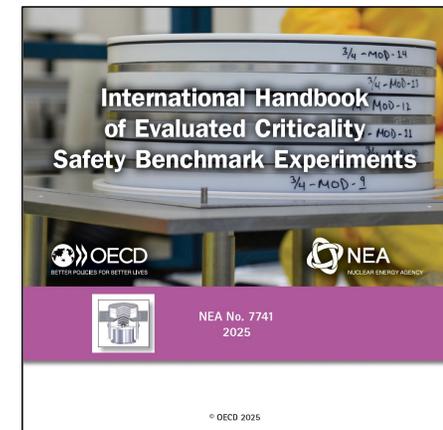
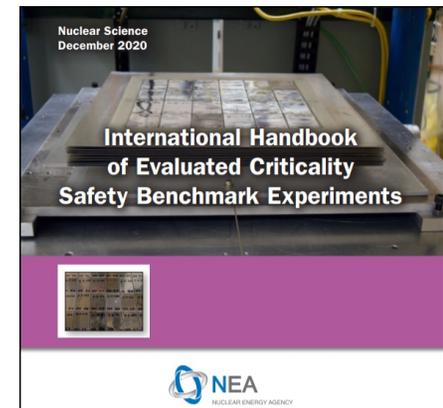
Designing Modern Critical Experiments

- 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 application
 - ML example of TEX-Cl to electrorefining operational criticality upset conditions

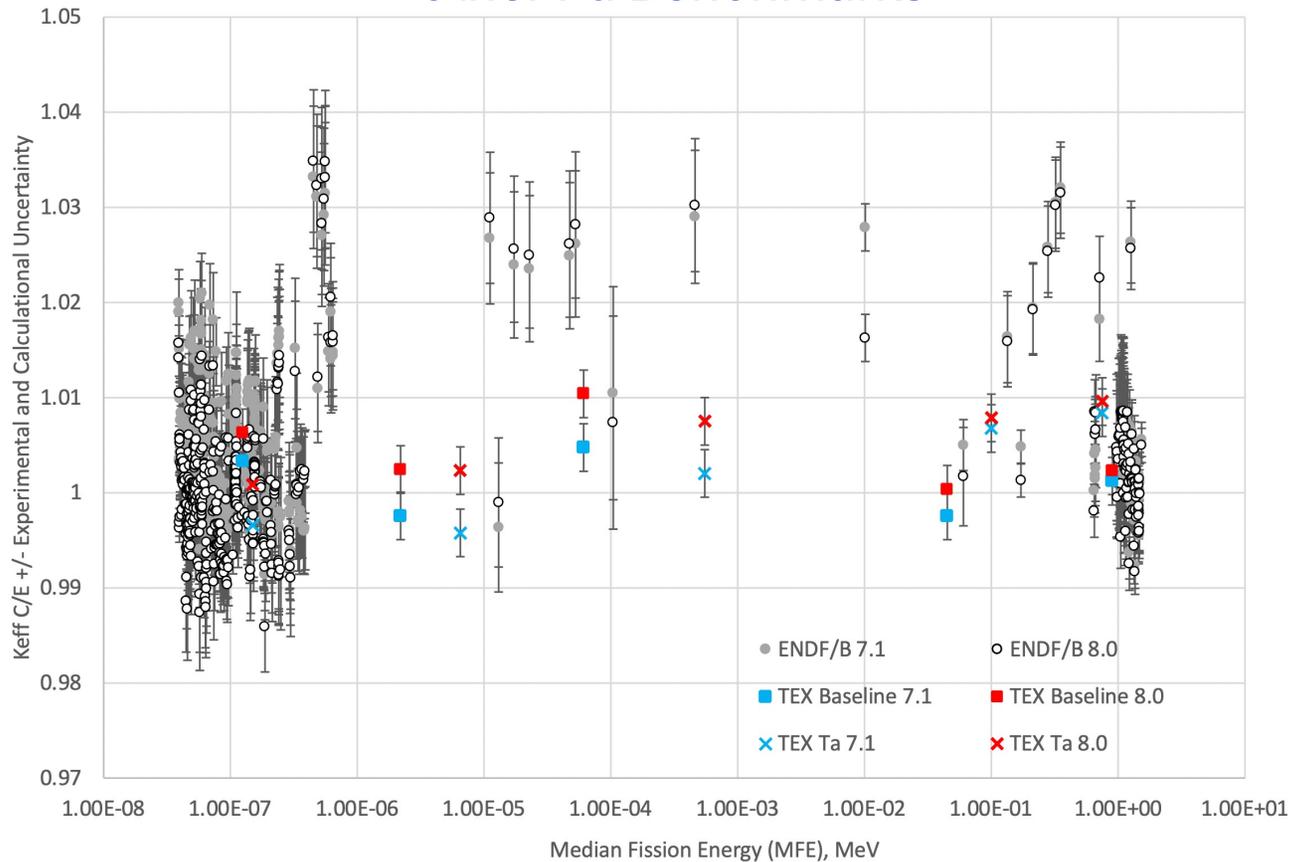


Six TEX Benchmarks Published

- 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
 - **HEU-MET-THERM-038-** TEX-Chlorine Assemblies: Highly Enriched Uranium Plates with **Sodium Chloride** Absorbers Using Polyethylene Moderator and Polyethylene Reflector



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



Additional Work for TEX

TEX-Pu

- Experimental campaign completed in November 2025 at NCERC for configurations using an **iron** diluent in thermal spectra
- Additional variants designed to investigate **²⁴⁰Pu** and **Mn** and additional baseline experiments targeting intermediate energy regime
- Design work ongoing for **Ni** and **Cr** variants

TEX-HEU

- Additional, intermediate and fast configurations with **chlorine**, more targeted at molten salt reactors, completed in February 2026 at NCERC
- **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
- Additional variants designed to investigate **⁶Li** neutron absorption in thermal/epithermal spectrum



The Good News

- The ICSBEP is healthy at the moment
 - Active international participation in yearly TRG meetings (50-100 people)
 - Pace of approximately 20 new benchmark configurations published each year
 - Many new experiments are being designed to fill validation gaps and target novel materials or neutron spectra
 - Epithermal/Intermediate neutron energies
 - Cl, Hf, Ta, Cu
 - Many of the new benchmarks are being evaluated soon after the experiment was conducted, with active participation from knowledgeable experimenters (better benchmarks!)
- New benchmark experiment capacity added with Japan's STACY facility and LLNL Pulsed Neutron Die Away experiment



The Not-So-Good News

- Overall integral experimental facility numbers have been declining for decades
- The other benchmark and integral experiment projects have been struggling
 - IRPhEP has not released new evaluations since 2021
 - SINBAD is undergoing a reimagining and reinvigoration after about a decade of stagnation
 - SFCompo currently working on few evaluations
- High quality benchmarking is expensive, time-consuming, and difficult
 - Many historical benchmarks should probably be re-evaluated, but might lack enough information to evaluate to a modern standard
 - Even though we conduct nuclear experiments everyday, sponsors aren't usually willing to pay the high cost of benchmarking an experiment



Perspective on the Next Decade in Integral Data

- More, and different kinds, of benchmarks are needed
- Not all benchmarks are good for nuclear data validation- should be curated
- Advanced reactor designs (both fission and fusion based) use novel materials and a variety of neutron energy spectra
 - Not well represented by current integral data
 - Need targeted, well-designed integral experiments that are sensitive to specific reactions that are important for these applications
 - Sensitivity studies needed to design and prioritize experiments
- Pilot facilities are being built and planned and could be a good source of new integral data
 - Advanced fission reactor data could suffer from being proprietary, not aid the general library validation
 - Brighter fusion sources can result in more relevant experiments, but source characterization will be important for benchmarks



Questions/Discussion



Backup Slides



Evolution of ICSBEP Uncertainty Assessment Methodology

- **Historically (pre ~2010)- More than 90% of the benchmarks**
 - Some uncertainties experimentally measured- e.g. remeasure outside to account for room return
 - Some deterministic or Monte Carlo calculations, generally with 100 pcm (0.001 in k_{eff}) calculation uncertainty for “most important” uncertainties
 - Simply assert some uncertainties are “negligible” with a threshold of 100 pcm (0.001 in k_{eff})
 - Ignore some uncertainties completely due to lack of data (impurities?)
 - Many of the historical benchmarks were evaluated in the 1990s/2000s for experiments that were conducted decades earlier without involvement or input from the experimenters
- **Modern method**
 - Run dozens or hundreds of perturbation calculations with Monte Carlo, uncertainties approaching 1 pcm
 - Use sensitivity analysis for mass and composition uncertainties
 - Threshold for negligible approaching 1 pcm
 - Account for stack heights, real as-built measurements (not just drawings), real compositions including impurities
 - Many modern benchmarks are completed soon after the experiments are conducted with active input from the experimenters

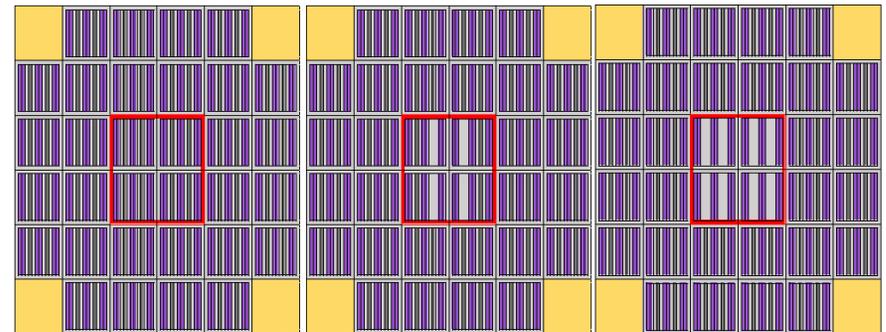
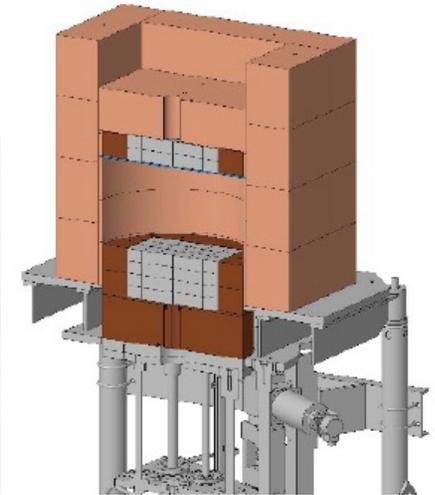
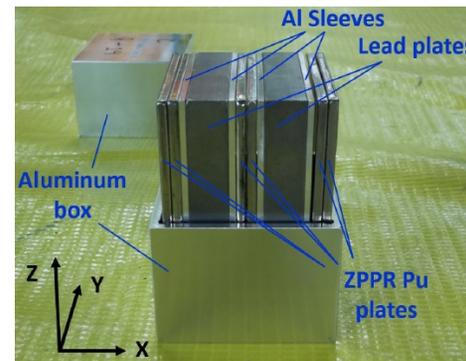
New Content for the 2025 Edition of the ICSBEP Handbook

- 8 new evaluations with 19 critical configurations, 4 fundamental physics configurations, and 2 alarm/shielding configurations
 - Volume I (PU): Two new fast Pu evaluations
 - Volume II (HEU): One new fast HEU, one intermediate HEU, and one thermal HEU evaluations
 - Volume IV (LEU): One new thermal LEU evaluation
 - Volume VII (ALARM): Two new ^{252}Cf source shielding evaluations
 - Volume IX (FUND): One new pulsed neutron die-away evaluation

New Evaluation 1 and 2: PU-MET-FAST-047 and PU-MET-FAST-050

The Jupiter Experiments: Plutonium Metal Plates Separated by Lead and Reflected by Copper

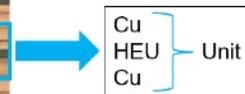
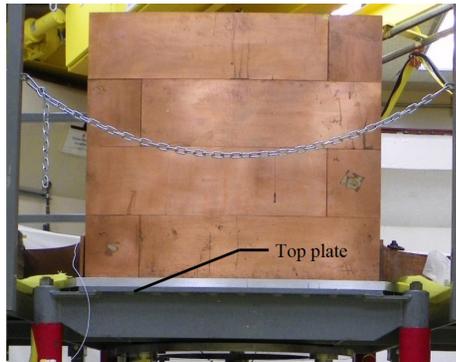
- Comet Assembly Machine at NCERC, USA
- Collaboration between LANL and the Japan Atomic Energy Agency (JAEA) for **fast reactor lead void reactivity studies**
- Plutonium Zero Power Physics Reactor (ZPPR) plates mixed with lead plates and ZEUS copper reflector
- 3 cases in PU-MET-FAST-047 with increasing central lead void
- 2 cases in PU-MET-FAST-050 with higher ^{240}Pu content ZPPR plates



New Evaluation 3: HEU-MET-FAST-106

CERBERUS: A Zeus Configuration with HEU and Copper Reflected by Copper

- Comet Assembly Machine at NCERC, USA
- Zeus Copper Reflector and HEU Jemima Plates
- 3 cases with increasing thicknesses of **interstitial copper plates**
- In combination with other Zeus experiments, goal is to provide a holistic test of copper nuclear data

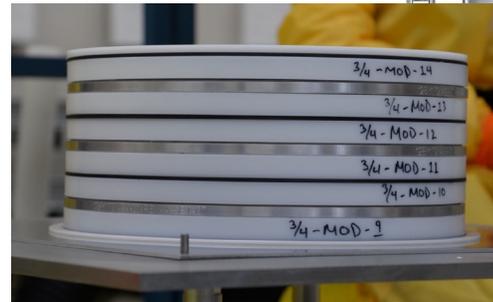
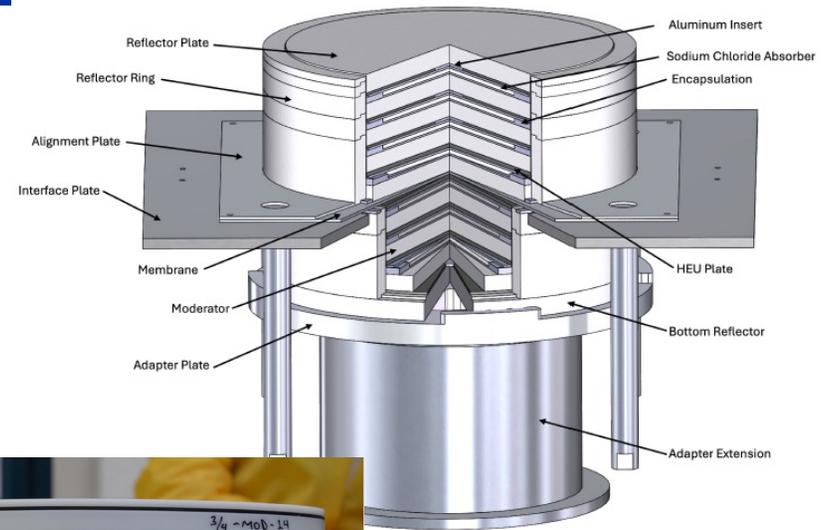


Top Reflector				
Cu 07-10	11149	B-2444-19	CR 6 (0.250 in.)	SR (8.13 in.)
Cu 07-09				
Cu 07-08	11017	B-2444-07	CR 3 (0.75 in.)	
Cu 07-07				SR (8.13 in.)
Cu 07-06	Q2-16	11018	B-2444-37	
Cu 07-05				
Cu 07-04	11019	B-2444-20	CR 4 (1.50 in.)	SR (8.13 in.)
Cu 07-03				
Cu 07-02	11147	B-2444-10		
Cu 07-01				SR (8.13 in.)
Steel Diaphragm				
Al Shim 400 mil				
Al Shim 500 mil				
Cu 05-12	10489	B-2444-33		SR (8.13 in.)
Cu 05-11				
Cu 05-10	10467	B-2444-29	CR 1 (5.68 in.)	
Cu 05-09				SR (8.13 in.)
Cu 05-08	10487	B-2444-36		
Cu 05-07				
Cu 05-06	10464	B-2444-01		SR (8.13 in.)
Cu 05-05				
Cu 05-03	10470	B-2444-24		
Cu 05-02				SR (8.13 in.)
Cu 05-01	10475	B-2444-02	CR 1 (5.68 in.)	
Bottom Reflector				
Platen Adapter Plate				
Platen				

New Evaluation 4: HEU-MET-THERM-038

TEX-Chlorine Assemblies: Highly Enriched Uranium Plates with Sodium Chloride Absorbers Using Polyethylene Moderator and Polyethylene Reflector

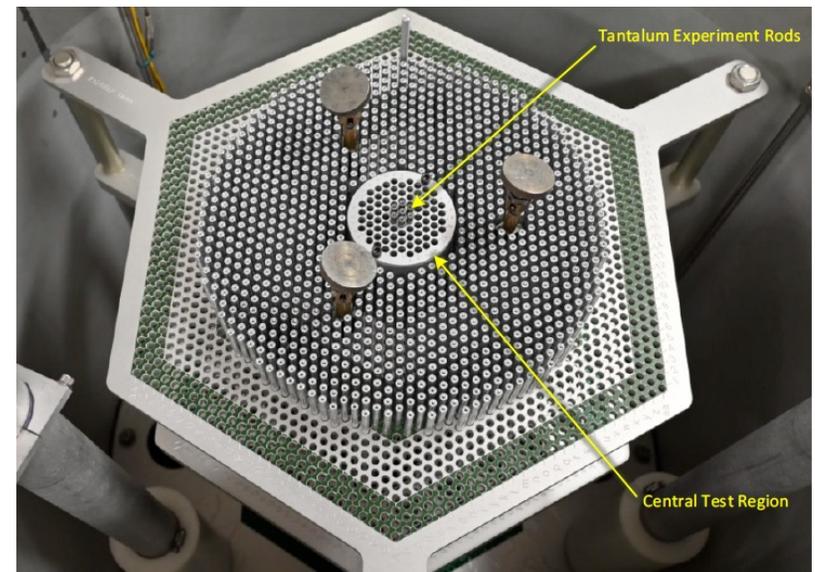
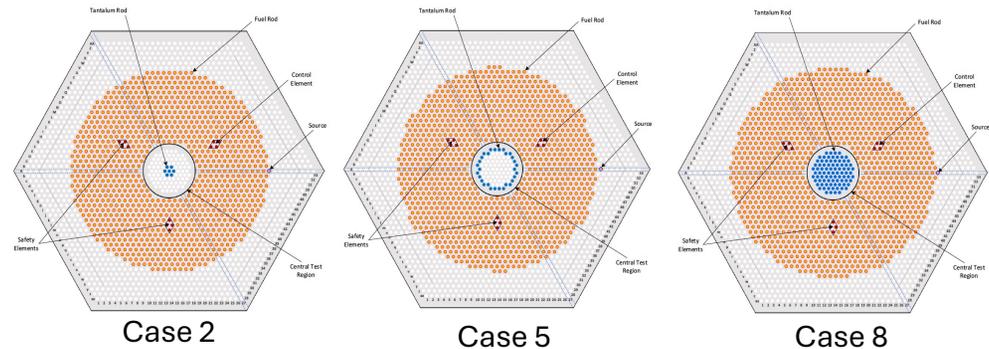
- Comet Assembly with HEU Jemima Plates at NCERC/NNSS
- Varied polyethylene moderator thickness to adjust neutron spectra
- Included vibro-packed **sodium chloride** absorber plates between layers
- 3 Cases, **2 thermal and 1 intermediate**
- Provide test of chlorine absorption for criticality safety validation cases for electrorefining and molten salt fuel fabrication



New Evaluation 5: LEU-COMP-THERM-112

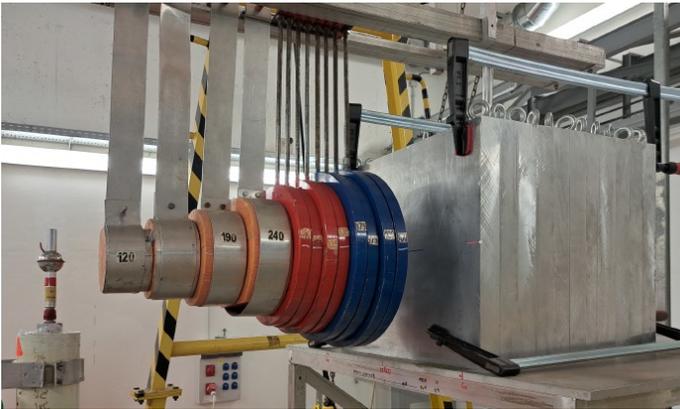
Tantalum Experiments in Fully-Reflected Water-Moderated Triangular-Pitched U(6.90)O₂ Fuel Rod Lattices (1.02 cm Pitch)

- Sandia Critical Experiments Facility (SCXF) with 7uP fuel
- Purpose of the experiment was to measure the effects of **Ta in epithermal systems**
- Fuel arranged around a central test region lined with Cd to absorb thermal neutrons and provide harder spectrum to the Ta rods
- 8 cases with varying configurations of Ta rods within the test region



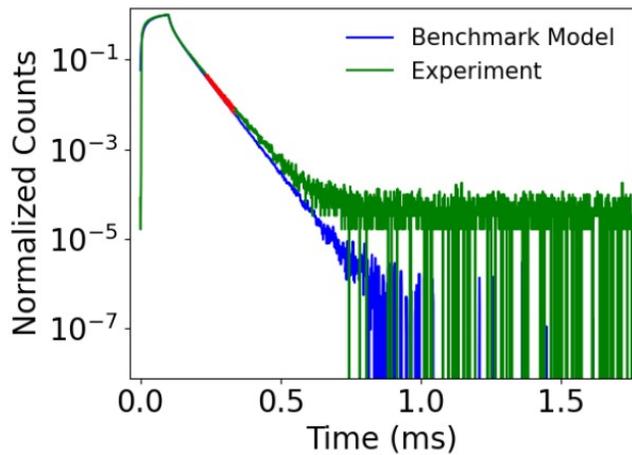
New Evaluation 6 and 7:

ALARM-CF-PTFE-SHIELD-001 and ALARM-CF-AL-SHIELD-001



Fast Neutron Leakage and Spatial Distribution of Activation Foils from an Polytetrafluoroethylene (PTFE) [or Aluminum] Block with a ^{252}Cf Source in the Center

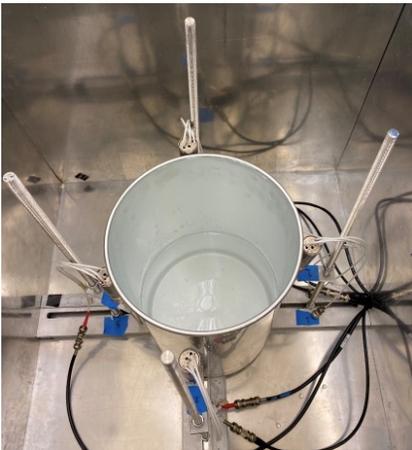
- Performed at Research Center Řež (RCR), Czechia
- Measured proton recoil method to obtain neutron leakage spectrum
- Activation foils placed within and outside the block
- Useful to test the validity of neutron cross section data, very sensitive to **scattering**
 - ^{19}F scattering (PTFE)
 - Aluminum scattering



New Evaluation 8: FUND-LLNL-DT-H2O-PNDA-001

Pulsed-Neutron Die-Away Response of H₂O Targets to a D-T Neutron Generator Pulse

- LLNL, USA
- Four different target sizes of **water**
- Benchmark quantity is characteristic exponential decay eigenvalue, α
- Useful to **test thermal scattering law data**
 - Smaller targets- more sensitive to scattering
 - Larger targets- more sensitive to absorption



- OECD/NEA
Headquarters, Boulogne
Billancourt, France
- April 13-16, 2026 (M-Th)
- International Reactor
Physics Evaluation
Project (IRPhEP) will meet
April 17



1. Autorité de Sûreté Nucléaire et de Radioprotection (France) – *Apparatus B Salt Water Configurations*
2. Centrum Výzkumu Řež (Czechia) – *Fast Neutron Leakage and Activation from a C₂Cl₄ Sphere with a ²⁵²Cf Source*
3. Idaho National Laboratory (USA) – *PROTEUS Critical Configurations with TRISO Fuel*
4. Instituto de Pesquisas Energéticas e Nucleares (Brazil) – *IPEN/MB-01 New Core Evaluation with U₃Si₂-Al, 19.75% enriched in U-235 Plate Type Fuel*
5. Lawrence Livermore National Laboratory (USA) – *Pulsed-Neutron Die-Away Experiments with Oil Targets (FUND)*
6. Los Alamos National Laboratory (USA) – *HEU-MET-FAST-086: Godiva IV Benchmark Revision*
7. Los Alamos National Laboratory (USA) – *Prompt Fission Uranium Neutron Spectrum (PFUNS) Critical Experiments*
8. Los Alamos National Laboratory (USA) – *MUSIC: Bare Highly-Enriched Uranium Shells Subcritical Measurements (FUND)*
9. Los Alamos National Laboratory (USA) – *Deimos: HALEU as Tri-structural isotropic (TRISO) Kernels Reflected by Graphite and Beryllium*
10. Rensselaer Polytechnic Institute (USA) – *Standard Core Critical Configurations of the Walthousen Reactor Critical Facility*