Successes and Challenges of Preserving Integral Data with the International Criticality Safety Benchmark Evaluation Project

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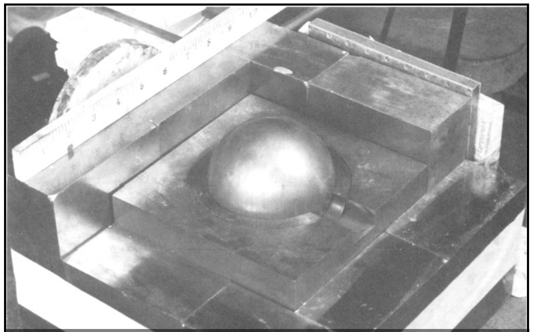
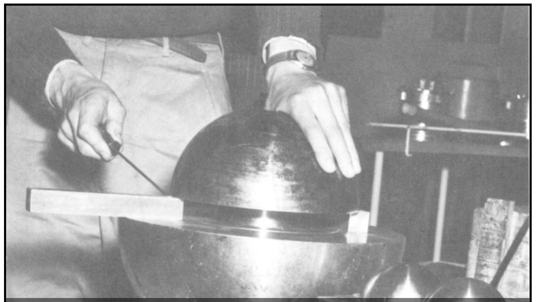
Nuclear Criticality Safety

- 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



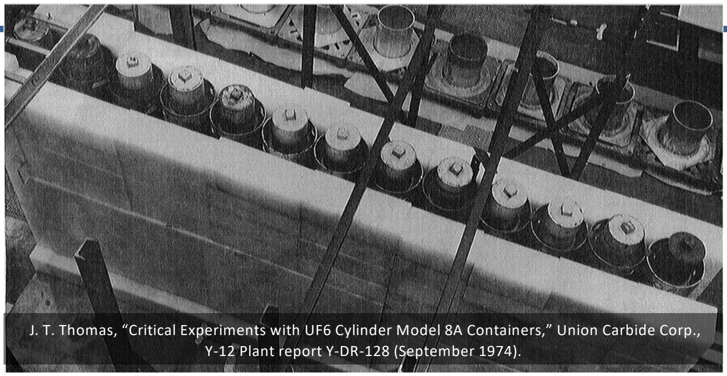
August 21, 1945
Los Alamos National Laboratory Criticality Accident #1



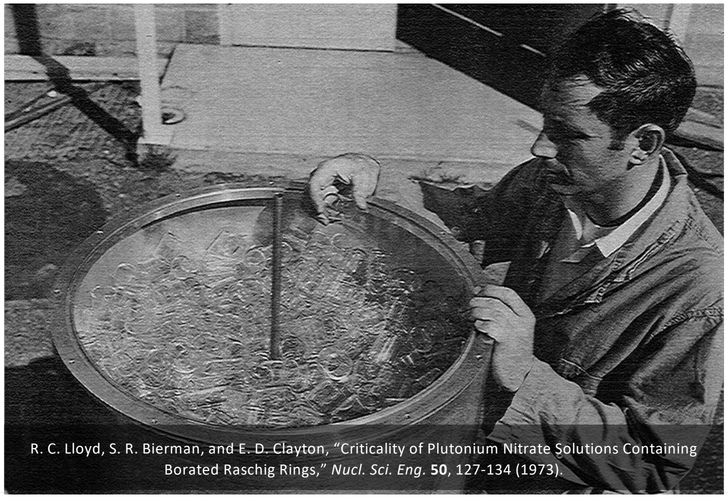
May 21, 1946
Los Alamos National Laboratory Criticality Accident #2

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).

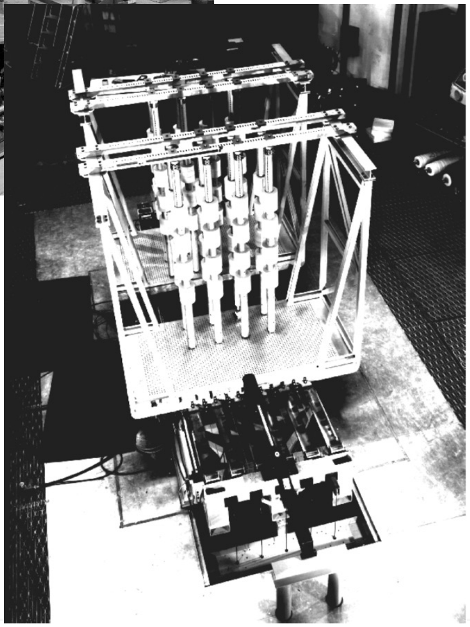


R. C. Lloyd, S. R. Bierman, and E. D. Clayton, "Criticality of Plutonium Nitrate Solutions Containing Borated Raschig Rings," *Nucl. Sci. Eng.* **50**, 127-134 (1973).

What are Critical Experiments?

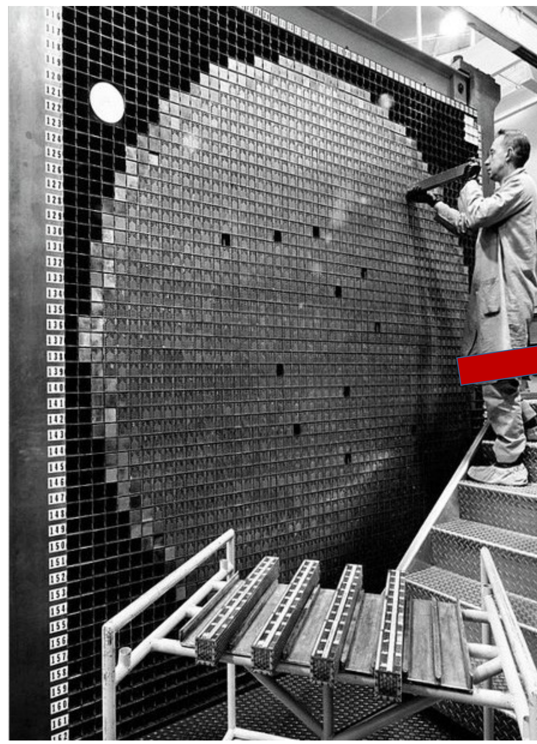
- Controlled assemblies of nuclear material designed to just achieve the critical point (or slightly lower/higher)
  - Critical point: neutrons have self-sustaining chain reaction within the assembly
  - Neutron production (mainly through fission) balance losses (through absorption and leakage)
  - Integral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

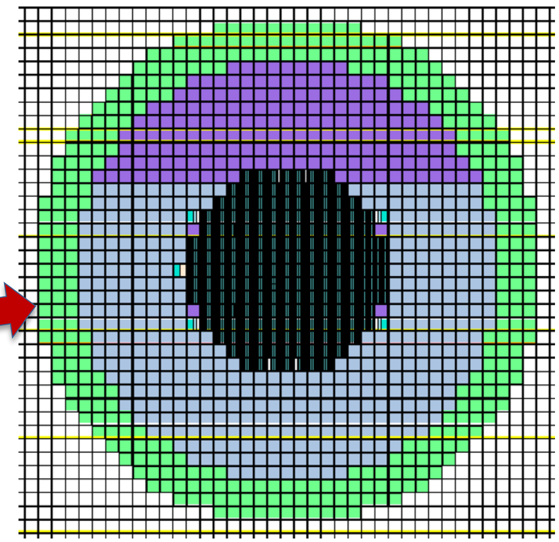
- Critical Experiment Measured Quantity (Effective Multiplication Factor, k_{eff})
  - Not actually directly measurable
  - Infer from subcritical configurations (extrapolate to critical, k_{eff} = 1.0)
  - Calculate from reactor period measurement (depends on other nuclear data like delayed neutron 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





Sources of Benchmark Uncertainty

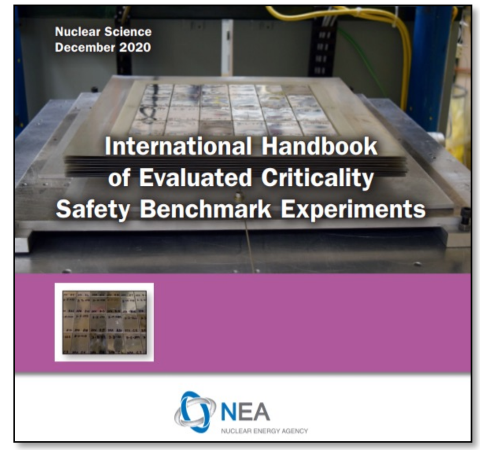
- **Experimental:** How certain are the experimenters of the data reported?
  - Uncertainty in measurement technique, reproducibility measurements, etc
  - Small contribution for k_{eff} and reactivity worth
  - Larger contribution for direct radiation measurements

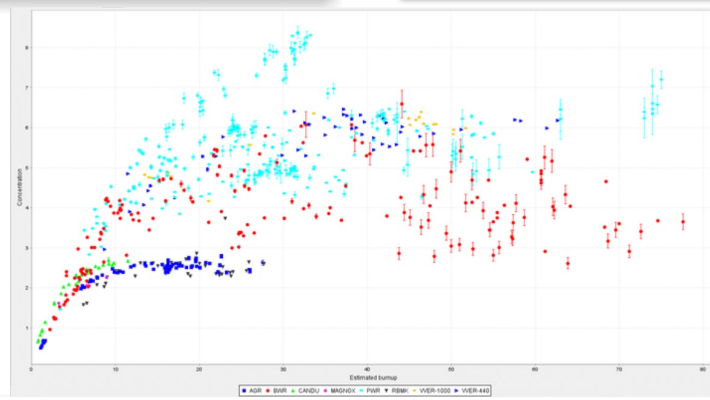
- **Benchmark Model Uncertainties:** How certain are the evaluators of the benchmark model? Model vs. Reality
  - Mass (are all masses or densities well known?)
  - Dimensions (were all parts measured? How do they fit together?)
  - Composition (what are the constituents of all parts, including impurities?)
  - Other Factors (Temperature, irradiation history, etc)

- **Complication:** Many benchmarks were evaluated decades after the experiment without access to the original experimenters

Established Integral Benchmark Handbooks

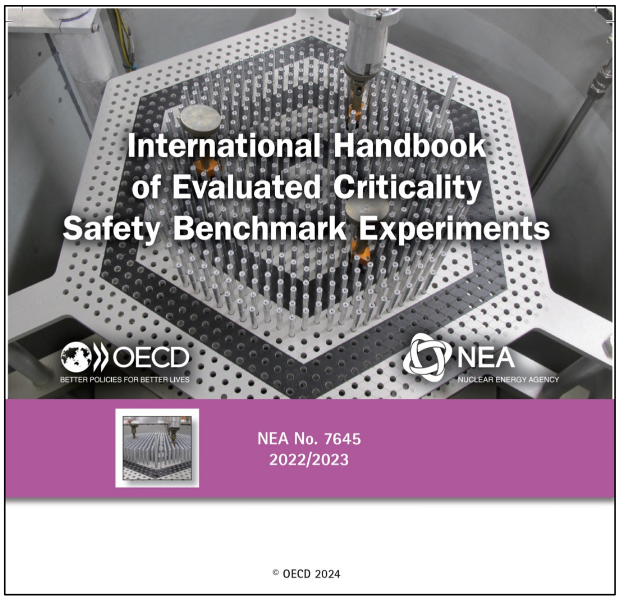
- **International Criticality Safety Benchmark Evaluation Project (ICSBEP)**
  - — >5000 Critical, subcritical, and physics configurations
- **International Reactor Physics Evaluation Project (IRPhEP)**
  - — 200 Reactor benchmarks
  - — 200 Spectra benchmarks
- **Shielding Integral Benchmark Database (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
- Main Goal: Provide standardized benchmarks for **criticality safety validation**
- Updated handbook with new evaluations released regularly- most November 2024 (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

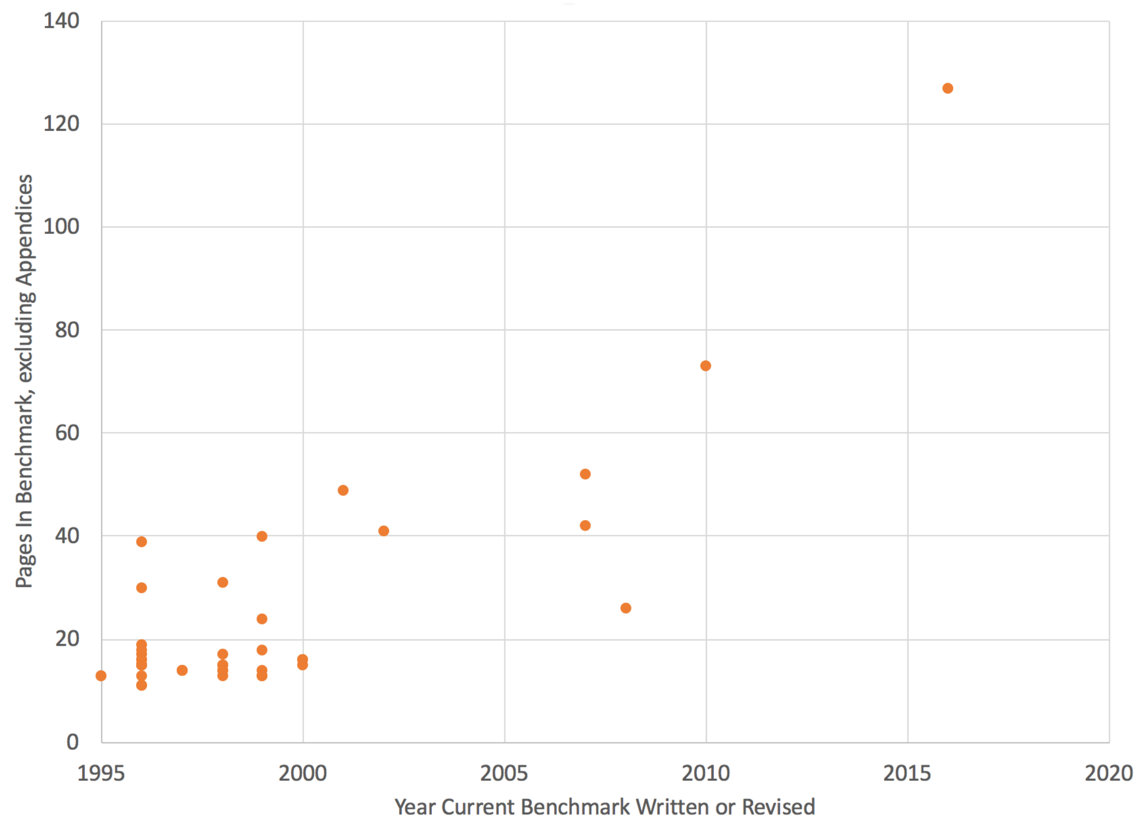
- Many Experts Involved
  - Evaluator(s) – primary assessment of the benchmark
  - Internal Reviewer(s) – in-house verification of the analysis and adherence to procedure
  - Independent Reviewer(s) – external verification of the analysis
  - Technical Working Group Meeting – annual international effort and panel review

Remember Context of ICSBEP Benchmarks

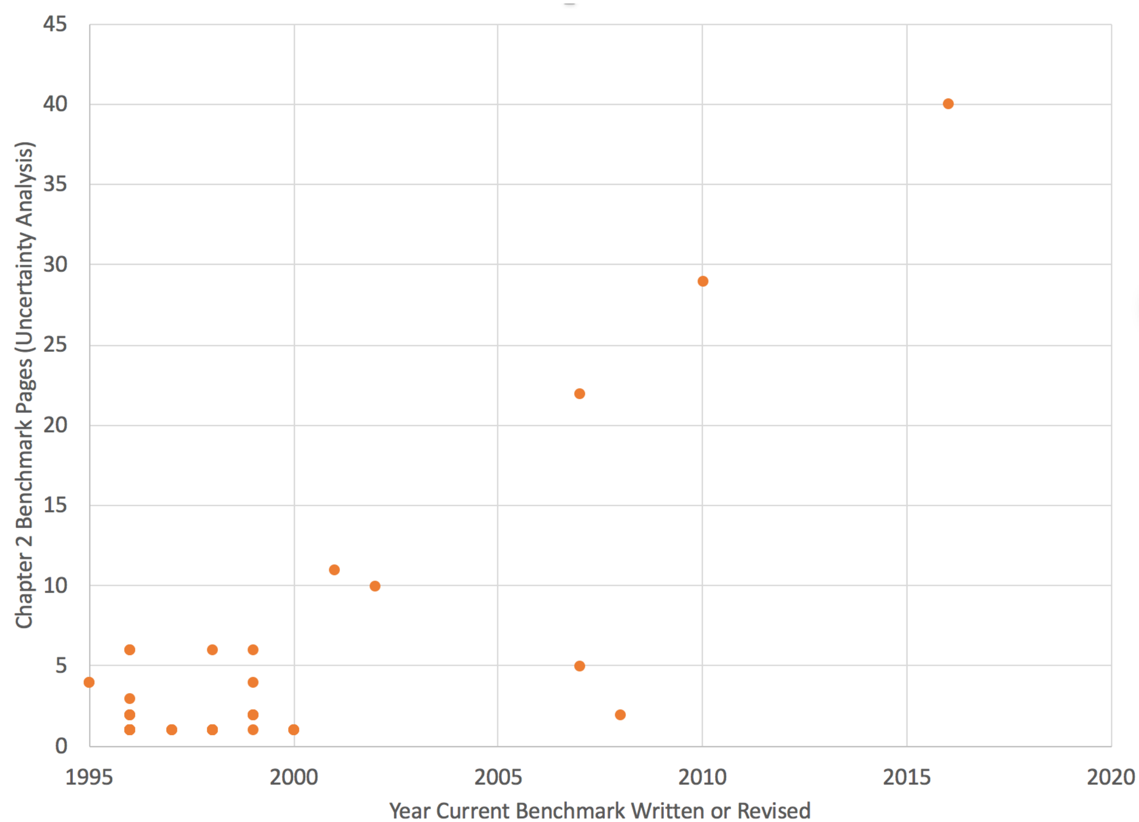
- For ICSBEP, Criticality safety validation was the driving force behind many of the evaluations, not nuclear data validation or adjustment
- Expectations have evolved over time with increasing computational power
  - Earlier evaluated benchmarks tend to be more brief
  - Many evaluated benchmarks are missing major sources of uncertainties

Example: PU-MET-FAST-001 (Jezebel) Section	Revision 2 pages (2007)	Revision 4 pages (2016)	Increase
1 (Experimental Data)	6	33	x5
2 (Experiment and Uncertainty Evaluation)	< 1	40	x40
3 (Benchmark Model)	3	46	x15
4 (Sample Calculations)	1	8	x8
Appendix (Supporting Documentation)	5	46	x9

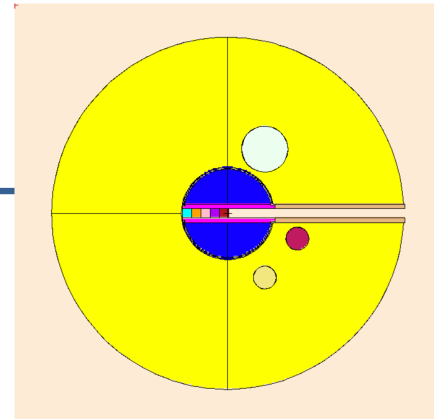
Total Page Count for Fast Pu Metal Cases over Time
(excluding appendices- sample inputs, etc)

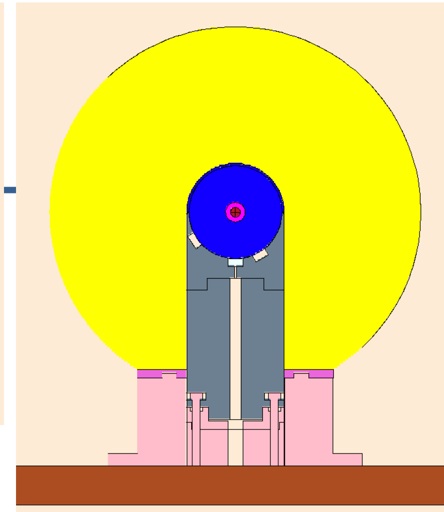


Uncertainty Analysis for Fast Pu Metal Cases over Time
(Length of Section 2)



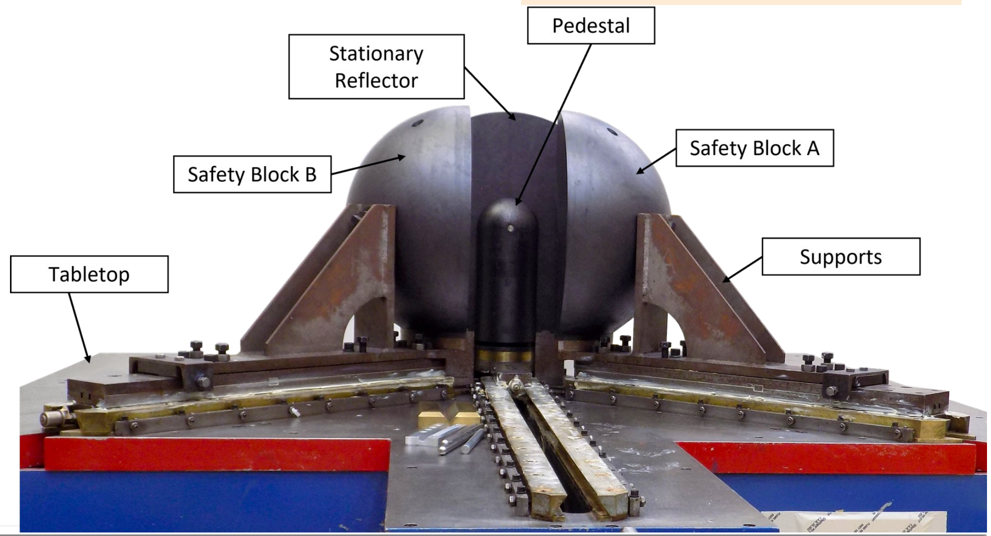
2024 Revised Evaluation: HEU-MET-FAST-028





Uranium-235 Sphere Reflected by Normal Uranium Using Flattop

- Flattop Assembly with HEU Core at NCERC/NNSS
- **Major revision based on new dimensional and critical measurements**
- New high fidelity models, replacing the two-sphere original model
  - Reduction in uncertainties from 300 to 131 pcm
  - **22 Pages to 224 Pages**

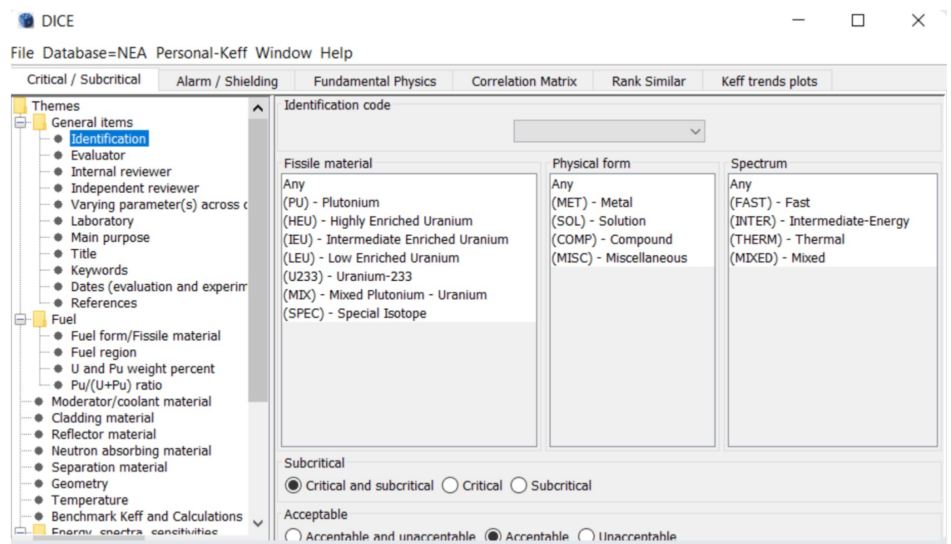


Keys to Success

- Sponsors willing to pay for evaluations (in the US, mainly Nuclear Criticality Safety Program)
- Format requires all relevant experimental data (with references), quantification of uncertainties, a code-agnostic recommended benchmark model (so anyone can use their code to make a model), and sample inputs
- Active international Technical Review Group that meets in person
  - TRG members made up of experimenters and benchmark users
  - High level of review ensures quality, useful product

Keys to Success (continued)

- Naming convention that makes it easier to locate relevant benchmarks
- Thoughtful metadata collection
- OECD/NEA provides venue for collaboration, distributes the handbook, and develops user software tools
  - Database of International Critical Experiments (DICE)

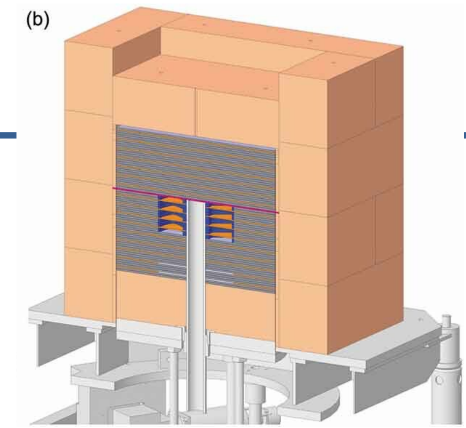


Challenges

- Benchmarking experiments is labor intensive and computationally expensive
  - Good benchmarks investigate all experimental uncertainties and their effects on benchmark quantity- could easily take hundreds of calculations
  - How to balance quantifying uncertainty with expense
- Historical experiments might lack enough information to adequately benchmark to a modern standard
  - Material (including impurities) and geometry unknowns
  - Many older benchmarks would not be approved by the TRG today, and there is not enough information in Section 1 to re-evaluate the experiment- would need to find additional data
- What to do about suspect benchmarks?
  - The TRG is focused on reviewing new benchmarks
  - There are many benchmarks that have issues of varying severity- should they be reviewed and declared “unacceptable”?

Challenges (continued)

- User communities would like experimental correlations
  - Many evaluators are ill-equipped to evaluate these correlations
  - Small assumptions can wildly change degree of correlation
    - Example: is the same grid plate used for multiple experiments, meaning that rod pitch is correlated between experiments. If yes, correlation of 0.9. If no, correlation of 0.2



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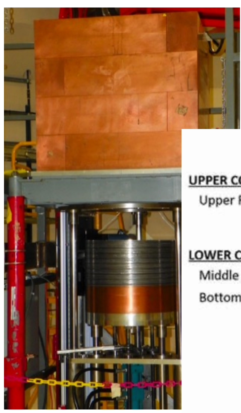

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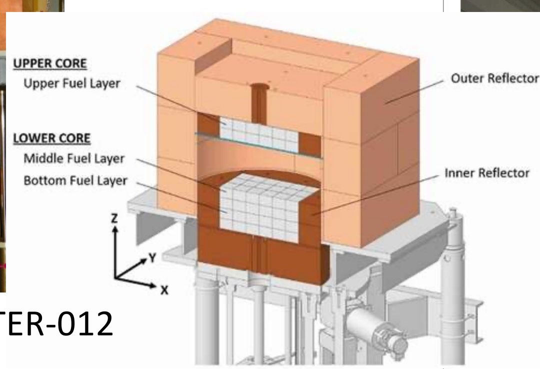
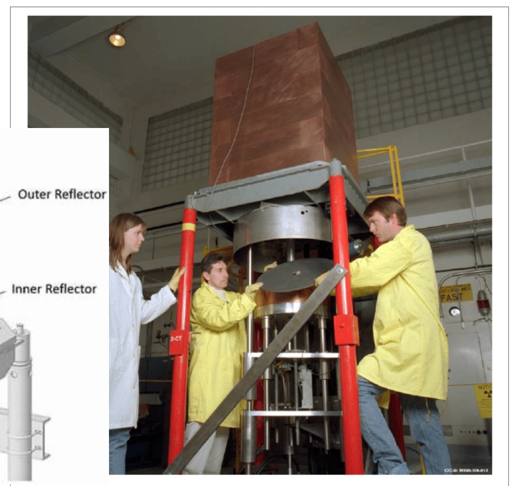


PU-MET-FAST-047



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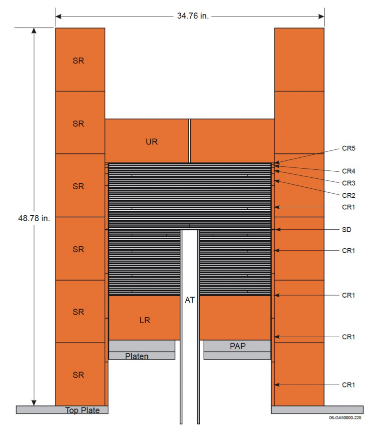
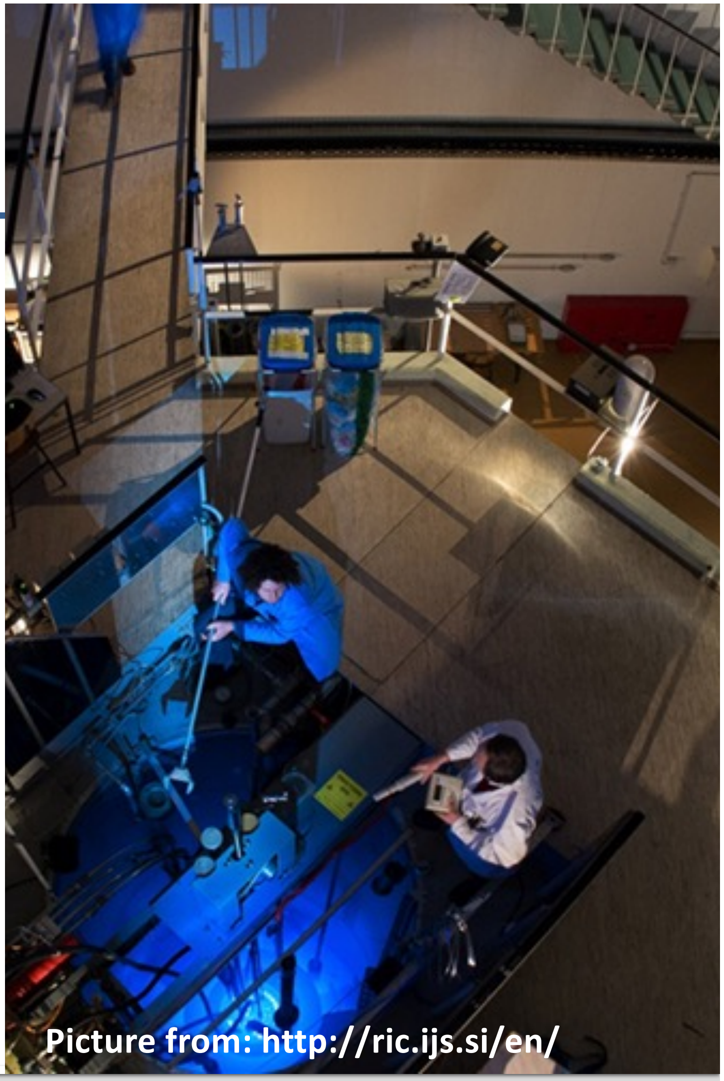


HEU-MET-FAST-072

Come Join Us at Our Next Meeting

- **Jožef Stefan Institute, Ljubljana, Slovenia**
- April 14-18, 2025
- Joint meeting with SINBAD, SFCOMPO and IRPhEP
- Tours of JSI experimental facilities


Picture from: http://ric.ijs.si/en/

Lawrence Livermore National Laboratory

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