WANDA 2021

Workshop for Applied Nuclear Data Activities

Connecting the humans behind the nuclear data

Expanding Benchmarks for Nuclear Data Validation

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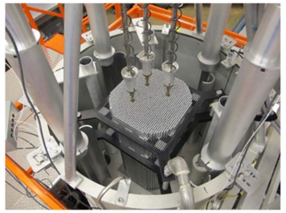
Los Alamos National Laboratory, USA

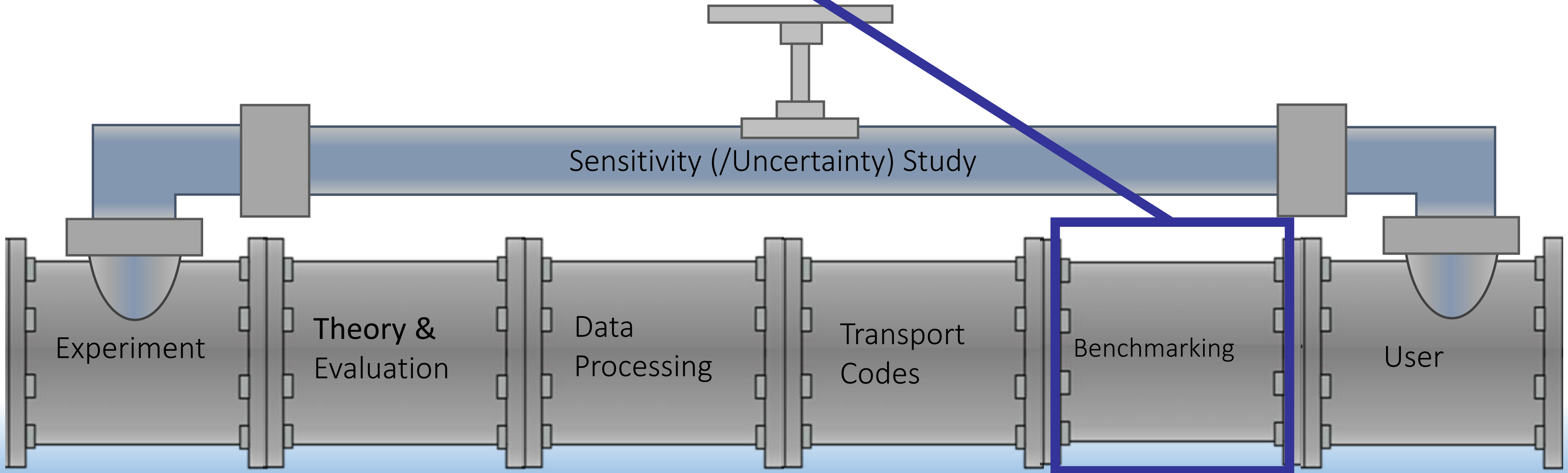
Benchmarking: Comparison to Experimental Truth

Validation that analytical method adequately represents reality for a given application

Integrated test of:

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





Sensitivity (/Uncertainty) Study

Experiment

Theory & Evaluation

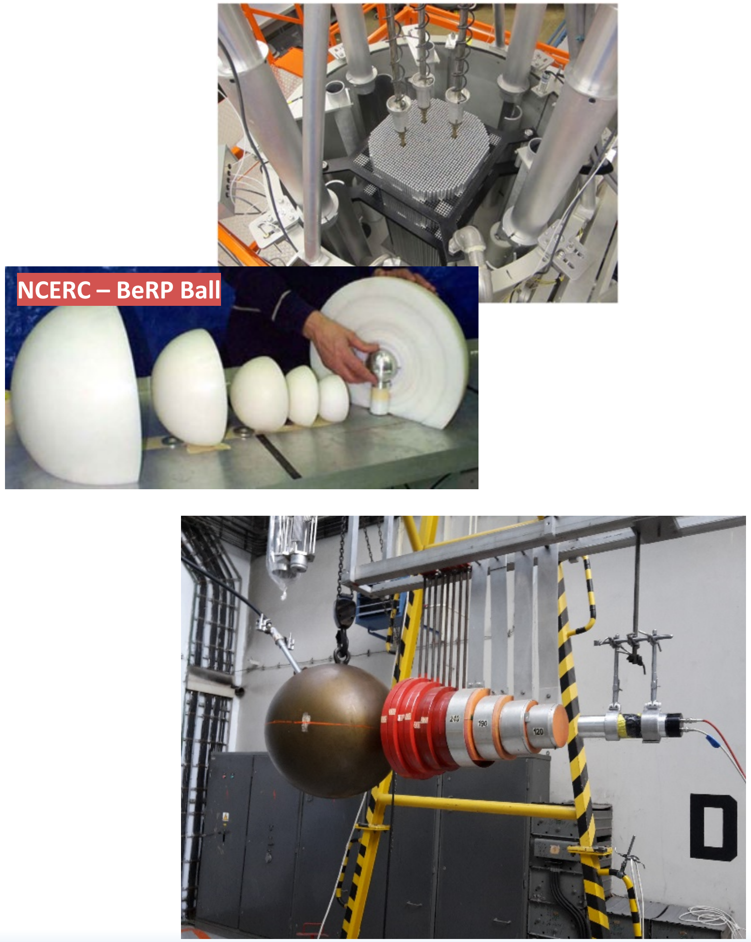
Data Processing

Transport Codes

Benchmarking

User

Integral Experiments

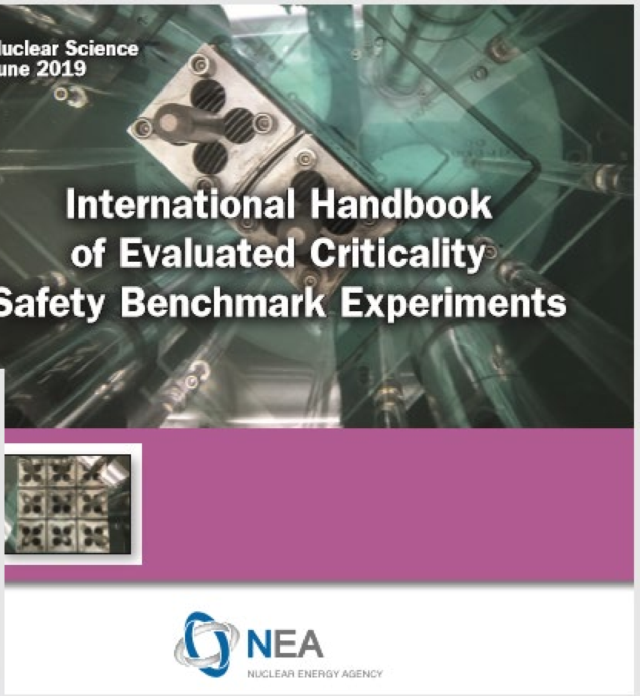


- Tests multiple data (isotopes, reactions, energies) at once
  - May be designed to be particularly sensitive to one piece of data
- Examples:
  - Critical assemblies
  - Subcritical assemblies
  - Engineering mockup critical assemblies
  - Reactor startup experiments
  - Reactor operation data
  - Shielding experiments

Benchmarks Are Evaluated 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
- Established Handbooks
  - ICSBEP (criticality safety)
  - IRPhEP (reactor physics)
  - SINBAD (shielding)

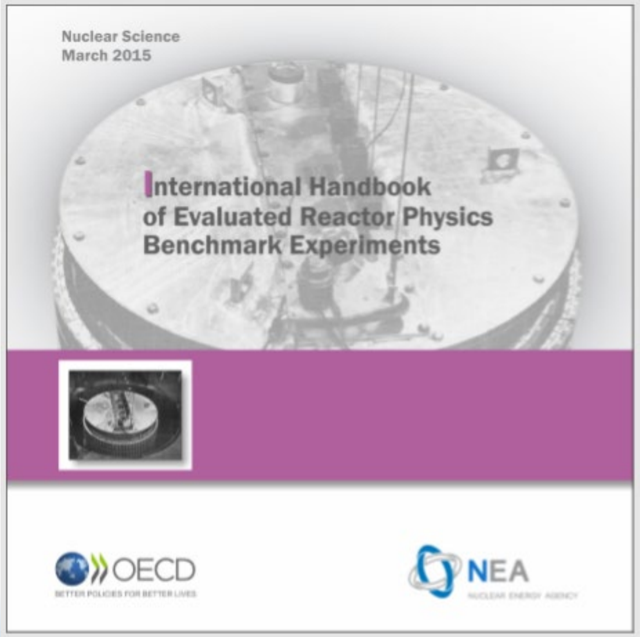
Skip Kahler and Ian Hill will discuss **Past, Present, and Future Benchmark Efforts**



Nuclear Science
June 2019

International Handbook
of Evaluated Criticality
Safety Benchmark Experiments

NEA
NUCLEAR ENERGY AGENCY



Nuclear Science
March 2015

International Handbook
of Evaluated Reactor Physics
Benchmark Experiments

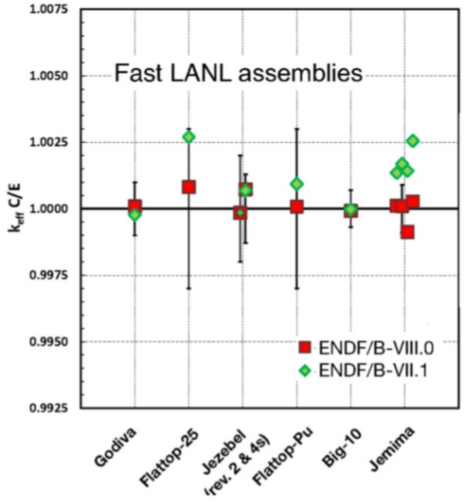
OECD
BETTER POLICIES FOR BETTER LIVES

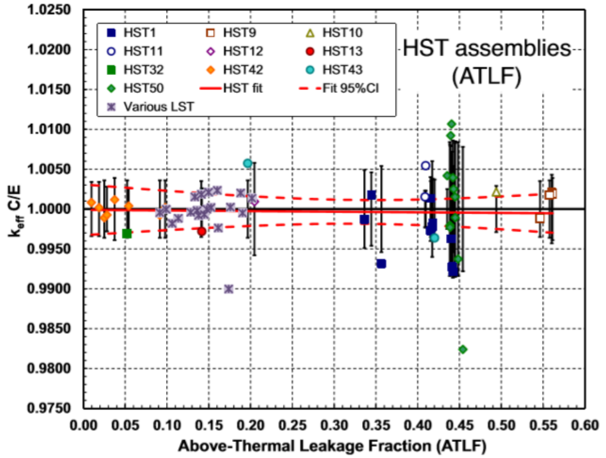
NEA
NUCLEAR ENERGY AGENCY

Jerry McKamy will discuss **The Nuclear Criticality Safety Validation Model**

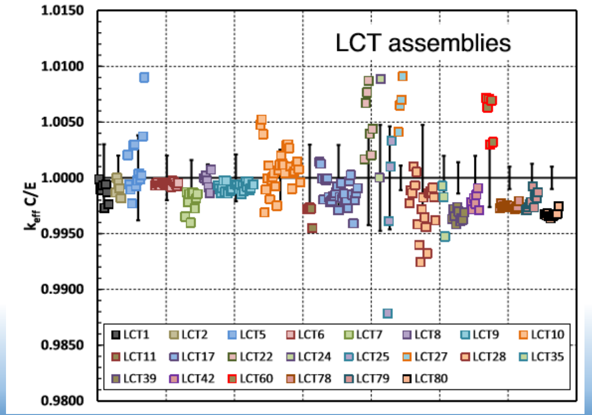
Validation Testing

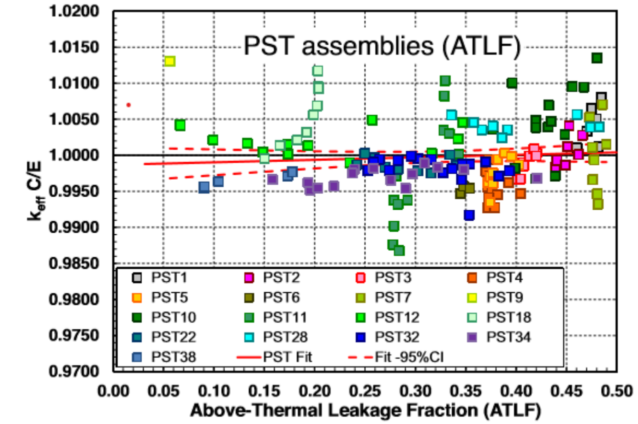
- Suite of benchmarks to validate evaluated nuclear data **for applications**
- Provides feedback to measurement and evaluation community
  - Currently dominated by critical benchmarks, NEED representation from other applications
- Drives improvements in evaluated nuclear data

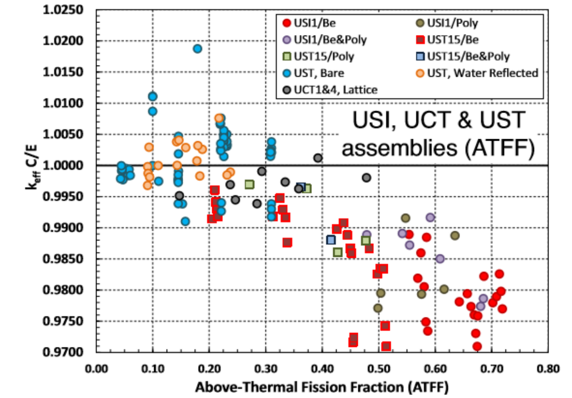




Ref: D. A. Brown, et al., *Nuclear Data Sheets*, **148**, 1 (2018)

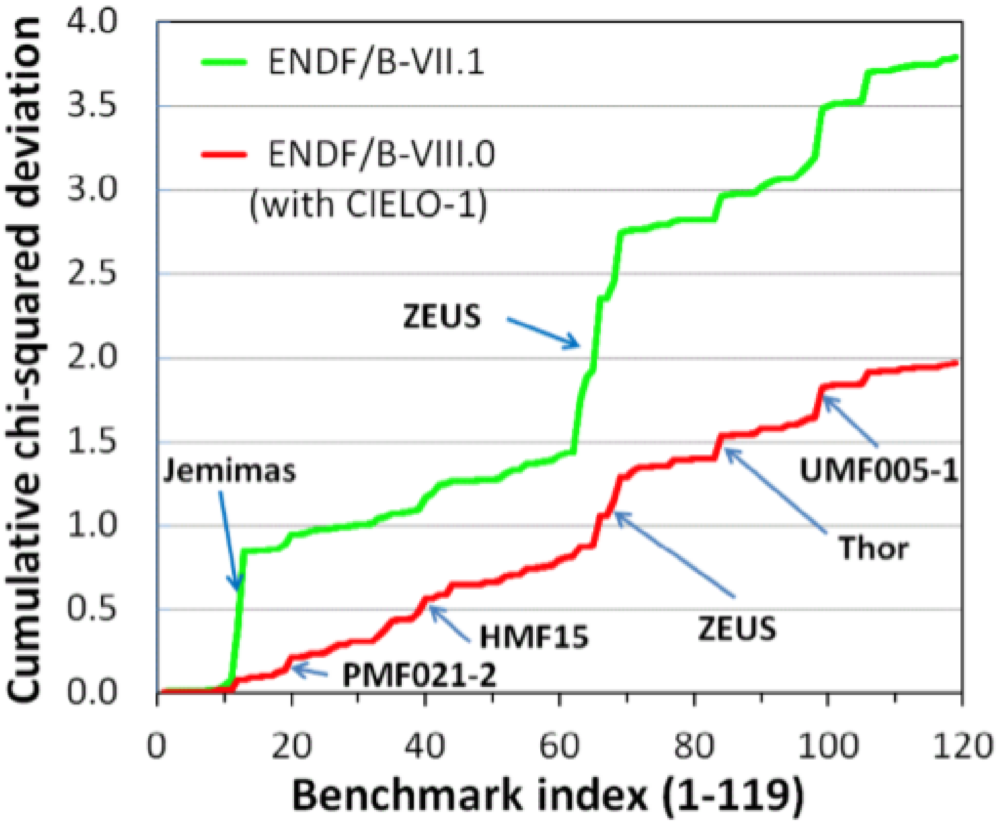






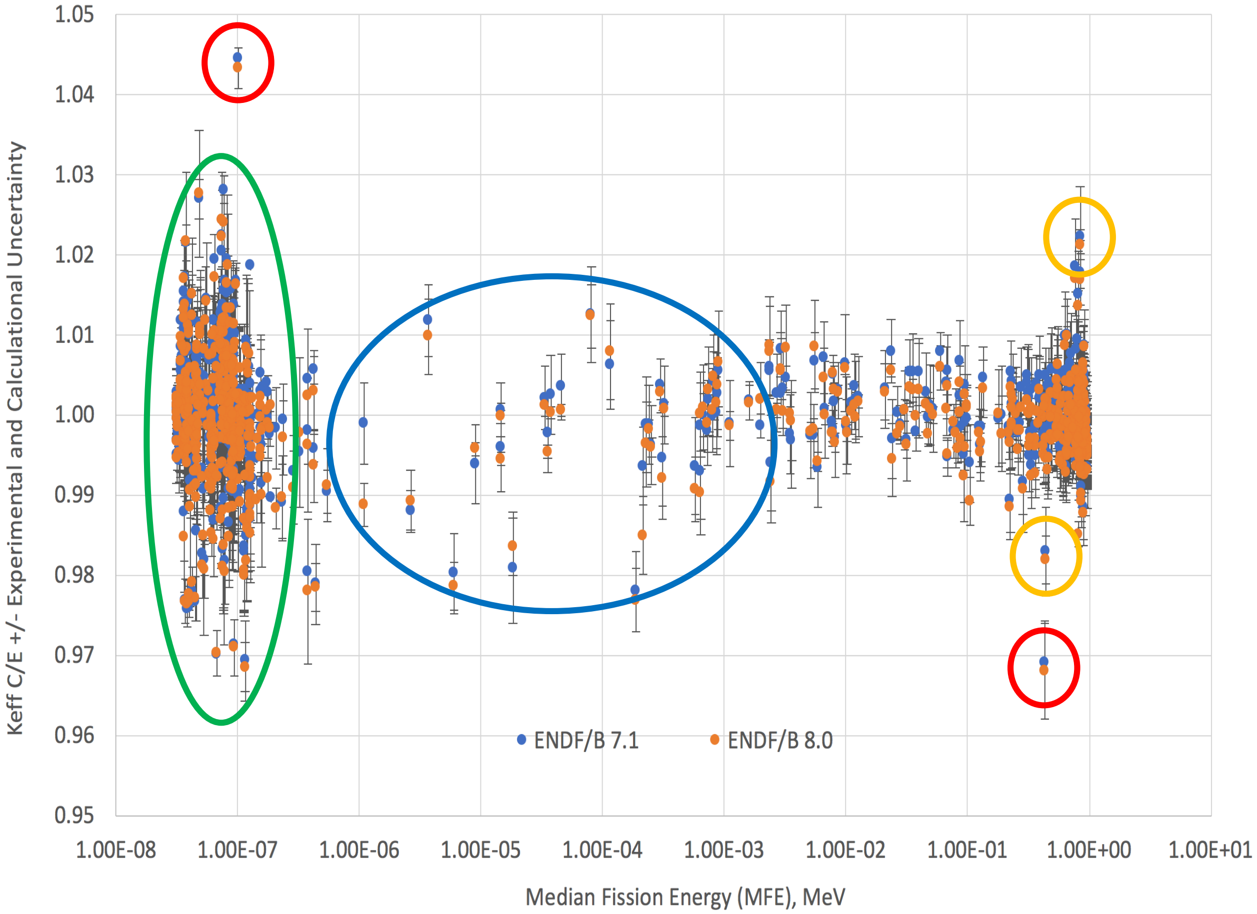
Validation End Product

- **Ultimate goal is to improve evaluated nuclear data for applications**
- Example shows improvement in fast metal systems for ENDF/B-VIII.0
  - Again, critical benchmark dominate
- 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)

Validation Highlights Errors in the Nuclear Data Pipeline that Affect Applications

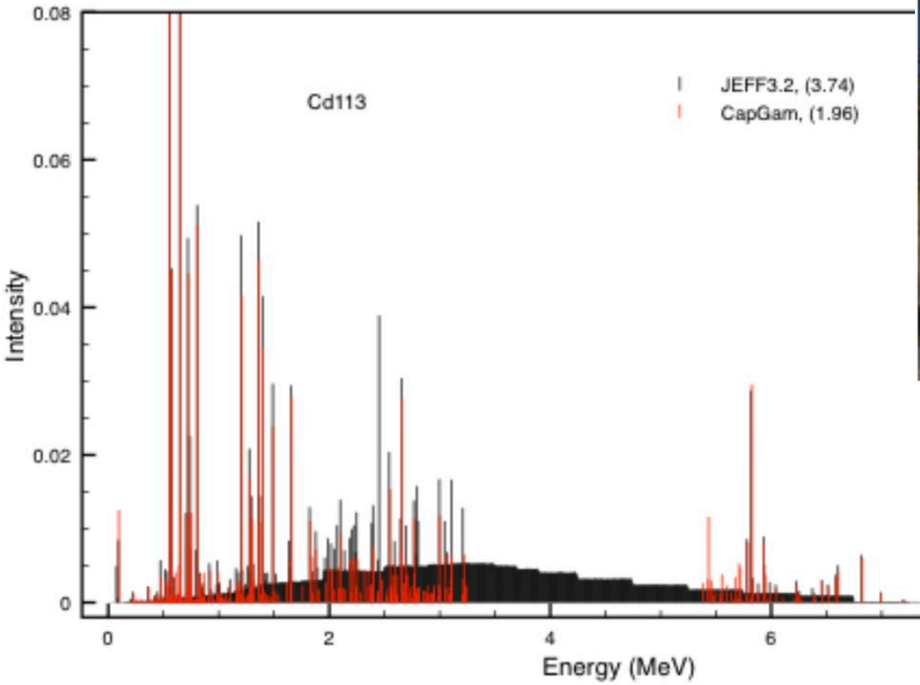


- Could be many issues:
  - Deficiencies in Differential Data
  - Theory/Model Limitations
  - Evaluation Assumptions or Errors
  - Data Processing Problems
  - Code Bug
  - Faulty Benchmark
- Validation allows for systematic prioritization of nuclear data needs
  - Helps determine which data really matters for your application
  - Where will you get the biggest bang for your buck

Example: Missing Cd Capture Gammas in ENDF

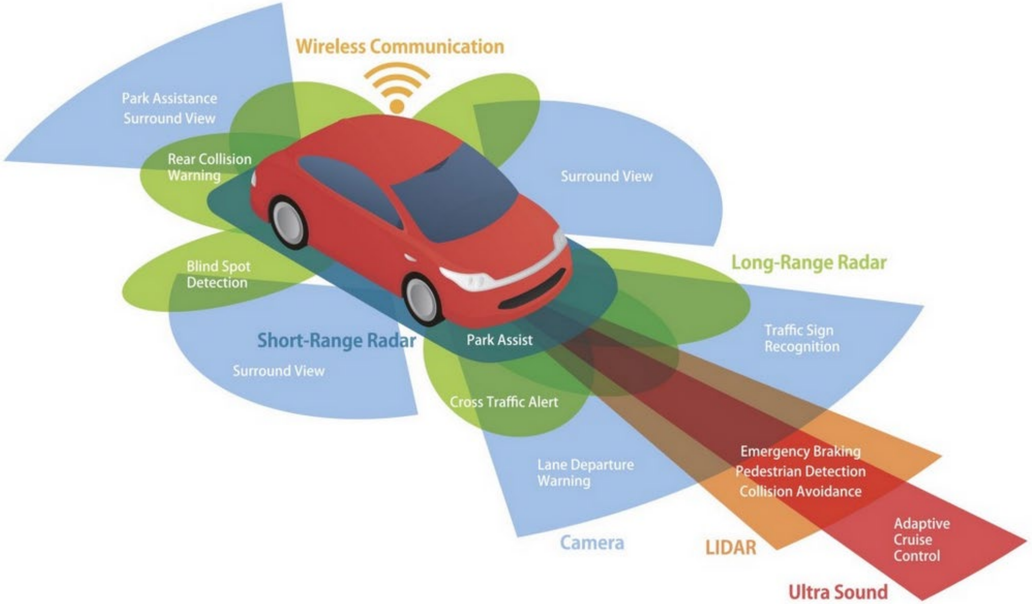
- Comparison of calculation to experiment of gamma dose from the SILENE Pulsed reactor showed **40% discrepancy** when the cadmium-lined polyethylene reactor shield was used

- ENDF/B-VII.1 had **NO gamma production data for ^{113}Cd**, a strong thermal neutron absorber
    - Likely introduced when switching from elemental evaluations to isotopic evaluations
- European data file (JEFF 3.2) did have capture gammas, but they differed significantly from US reference capture gamma database (CapGam)
- New (n, gamma) evaluation needed- still a problem in ENDF/B-VIII.0!



Additional Types of Experiments are Needed to Test Data Used in Applications

- Critical Experiments dominate current validation for all applications
  - Subject to fortuitous cancellation of errors
  - Doesn't test all data for all applications (gamma data, scattering data, time history of fission, etc)
- Many types of integral/semi-integral measurements can provide useful information for validation
  - These supplement/complement existing critical experiments
  - Overlapping coverage, similar to sensor fusion
  - Having multiple types of experiments within validation will help to constrain potential solutions (in this case constrain the nuclear data)
- Here we will present some examples of types of experiments which provide such complimentary information

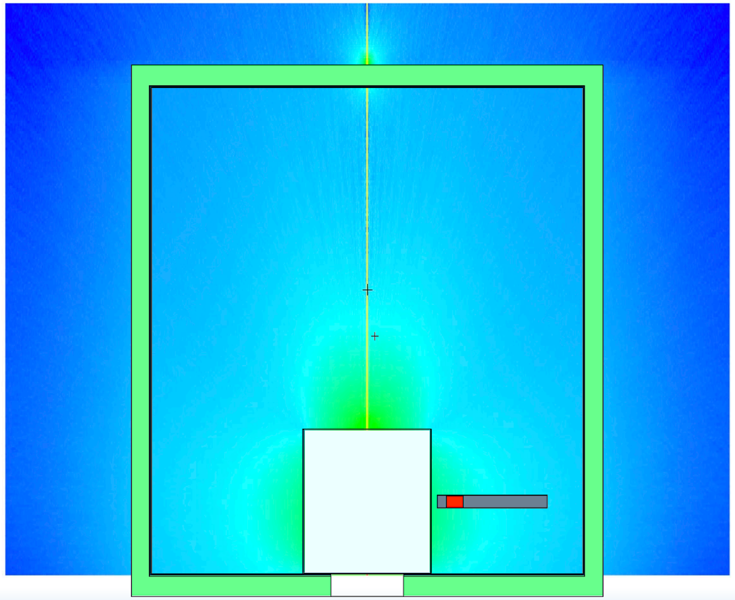


Sensor fusion example of a self-driving car.

Validation Experiments Do Not Have To Be Complicated and Expensive

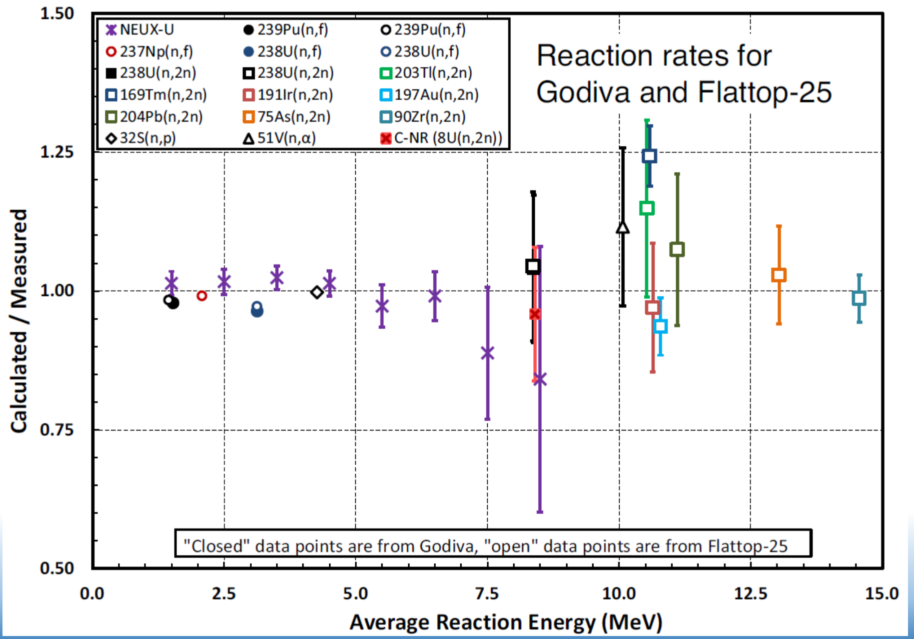
Many existing experiments can become benchmarks in the future (this will be discussed by 5 speakers).

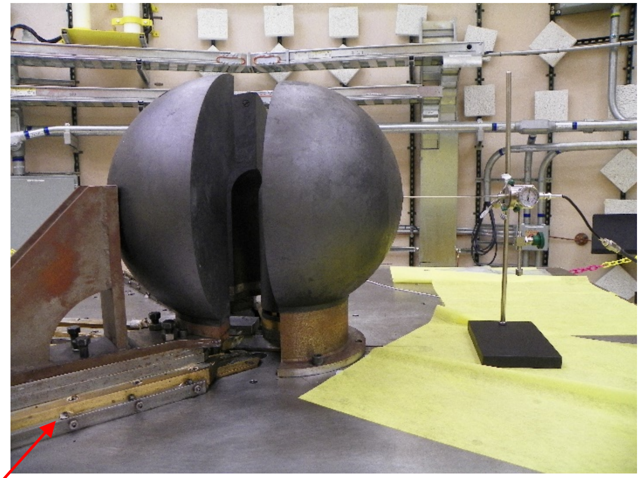
- Example: Pulsed Neutron Die-Away Experiments
- Setup: Neutron Generator, Block of Test Material, Shielded Box, Neutron Detector
  - Uses neutron generator incident on a moderating target, neutrons detected as a function of time highly reliant on Thermal Scattering Law
- Validation: Model experiment in radiation transport code, see how well you can predict neutron detector response



Activation Foil and Fission Chamber Measurements

- Used to help infer neutron spectra and reaction rate ratios
  - Ratios have low uncertainties because measurements are correlated
- There is a section on these types of measurements in the ENDF/B-VIII.0 paper (Section XII.D), but it only uses very old critical assemblies





Fission chamber measurements with Flat-Top

Foils used for Comet Zeus irradiation

Reactor Kinetics Measurements

- Reactor kinetics parameters including α, neutron lifetime, and delayed neutron fraction
- The ENDF/B-VIII.0 paper only uses very old critical assemblies for validation
- Recent measurements have been performed on many critical assemblies (NCERC, IPEN, etc.)

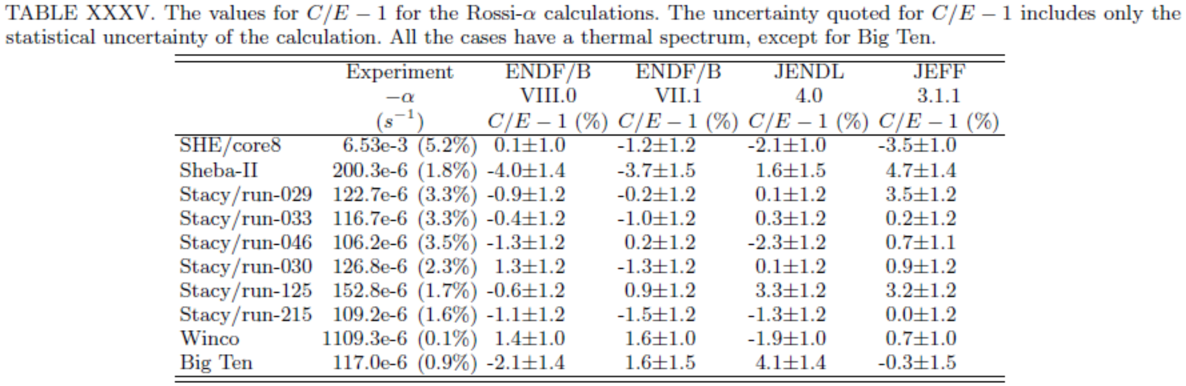
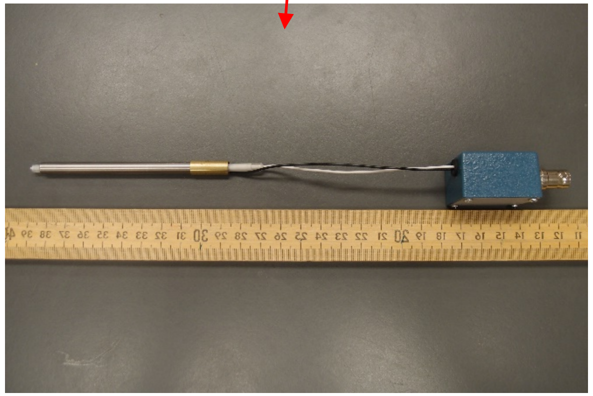


TABLE XXXV. The values for $C/E-1$ for the Rossi-α calculations. The uncertainty quoted for $C/E-1$ includes only the statistical uncertainty of the calculation. All the cases have a thermal spectrum, except for Big Ten.

	Experiment $-\alpha$ (s^{-1})	ENDF/B VIII.0 $C/E-1$ (%)	ENDF/B VII.1 $C/E-1$ (%)	JENDL 4.0 $C/E-1$ (%)	JEFF 3.1.1 $C/E-1$ (%)
SHE/core8	6.53e-3 (5.2%)	0.1±1.0	-1.2±1.2	-2.1±1.0	-3.5±1.0
Sheba-II	200.3e-6 (1.8%)	-4.0±1.4	-3.7±1.5	1.6±1.5	4.7±1.4
Stacy/run-029	122.7e-6 (3.3%)	-0.9±1.2	-0.2±1.2	0.1±1.2	3.5±1.2
Stacy/run-033	116.7e-6 (3.3%)	-0.4±1.2	-1.0±1.2	0.3±1.2	0.2±1.2
Stacy/run-046	106.2e-6 (3.5%)	-1.3±1.2	0.2±1.2	-2.3±1.2	0.7±1.1
Stacy/run-030	126.8e-6 (2.3%)	1.3±1.2	-1.3±1.2	0.1±1.2	0.9±1.2
Stacy/run-125	152.8e-6 (1.7%)	-0.6±1.2	0.9±1.2	3.3±1.2	3.2±1.2
Stacy/run-215	109.2e-6 (1.6%)	-1.1±1.2	-1.5±1.2	-1.3±1.2	0.0±1.2
Winco	1109.3e-6 (0.1%)	1.4±1.0	1.6±1.0	-1.9±1.0	0.7±1.0
Big Ten	117.0e-6 (0.9%)	-2.1±1.4	1.6±1.5	4.1±1.4	-0.3±1.5

ENDF/B-VIII.0 α validation



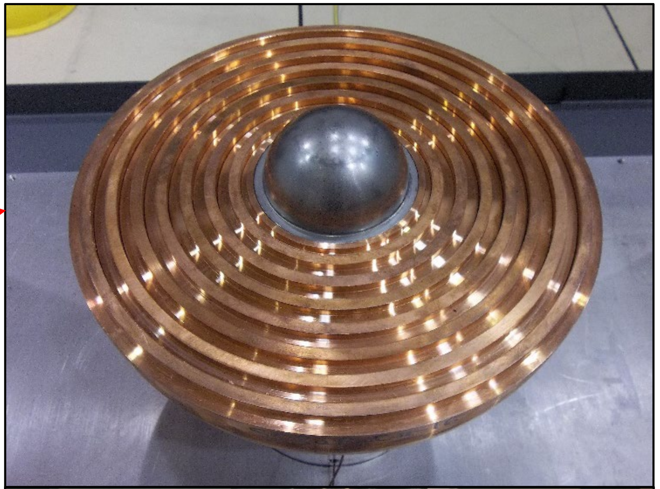
Small He-3 tubes: 4 He-3 tubes (40 atm), ¼" in diameter, often used for Rossi-α measurements

Experiment	Measured (s^{-1})	Simulated (s^{-1})	(C-E)/E
Polyethylene Class Foils	-1.994 E2	-2.040 E2	0.0231
HEU Zeus	-8.991 E4	-1.000 E5	0.1128
HEU/Pb Zeus	-3.826 E4	-4.626 E4	0.2092
IEU/Pb Zeus	-5.635 E4	-6.229 E4	0.1053
KRUSTY	-1.136 E3	-1.201 E3	0.0568
Jupiter	-1.731 E4	-1.930 E4	0.1145

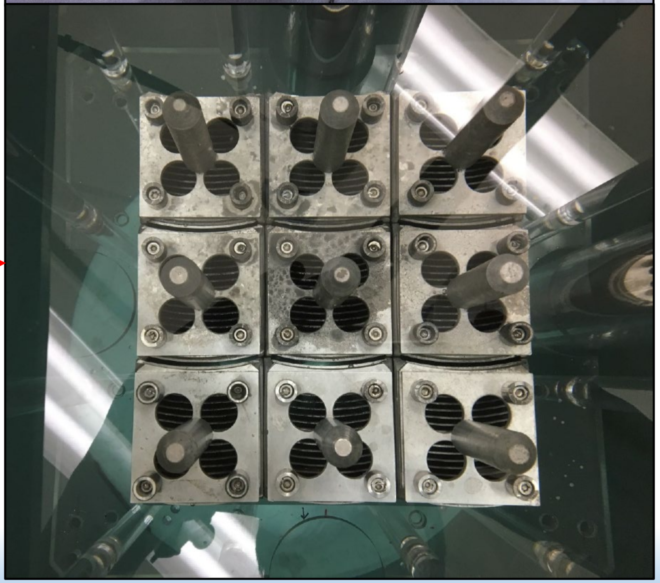
McKenzie, ICNC 2019

Subcritical Measurements

- Subcritical experiments can provide useful information about neutron multiplicity
- Useful for both nuclear data (detailed physics of fission) and computational methods validation (FREYA and CGMF)
- Many different data can be validated from a single measurement
- Important for several application areas
  - Safeguards and treaty verification
  - Nonproliferation
  - In-core/spent fuel monitoring



SCRaP experiment (4.5 kg Pu with Cu reflection)



ISSA experiment (water-moderated HEU uranium oxide)

Experiment summary

- In addition to the measurement types discussed here, many other integral/semi-integral measurements should be considered for use in validation:
  - Pulsed spheres/transmission measurements
  - Gamma/neutron spectra
  - Reactivity coefficients
  - And many others
- Three types of experiments will be explored in this session:
  - Those that are already benchmarks but are under-utilized
  - Those that have been performed but are not benchmarks
  - Gaps in which new experiments are needed to meet application needs

All Applications Need Validation

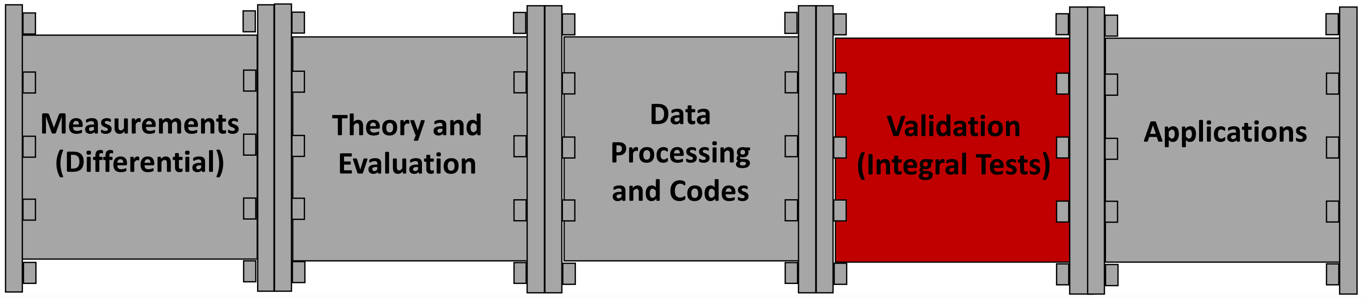
1) Understand what nuclear data are being used (reactions, isotopes, etc)

2) Look at your validation suite and ensure all the important data are being tested and benchmarked against “ground truth”

3) Ensure that the validation data (and sensitivities) can be easily utilized

4) Ultimately use results of validation to prioritize funding of all other pipeline sections
   - Likely starting with funding validation experiments and expanding benchmarks!

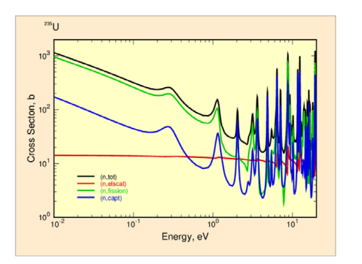
Four specific application areas will be presented (and additional application areas will be discussed).

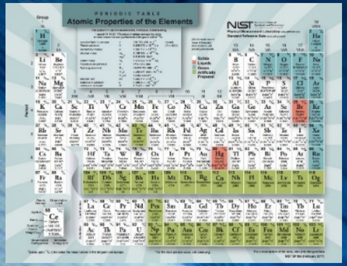


Mike Rising and Denise Neudecker will discuss **Data Evaluation and Sensitivity and Uncertainty Methods Development**

Session Schedule

- **Overview of Benchmarks and their Uses for Nuclear Data**
  - Jesson Hutchinson (LANL), Catherine Percher (LLNL), Michael Zerkle (NNL)
- **Past, Present, and Future Benchmark Efforts for Nuclear Data Validation**
  - Skip Kahler (LANL retired), Ian Hill (OECD/NEA)
- **Experimental Measurements that Could Become Benchmarks**
  - Sara Pozzi (UM), Jesse Holmes (NNL), Yaron Danon (RPI), Amanda Lewis (NNL), John Mattingly (NCSU)
- **The Nuclear Criticality Safety Validation Model**
  - Jerry McKamy (DOE NCSP, retired)
- **Application Areas- Nuclear Data, Validation Methods, and Integral Needs**
  - Thomas Miller (ORNL), Brad Reardon (X-Energy), David Matters (NA-22), Pablo Romojaro (SCKCEN)
- **Data Evaluation and Sensitivity and Uncertainty Methods Development**
  - Denise Neudecker (LANL), Michael Rising (LANL)





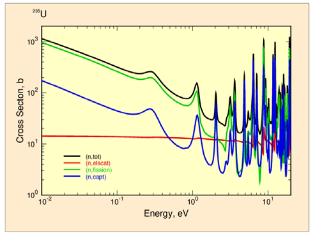
Don’t Forget What We Already Know

DR. A. C. (SKIP) KAHLER
KAHLER NUCLEAR DATA SERVICES, LLC

PRESENTED AT

WORKSHOP FOR APPLIED NUCLEAR DATA ACTIVITIES (WANDA 2021)

EXPANDED BENCHMARKS AND VALIDATION FOR NUCLEAR DATA
JANUARY 25, 2021 – FEBRUARY 03, 2021



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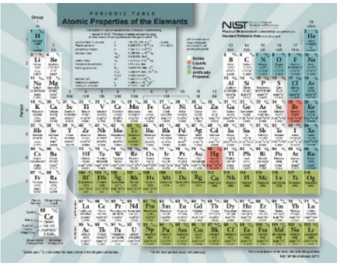
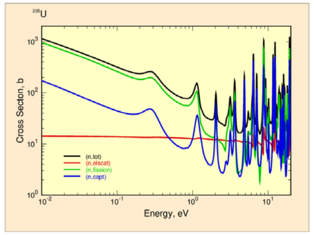


- Among the more commonly known benchmark compilations are …
  - ICSBEP, the International Criticality Safety Benchmark Evaluation Project
  - IRPhEP, the International Reactor Physics Evaluation Project
  - SINBAD, the Shielding Integral Benchmark Archive Database
- In the cross section evaluation world we talk about the “Big 3” nuclides; namely ^{235,238}U and ^{239}Pu
- By the same token, the ICSBEP, IRPhEP and SINBAD benchmark compilations might be referred to as the “Big 3” of benchmarks
- … but just as there are other cross section evaluations there are other benchmark compilations ... such as …



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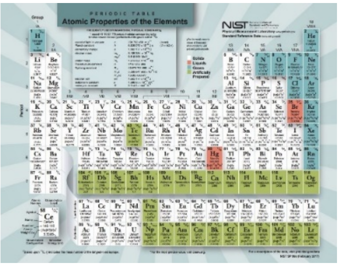
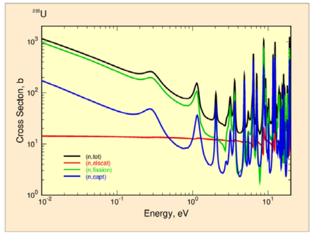


- CSEWG Benchmark Book
  - See links to ENDF-202, and more, at https://www.nndc.bnl.gov/endfdocs/.
    - First published in the early 1970s, with updates in the late 1970s, 1980s and early 1990s.
  - Includes categories for …
    - FAST Reactor Benchmarks
    - THERMAL Reactor BenchmarksS

      Many of these are already in ICSBEP & IRPhEP
    - SHIELDING Benchmarks
      - Some overlap with SINBAD
    - DOSIMETRY Benchmark
      - Coupled Fast Reactor Measurements Facility (CFRMF)
        - CFRMF was part of the Inter-Laboratory Reaction Rate (ILRR) Program
- and while many FAST and THERMAL CSEWG Benchmarks are part of the ICSBEP …
  - Other information such as actinide reaction rates, activation rates, Rossi-α, reactivity worth, and leakage spectra data may be included in the CSEWG description but are not part of the ICSBEP evaluation.
    - Aside from the CSEWG Benchmark Book, see ENDF/B-VII.0, ENDF/B-VII.1 & ENDF/B-VIII.0 Nuclear Data Sheet “Big” Papers; ENDF/B-VII.1 Data Testing Nuclear Data Sheet Paper; ND2013 Chadwick *et al* “CIELO” paper.



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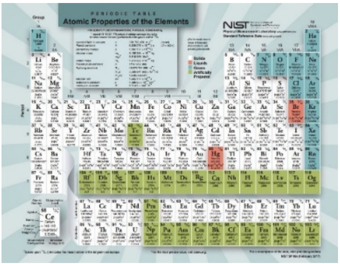
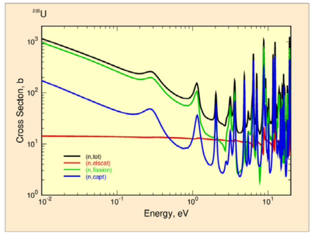


- CSEWG Shielding Benchmarks …
  - Initially (1974), a suite of 12 Shielding Data Test (SDT) experiments were identified …
    - Philosophy was not to define benchmark specifications, but to just cite the original Laboratory report
      - SDT1 = Iron Broomstick Experiment (ORNL-3867, revised; ENDF-166 … 1974 book incorrectly says ORNL-3876).
      - SDT2,3,4,5 = Oxygen, Nitrogen, Sodium, SS Broomsticks (ORNL-3868, 3869, 3870, 3871; ENDF-167, 168, 169, 170)
      - SDT6, SDT7 … replaced by SB2, SB3 (see below)
      - SDT8 = Zero Power Plutonium Reactor (ZPPR)/Fast Test Reactor Shield (LA-5288; ENDF-193?) … original document lost?
      - SDT9 = Fast Flux Test Reactor (FFTF) Radial Shield (AI-AEC-13048; ENDF-181)
      - SDT10 = LLL Pulsed Spheres (UCID-16372)
      - SDT11 = Neutron Transport through Iron and Stainless Steel (ORNL-TM-4222; ENDF-188)
      - SDT12 = Neutron Transport through Sodium (ORNL-TM-4223; ENDF-189)
  - Later was augmented with the SB (Shielding Benchmark) Series
    - Self-contained benchmark specifications are provided
      - SB2, SB3 = Secondary Gamma Production from Thermal and Fast Capture (ORNL-TM-5203, 5204; ENDF-227, 228)
      - SB4 = CRBR Upper Axial Shield (ORNL-5259, ENDF-258)
      - SB5 = Fusion Shielding Benchmark; Attenuation Experiments and Analysis (ENDF-202, Volume II (1983))
      - SB6 = Fusion Shielding Benchmark II; Duct Streaming Experiment and Analysis (ENDF-202, Volume II Supplement (1986))



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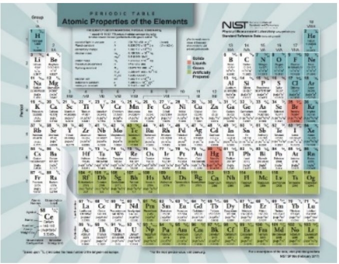
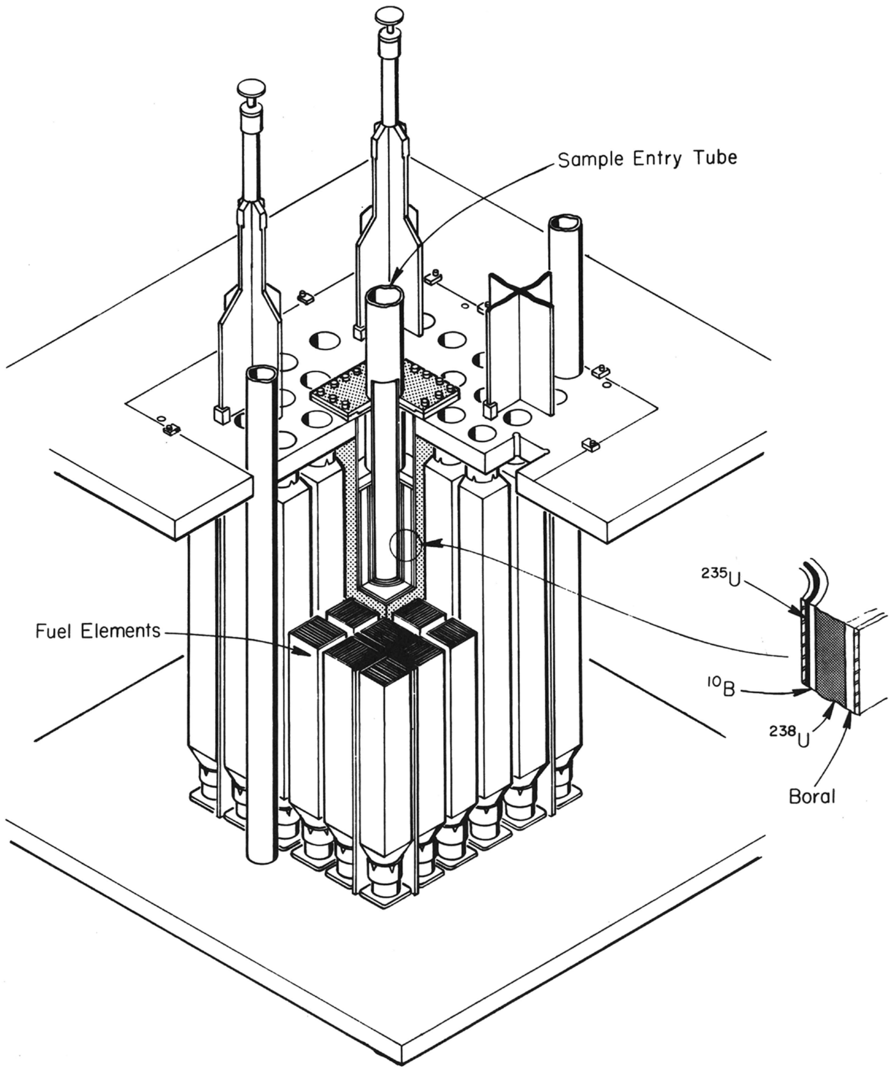
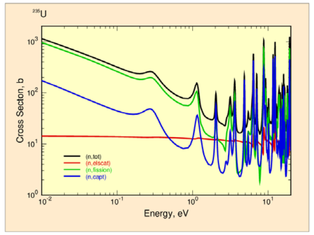
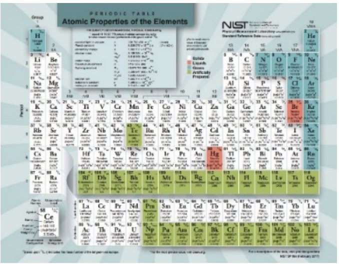




- CSEWG Dosimetry Benchmark (1982) … Coupled Fast Reactor Measurements Facility (CFRMF)
  - A 1D cylindrical model with detailed center region and homogenized outer regions.
  - See J.W.Rogers, D.A.Millsap & Y.D.Harker (1975), “CFRMF Neutron Field Flux Spectral Characterization,” Nuclear Technology, 25:2, 330-348, DOI: 10.13182/NT75-A24372
- … an R-Z model (detailed center region with axial and radial homogenized regions) is defined in
  - J.W.Rogers, Y.D.Harker and D.A.Millsap, “The Coupled Fast Reactivity Measurements Facility (CFRMF),” in Neutron Cross Sections for Reactor Dosimetry, IAEA-208, Vol. 2, pg 117-176 (1978).
    - See https://www-nds.iaea.org/publications/group_list.php?group=IAEA

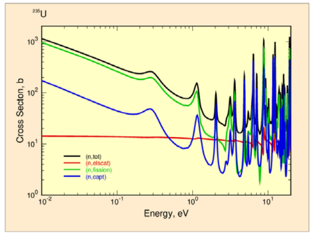


Don’t Forget What We Already Know

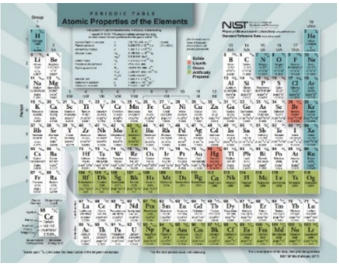


ATI (Austria, 2020);
ETRR-2 (Egypt, 2015 and 2020);
IEA-R1 (Brazil, 2015);
INR-1 (Romania, 2020);
IPEN-MB-01 (Brazil, 2020);
IRR-1 (Israel, 2020);
JSI-1 (Slovenia, 2020);
McMaster (Canada, 2015);
MINERVE (France, 2015);
SRR-1/MNSR (Syrian Arab Republic, 2015);
OPAL (Australia, 2015 and 2020);
RSG-GAS (Indonesia, 2015);
SAFARI-1 (South Africa, 2020);
SPERT III (United States of America, 2015);
SPERT IV (Canada, 2015);
TRR-1-M1 (Thailand, 2020).

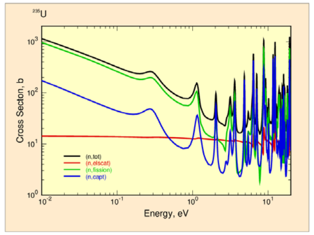
- IAEA Technical Report Series #480: Research Reactor Database: Facility Specification and Experimental Data
  - The outgrowth of IAEA CRPs on
    - “Innovative Methods in Research Reactor Analysis: Benchmark against Experimental Data on Neutronics and Thermalhydraulic Computational Methods and Tools for Operation and Safety Analysis of Research Reactors”, and
    - “Benchmarks of Computational Tools against Experimental Data on Fuel Burnup and Material Activation for Utilization, Operation and Safety Analysis of Research Reactors”
  - TRS-480 was initially published in 2015 (first CRP), with a second edition in 2020 (containing additional information generated during the second CRP)
    - Research reactors from 16 countries are represented …
    - The US contribution is identified as “SPERT III”, but is very different from the ICSBEP’s HEU-COMP-THERM-022 “SPERT III” evaluation (LEU UO_2 fuel pins versus HEU fuel plates)
    - Slovenia/Josef Stefan Institute TRIGA (ICSBEP IEU-COMP-THERM-003)



Don’t Forget What We Already Know



- Miscellaneous sources (for the adventurous …)
  - From https://www.osti.gov/biblio/6489025-nuclear-criticality-safety-experiments-calculations-analyses-volume-summaries-complilation-papers-from-transactions-american-nuclear-society
    - “This compilation contains 688 complete summaries of papers on nuclear criticality safety as presented at meetings of the American Nuclear Society (ANS) … reproduced here by permission of the American Nuclear Society from their Transactions, volumes 1-41.”
  - Seventy-Five Years of Nuclear Criticality Safety Documents – A Bibliography (LLNL-TR-760080)
    - From https://www.osti.gov/biblio/1479075-seventy-five-years-nuclear-criticality-safety-documents-bibliography … a mere 23,208 page pdf.
  - Also … Nuclear Criticality Experiments from 1943 to 1978: An Annotated Bibliography (UCRL-52769-Volumes 1, 2 & 3)
    - https://www.osti.gov/biblio/6392867-nuclear-criticality-safety-experiments-calculations-analyses-volume-lookup-tables
    - https://www.osti.gov/biblio/5948995-nuclear-criticality-experiments-from-annotated-bibliography-volume-lookup-tables
    - https://www.osti.gov/biblio/5887072-nuclear-criticality-experiments-from-annotated-bibliography-volume-subject-index



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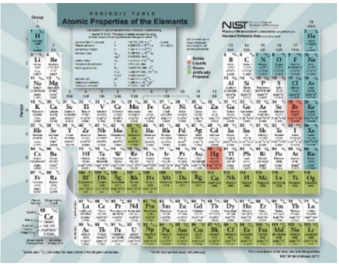
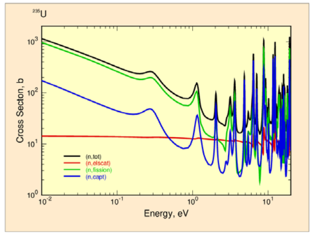


- Closing Comments
  - Computational resources have never been greater …
  - Theoretical and Experimental Capabilities have never been greater …
  - Accessibility to and Sharing of Data has never been greater …

  - … and so as we continue to march forward … don’t forget what we already know!



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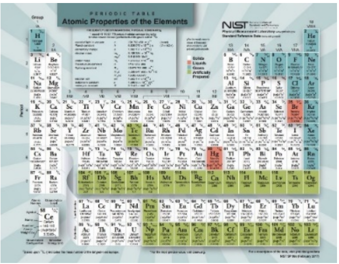
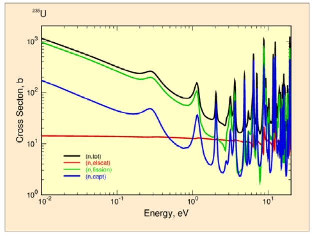


Backup/Extra Slides



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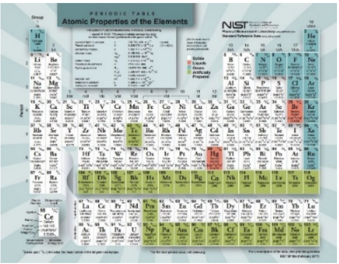
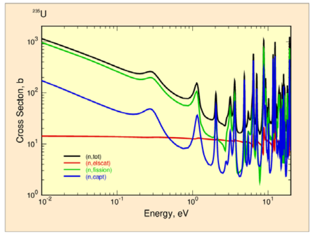


- Legacy benchmark reports …
  - ENDF-230 (BNL-NCS-21118, Vol I & II), Benchmark Testing of ENDF/B-IV (1976).
  - ENDF-234 (ORNL-5262), Compilation of Sensitivity Profiles for Several CSEWG Fast Benchmarks (1977).
  - ENDF-253 (ORNL-5336), A Compendium of Energy-Dependent Sensitivity Profiles for TRX-2 Thermal Lattice (1978).
  - ENDF-265 (BNL-NCS-24853), Sensitivity Coefficient Compilation for CSEWG Data Testing Benchmarks (1978).
    - No electronic copy available … anyone?
  - ENDF-311 (BNL-NCS-31531), Benchmark Data Testing of ENDF/B-V (1982).
    - No electronic copy available … anyone?
  - ENDF-313 (BNL-NCS-29891), Benchmark Testing of ENDF/B Data for Thermal Reactors (1981)
    - No electronic copy available … anyone?
  - ENDF-314 (LA-8950-MS), ENDF/B-V, LIB-V, CSEWG Benchmarks (1981)
  - ENDF-318 (LA-9037-MS), Los Alamos Benchmarks: Calculations Based on ENDF/B-V Data (1981).
  - ENDF-340 (LA-10230-MS), Analysis of Central Worths and Other Integral Data from the Los Alamos Benchmark Assemblies (1984)



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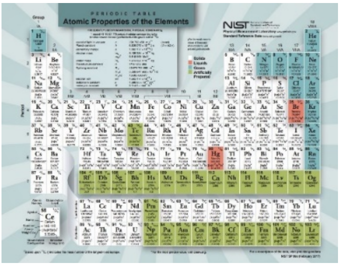
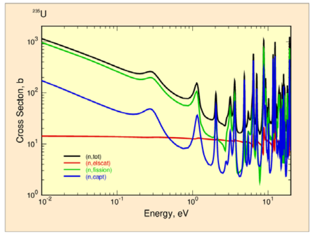


ICSBEP Identifiers for CSEWG Fast-Reactor Benchmarks			ICSBEP Identifiers for CSEWG Thermal-Reactor Benchmarks		
Name	**Benchmark Identifier**		**Name**	**Benchmark Identifier**	
	CSEWG	**ICSBEP or IRPhEP**		**CSEWG**	**ICSBEP or IRPhEP**
Jezebel	Fast Reactor #1	Pu-MET-FAST-001	ORNL-1 to ORNL-4	Thermal Reactor #1-#4	HEU-SOL-THERM-013.x
VERA-11A	Fast Reactor #2	…	ORNL-10	Thermal Reactor #5	HEU-SOL-THERM-032
ZPR-3-48	Fast Reactor #3	MIX-COMP-FAST-003	TRX-1 to TRX-4	Thermal Reactor #6-#9	…
ZEBRA-3	Fast Reactor #4	…	MIT-1, -2, -3	Thermal Reactor #10-#12	…
Godiva	Fast Reactor #5	HEU-MET-FAST-001	PNL-1, -2	Thermal Reactor #13-#14	Pu-SOL-THERM-021.x
VERA-1B	Fast Reactor #6	…	PNL-3, -4, -5	Thermal Reactor #15-#17	Pu-SOL-THERM-011.x
ZPR-3-6F	Fast Reactor #7	IEU-MET-FAST-015	BAPL-UO_2-1, -2, -3	Thermal Reactor #18-#20	…
…	…	…	BNL-ThO_2-1, -2, -3	Thermal Reactor #21-#23	…
SNEAK-7A, -7B	Fast Reactor #16, #17	SNEAK-LFMR-EXP-001	PNL-6 to PNL-12	Thermal Reactor #24-#30	Various Pu-SOL-THERM
…	…	…	PNL-30 to PNL-35	Thermal Reactor #31-#36	MIX-COMP-THERM-002
Jezebel-233	Fast Reactor #19	U233-MET-FAST-001	L7	Thermal Reactor #37	HEU-SOL-THERM-009.3
Big-10	Fast Reactor #20	IEU-MET-FAST-007	L8, L9	Thermal Reactor #38-#39	HEU-SOL-THERM-043.x
Jezebel-240	Fast Reactor #21	Pu-MET-FAST-002	L10	Thermal Reactor #40	HEU-SOL-THERM-009.4
Flattop-25	Fast Reactor #22	HEU-MET-FAST-028	L11	Thermal Reactor #41	HEU-SOL-THERM-012
Flattop-Pu	Fast Reactor #23	Pu-MET-FAST-006	HISS/HUG	Thermal Reactor #42	HEU-COMP-INTER-004
Flattop-23	Fast Reactor #24	U233-MET-FAST-006	HISS/HPG	Thermal Reactor #43	Pu-COMP-INTER-003
THOR	Fast Reactor #25	Pu-MET-FAST-008			

Only a partial list is given



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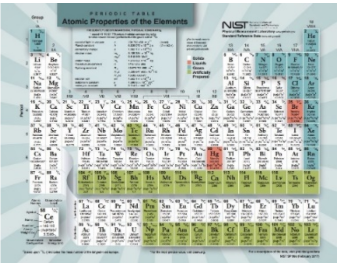
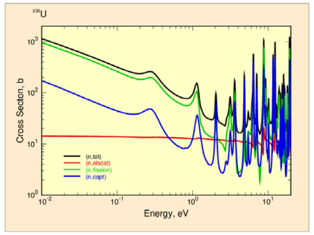


- Among the more commonly known benchmark compilations are …
  - ICSBEP, the International Criticality Safety Benchmark Evaluation Project
    - See https://www.oecd-nea.org/jcms/pl_24498/international-criticality-safety-benchmark-evaluation-project-icsbep
  - IRPhEP, the International Reactor Physics Evaluation Project
    - See https://www.oecd-nea.org/science/wprs/irphe/, or
    - https://www.oecd-nea.org/tools/abstract/detail/nea-1765
  - SINBAD, the Shielding Integral Benchmark Archive Database
    - See https://www.oecd-nea.org/science/wprs/shielding/, or
    - https://www.oecd-nea.org/tools/abstract/detail/nea-1517 (reactors)
    - https://www.oecd-nea.org/tools/abstract/detail/nea-1552 (accelerator shielding)
    - https://www.oecd-nea.org/tools/abstract/detail/nea-1553 (fusion neutronics)
    - Also https://www.oecd-nea.org/jcms/pl_23391/wpec-subgroup-47-sg47-use-of-shielding-integral-benchmark-archive-and-database-for-nuclear-data-validation.
    - https://www.oecd-nea.org/science/wprs/shielding/sinbad/sinbadis.htm
    - https://rsicc.ornl.gov/codes/dlc/dlc2/dlc-237.html



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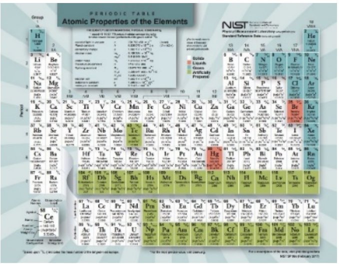
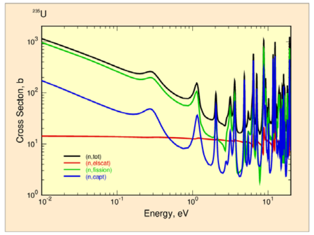


- ➢Link to ENDF/B-VIII.0 “Big Paper”, and more, at https://www.nndc.bnl.gov/endf/b8.0/index.html

- ➢Link to ENDF/B-VII.1 “Big Paper”, and more, at https://www.nndc.bnl.gov/endf/b7.1/index.html

- ➢Link to ENDF/B-VII.0 “Big Paper”, and more, at https://www.nndc.bnl.gov/endf/b7.0/index.html

- ➢Link to ND2013 “CIELO” paper by Chadwick et al at https://www.oecd-nea.org/jcms/pl_23285/wpec-subgroup-40-sg40-collaborative-international-evaluated-library-organisation-cielo-pilot-project



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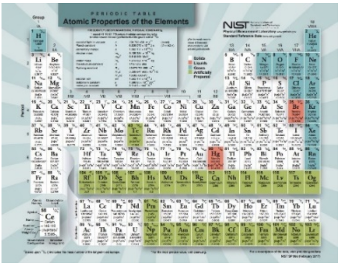


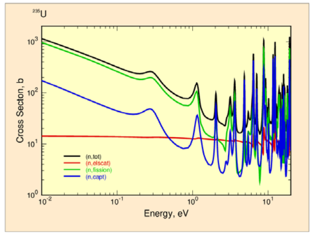
HEU-MET-FAST-001 (Godiva)

- Sphere, r=8.7407 cm
- HEU
  - ^{234}U = 4.9184e-4
  - ^{235}U = 4.4994e-2
  - ^{238}U =2.4984e-3
- k(benchmark) = 1.000 ± 0.001
  - k(calc, e80) = 1.00004 ± 0.00002
  - Central Region Flux = 0.005080 ± 0.05%
  - ^{235}U(n,f) = 0.006317 ± 0.05%
  - ^{238}U(n,f) = 0.001004 ± 0.08%
  - ^{238}U(n,γ) = 0.0004697 ± 0.08%
  - ^{238}U(n,2n) = 0.0000497 ± 0.5%

CSEWG Fast Benchmark #5 (Godiva)

- Sphere, r=8.741 cm
- HEU
  - ^{234}U = 4.92e-4
  - ^{235}U = 4.500e-2
  - ^{238}U =2.498e-3
- k(benchmark) = 1.000 ± 0.001
  - k(calc, e80) = 1.00021 ± 0.00002
  - Central Region Flux = 0.005079 ± 0.05%
  - ^{235}U(n,f) = 0.006316 ± 0.05%
  - ^{238}U(n,f) = 0.001000 ± 0.08%
  - ^{238}U(n,γ) = 0.0004697 ± 0.08%
  - ^{238}U(n,2n) = 0.0000502 ± 0.5%

MCN6.2, ENDF/B-VIII.0 xs, 1B histories



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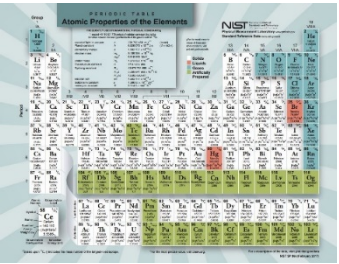


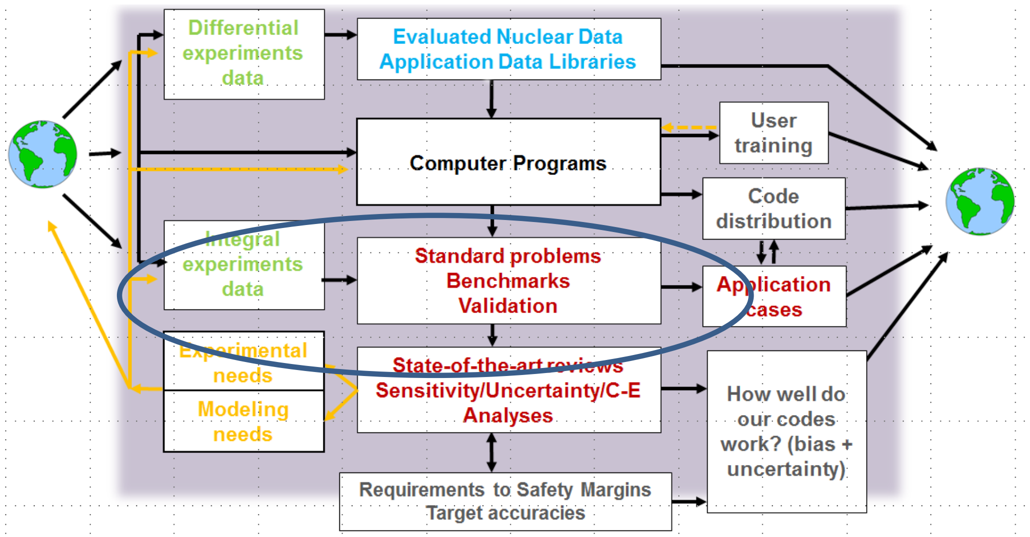
Past, Present, and Future Benchmark Efforts for Nuclear Data Validation

Ian Hill
Deputy Head of Nuclear Science
OECD/NEA

WANDA2021
January 27th 2021

Validation Benchmarks

Experiments, Nuclear Data, Computer Programs,
Verification & Validation, Feedback, Users



Differential experiments data

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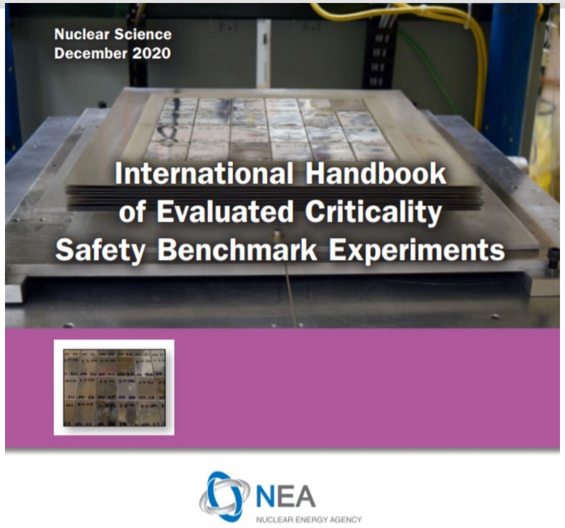
How well do our codes work? (bias + uncertainty)

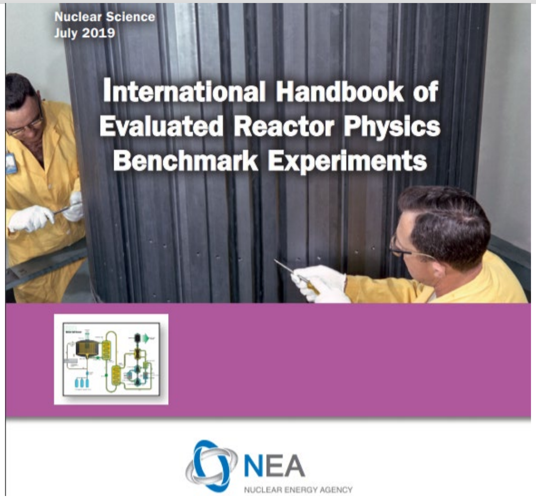
Requirements to Safety Margins Target accuracies



Nuclear Science
December 2020

International Handbook of Evaluated Criticality Safety Benchmark Experiments

NEA
NUCLEAR ENERGY AGENCY



Nuclear Science
July 2019

International Handbook of Evaluated Reactor Physics Benchmark Experiments

NEA
NUCLEAR ENERGY AGENCY

ICSBEP
~5000 Cases
~620 Evaluations
~4000 SDFs
IRPhEP
~200 REAC
~200 SPEC
SINBAD
~100 Experiments
SFCOMPO
~700 Samples

ICSBEP → IRPhEP → SINBAD** → SFCOMPO

CIELO
O16

Sized by: Trust, Usability*

* Knowledge/retrievability of resource, Availability of inputs, Response functions
**In cooperation with RSICC

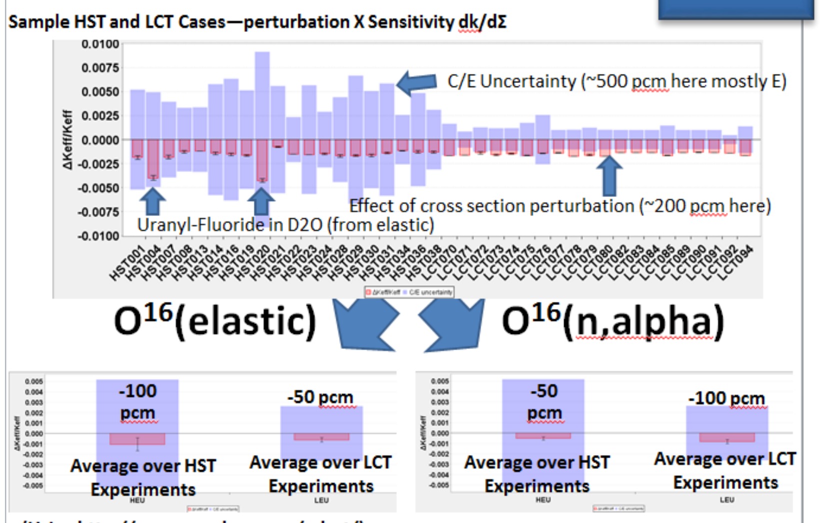
Efforts underway to improve SINBAD and SFCOMPO

Speed and Signal to Noise Ratio:

Recently Developed Rapid feedback tools linking sensitivity profiles and Integral experiments were used for ENDF/B-VIII.0

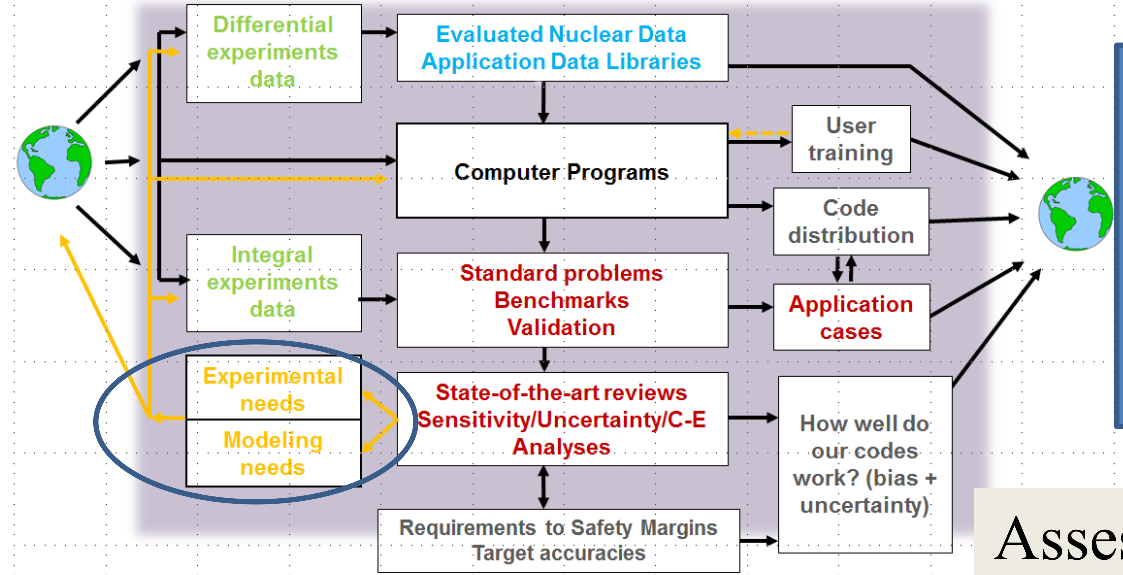
- Feedback loop changed months into minutes.
- But some feedback loops take years (even a decade); can be reduced to minutes also!
- NDaST, ADVANCED, CRATER.

O^{16}(elastic + n,alpha)



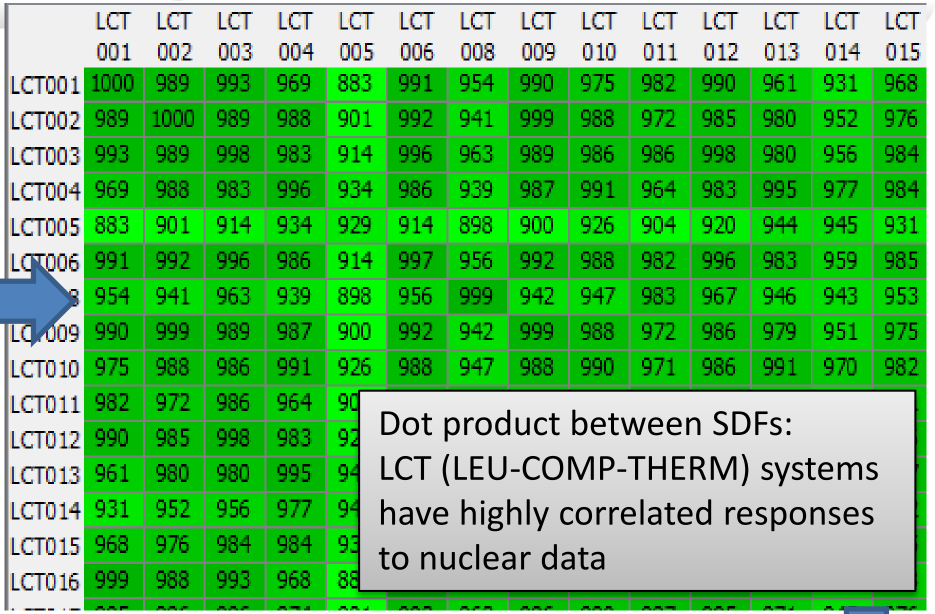
(Using http://www.oecd-nea.org/ndast/)

C/E spread from ND or Experiments



Q: Are C/E differences between cases due to Nuclear Data uncertainty, or due to Experimental uncertainty?

Can we Check Reduced Chi Squared?



	LCT 001	LCT 002	LCT 003	LCT 004	LCT 005	LCT 006	LCT 008	LCT 009	LCT 010	LCT 011	LCT 012	LCT 013	LCT 014	LCT 015
LCT001	1000	989	993	969	883	991	954	990	975	982	990	961	931	968
LCT002	989	1000	989	988	901	992	941	999	988	972	985	980	952	976
LCT003	993	989	998	983	914	996	963	989	986	986	998	980	956	984
LCT004	969	988	983	996	934	986	939	987	991	964	983	995	977	984
LCT005	883	901	914	934	929	914	898	900	926	904	920	944	945	931
LCT006	991	992	996	986	914	997	956	992	988	982	996	983	959	985
8	954	941	963	939	898	956	999	942	947	983	967	946	943	953
LCT009	990	999	989	987	900	992	942	999	988	972	986	979	951	975
LCT010	975	988	986	991	926	988	947	988	990	971	986	991	970	982
LCT011	982	972	986	964	90									
LCT012	990	985	998	983	92									
LCT013	961	980	980	995	94									
LCT014	931	952	956	977	94									
LCT015	968	976	984	984	93									
LCT016	999	988	993	968	88									

Dot product between SDFs:
LCT (LEU-COMP-THERM) systems have highly correlated responses to nuclear data

Assessing C/E Spread

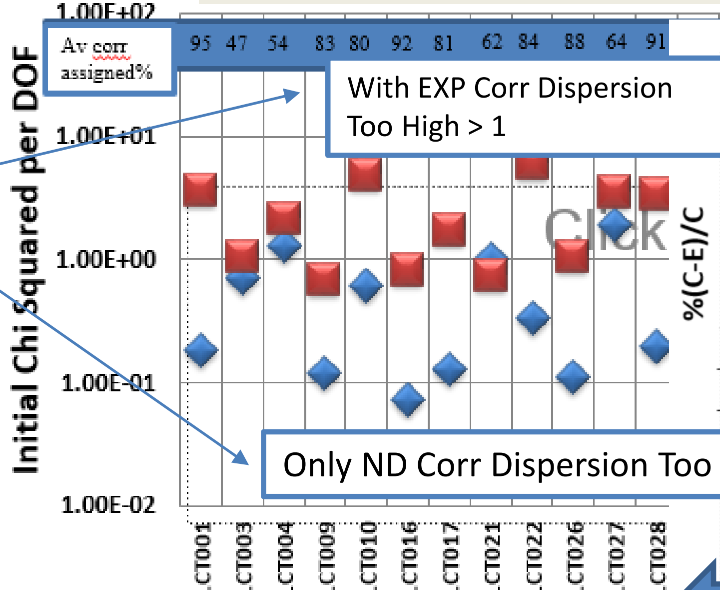
Bad news: We don't have the data to assess reduced chi squared. Good news New methods may prove useful here.

Creates difficulty unfolding reactivity

$$\chi^2 = \sum_i \sum_j d_i V_{i,j}^{-1} d_j$$

d=c-e

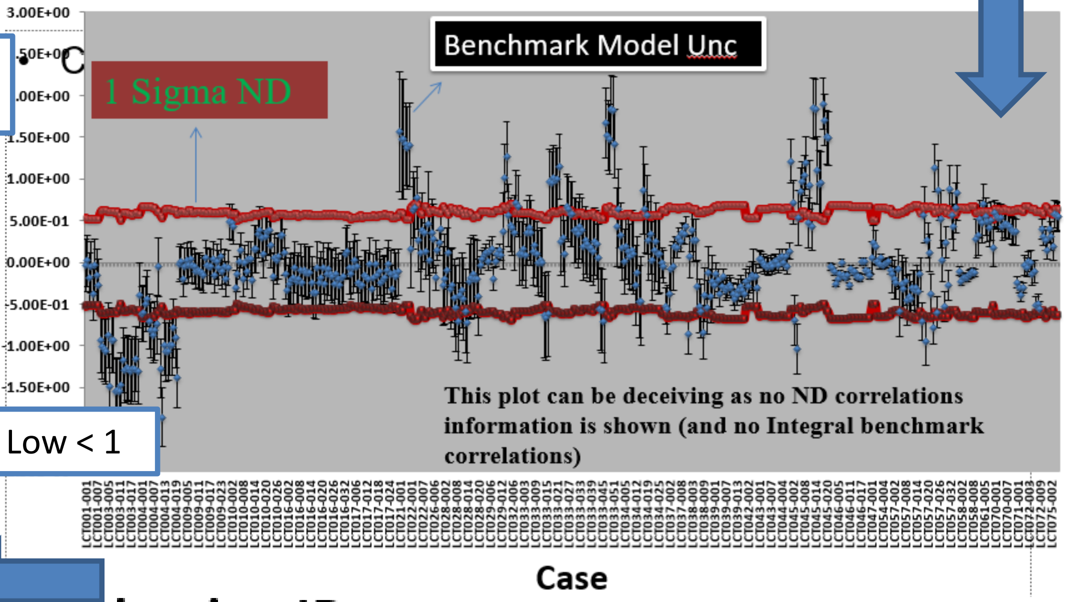
ND+Int.BM



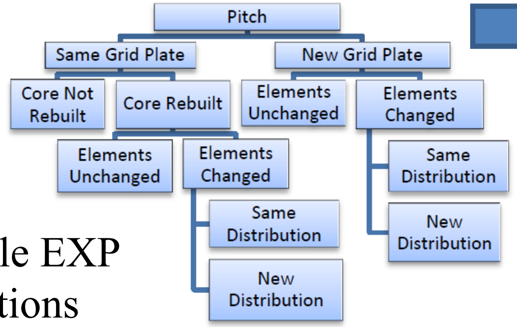
With EXP Corr Dispersion Too High > 1

Only ND Corr Dispersion Too Low < 1

Evaluation ID

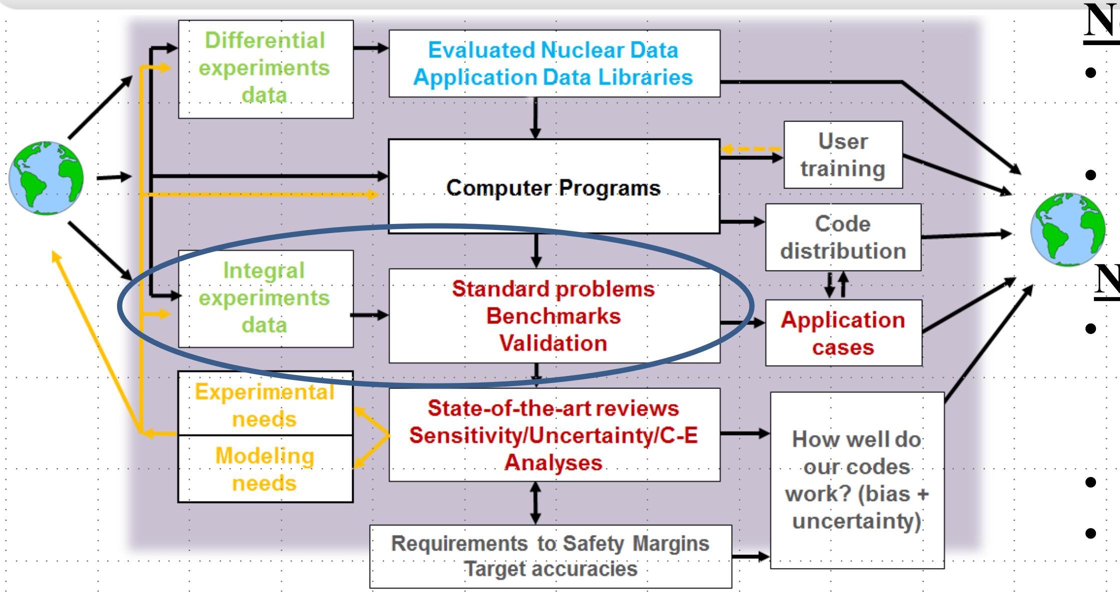


This plot can be deceiving as no ND correlations information is shown (and no Integral benchmark correlations)



Example EXP correlations

• Science and the ‘Knowledge Machine’



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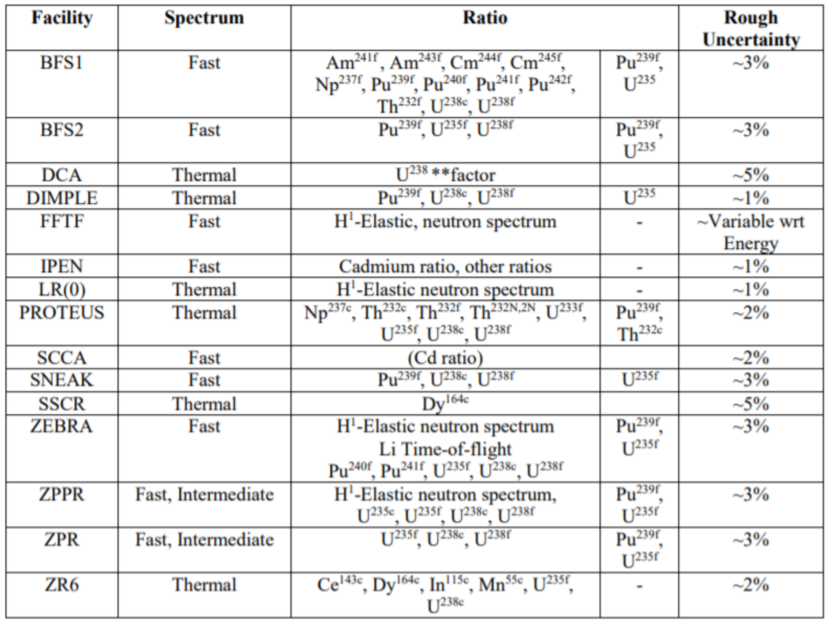
Needs: Faster Feedback with good Signal to Noise Ratio (SNR)

- Usachev[1] notes that sensitivity analysis is needed for communication between specialists. Also he applies SA for experiment design optimisation.
- Salvatores reduces recommended adjustment group structure from 33 groups to 7 groups [SG46]. SNR!

Needs: Efforts to share models and response functions

- Developments in GPT should increase attractiveness of IRPhEP (SINBAD, SFCOMPO). Recent substantial progress from 2D deterministic to 3D MC sensitivity
- Models (future CAD) and computations of response functions needed!
- Sensitivity Methods improvement still needed (Examples: angular sensitivity, XGPT, availability subcritical SDFs)

Table I.: Spectral characteristic experimental benchmarks in the IRPhEP Handbook



Facility	Spectrum	Ratio		Rough Uncertainty
BFS1	Fast	Am^{241f}, Am^{243f}, Cm^{244f}, Cm^{245f}, Np^{237f}, Pu^{239f}, Pu^{240f}, Pu^{241f}, Pu^{242f}, Th^{232f}, U^{238c}, U^{238f}	Pu^{239f}, U^{235}	~3%
BFS2	Fast	Pu^{239f}, U^{235f}, U^{238f}	Pu^{239f}, U^{235}	~3%
DCA	Thermal	U^{238} **factor		~5%
DIMPLE	Thermal	Pu^{239f}, U^{238c}, U^{238f}	U^{235}	~1%
FFTF	Fast	H^1-Elastic, neutron spectrum	-	~Variable wrt Energy
IPEN	Fast	Cadmium ratio, other ratios	-	~1%
LR(0)	Thermal	H^1-Elastic neutron spectrum	-	~1%
PROTEUS	Thermal	Np^{237c}, Th^{232c}, Th^{232f}, $Th^{232N,2N}$, U^{233f}, U^{235f}, U^{238c}, U^{238f}	Pu^{239f}, Th^{232c}	~2%
SCCA	Fast	(Cd ratio)		~2%
SNEAK	Fast	Pu^{239f}, U^{238c}, U^{238f}	U^{235f}	~3%
SSCR	Thermal	Dy^{164c}		~5%
ZEBRA	Fast	H^1-Elastic neutron spectrum Li Time-of-flight Pu^{240f}, Pu^{241f}, U^{235f}, U^{238c}, U^{238f}	Pu^{239f}, U^{235f}	~3%
ZPPR	Fast, Intermediate	H^1-Elastic neutron spectrum, U^{235c}, U^{235f}, U^{238c}, U^{238f}	Pu^{239f}, U^{235f}	~3%
ZPR	Fast, Intermediate	U^{235f}, U^{238c}, U^{238f}	Pu^{239f}, U^{235f}	~3%
ZR6	Thermal	Ce^{143c}, Dy^{164c}, In^{115c}, Mn^{55c}, U^{235f}, U^{238c}	-	~2%

PIA[2]: Progressive Incremental Adjustment

1. Fission spectral indices
2. Irradiation experiments: sensitive to capture cross sections (and second order to fission) and (n,2n)
3. Sample oscillation experiments and other experiment sensitive to inelastic
4. Critical masses
5. Reactivity variations (both reactivity coefficients and reactivities associated to fissile isotope variations in the same core geometry)

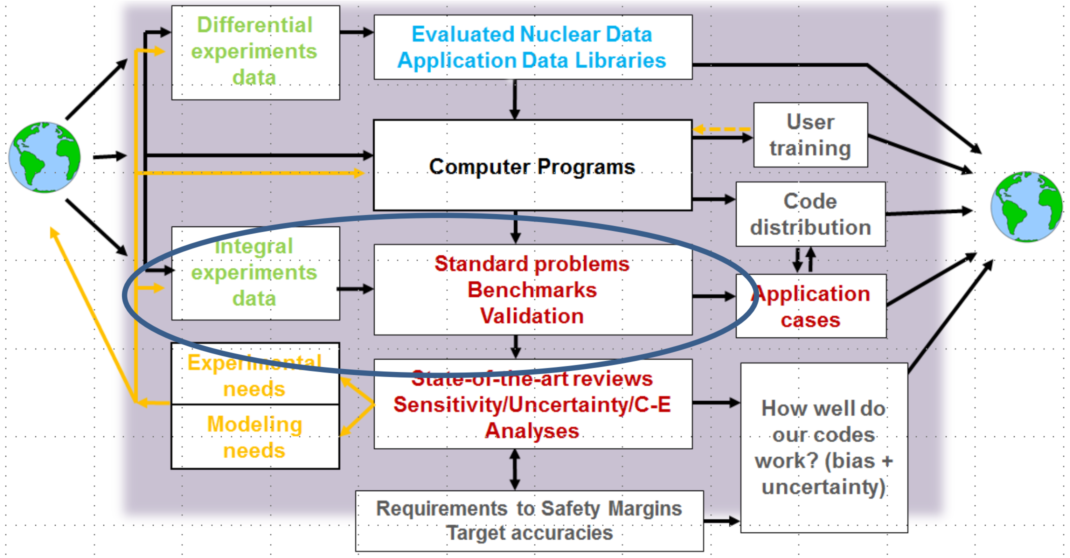
---

1) L.N. Usachev, “Can Experimental Scientists, Data Evaluators and Compilers, and Nuclear Data Users Understand One Another” INDC/166, (1967). Translated from Russian.

2) G. Palmiotti and M. Salvatores “PIA and REWIND: Two new methodologies for cross section adjustment,” MC2017, Jeju, Korea, April 16-20 (2017).

What’s old is new?

Experiments, Nuclear Data, Computer Programs, Validation, Feedback, Users



Evaluate and Add to Checking Suite!

Recently added primary documentation archives (Last update December 2008)

- IRPHE/B&W-SS-LATTICE, Spectral Shift Reactor Lattice Experiments
- IRPHE-JAPAN, Reactor Physics Experiments carried out in Japan
- IRPHE/JOYO MK-II, JOYO MK-II core management and characteristics database
- IRPhE/RRR-SEG, Reactor Physics Experiments from Fast-Thermal Coupled Facility
- IRPHE-SNEAK, KFK SNEAK Fast Reactor Experiments, Primary Documentation
- IRPhE/STEK, Reactor Physics Experiments from Fast-Thermal Coupled Facility
- IRPHE-ZEBRA, AEEW Fast Reactor Experiments, Primary Documentation
- IRPHE-DRAGON-DPR, OECD High Temperature Reactor Dragon Project, Primary Documents
- IRPHE-HTR-ARCH-01, Archive of HTR Primary Documents
- IRPHE/AVR, AVR High Temperature Reactor Experience, Archival Documentation
- IRPHE-KNK-II-ARCHIVE, KNK-II fast reactor documents, power history and measured parameters
- IRPhE/BERENICE, effective delayed neutron fraction measurements
- IRPhE-TAPIRO-ARCHIVE, fast neutron source reactor primary documents, reactor physics experiments

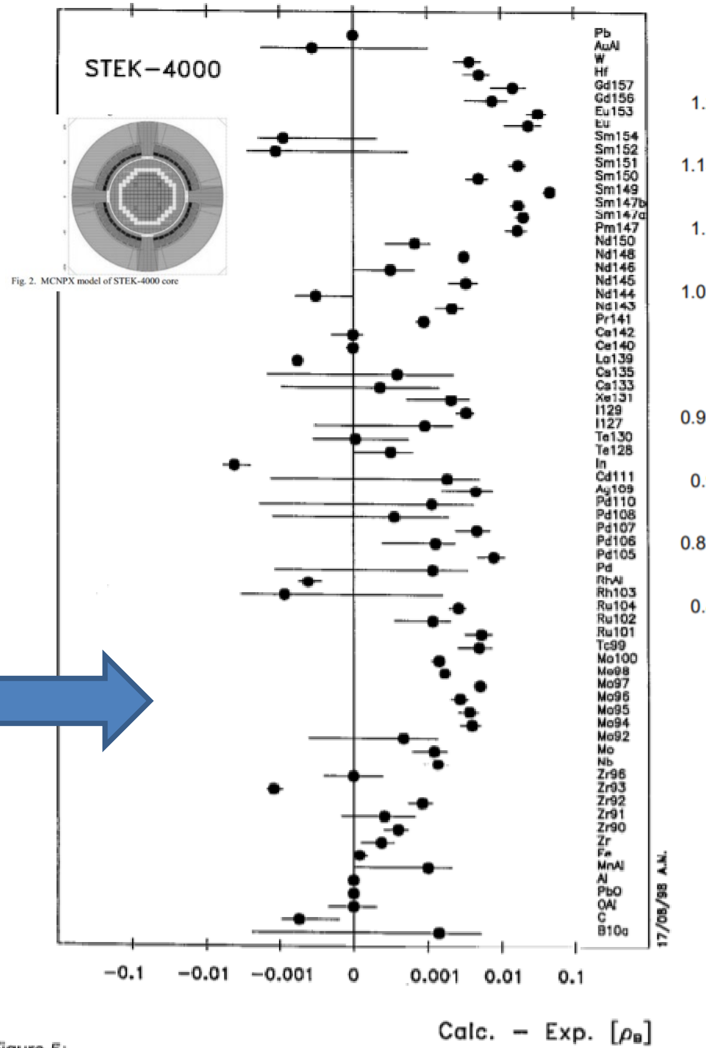
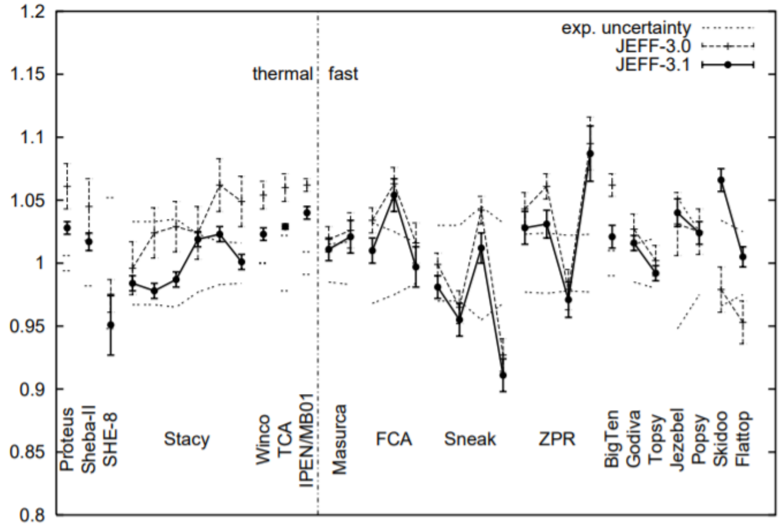
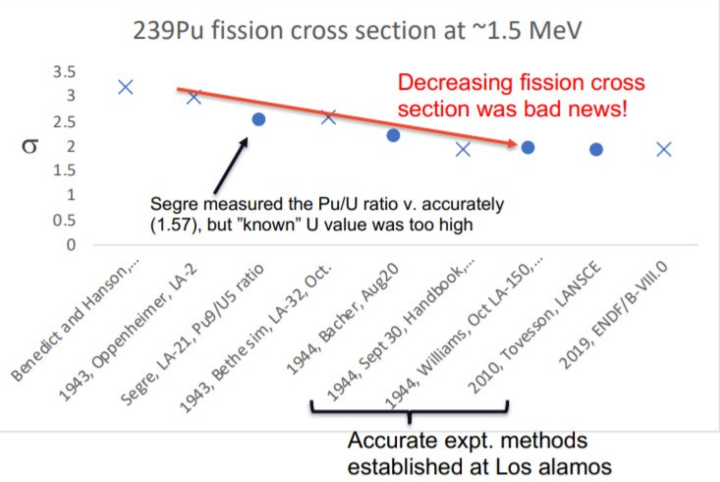


Figure 5:
Differences between the calculated and experimental reactivity worths measured in STEK-4000. The error bars refer to the total error of the experimental data. The reactivity worth is for 1g of sample substance and it is normalised to the value of 1g Boron (about 13 pcm).





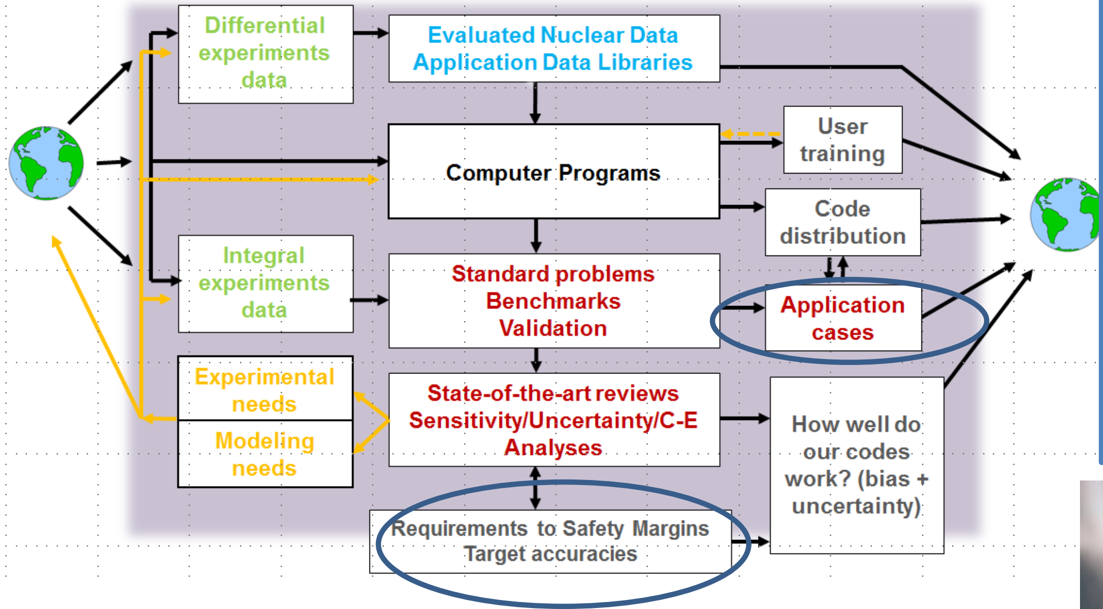
STEK FACILITY The STEK experiment was constructed at ECN at the end of the 60’s in the framework of the co-operation between the former German Federal Republic, Belgium and the Netherlands on research for fast breeder reactor development. The main goal of the experiment was to measure integral cross sections of fission products. This was a rather unique experiment by the comprehensive list of fission products (and other materials) measured, and the diversity of core configurations. It is also considered worldwide as an important source of validation data.

M.B. Chadwick 75th anniversary trinity talk

Verification

Nuclear Energy Agency

NEA NUCLEAR ENERGY AGENCY



Differential experiments data

Evaluated Nuclear Data Application Data Libraries

User training

Computer Programs

Code distribution

Integral experiments data

Standard problems Benchmarks Validation

Application cases

Experimental needs

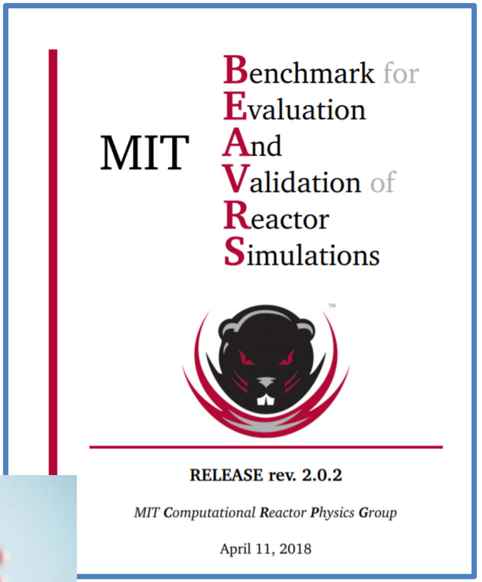
Modeling needs

State-of-the-art reviews Sensitivity/Uncertainty/C-E Analyses

How well do our codes work? (bias + uncertainty)

Requirements to Safety Margins Target accuracies

Collect benchmarks and automate the impact of new data on these activities



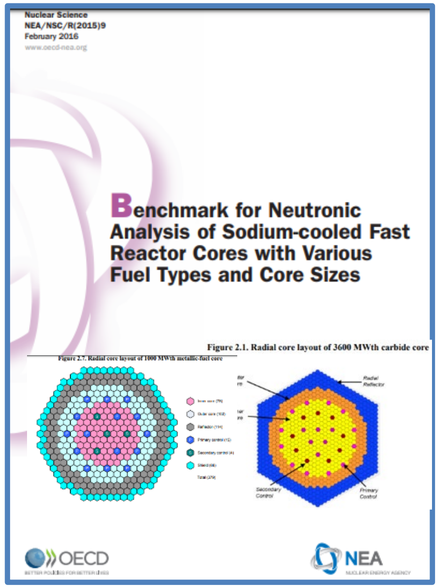
MIT

Benchmark for **E**valuation **A**nd **V**alidation of **R**eactor **S**imulations

RELEASE rev. 2.0.2

MIT Computational Reactor Physics Group

April 11, 2018



Nuclear Science
NEA/NSC/R(2015)9
February 2016
www.oecd-nea.org

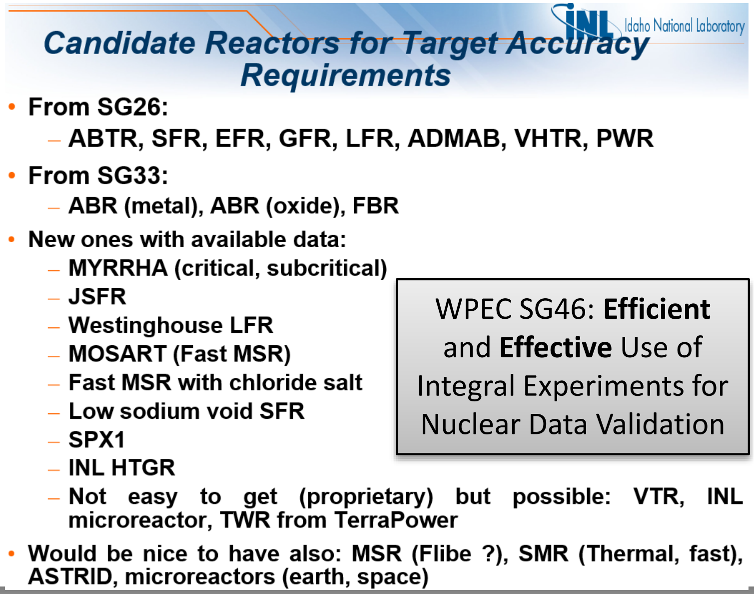
Benchmark for Neutronic Analysis of Sodium-cooled Fast Reactor Cores with Various Fuel Types and Core Sizes

Figure 2.1. Radial core layout of 3600 MWth carbide core

Figure 2.7. Radial core layout of 1000 MWth metallic-fuel core

OECD

NEA



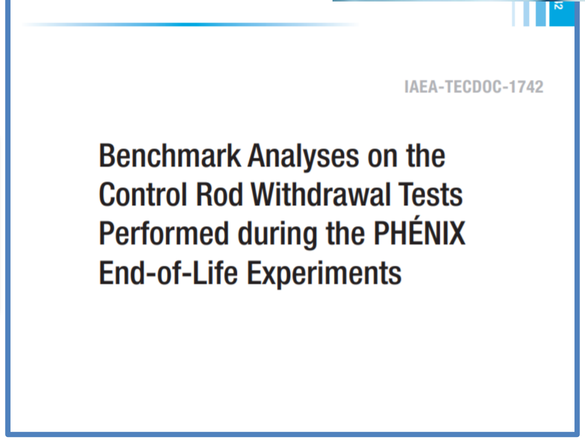
Candidate Reactors for Target Accuracy Requirements

INL Idaho National Laboratory

- From SG26:
  - ABTR, SFR, EFR, GFR, LFR, ADMAB, VHTR, PWR
- From SG33:
  - ABR (metal), ABR (oxide), FBR
- New ones with available data:
  - MYRRHA (critical, subcritical)
  - JSFR
  - Westinghouse LFR
  - MOSART (Fast MSR)
  - Fast MSR with chloride salt
  - Low sodium void SFR
  - SPX1
  - INL HTGR
  - Not easy to get (proprietary) but possible: VTR, INL microreactor, TWR from TerraPower
- Would be nice to have also: MSR (Flibe ?), SMR (Thermal, fast), ASTRID, microreactors (earth, space)

WPEC SG46: **Efficient** and **Effective** Use of Integral Experiments for Nuclear Data Validation

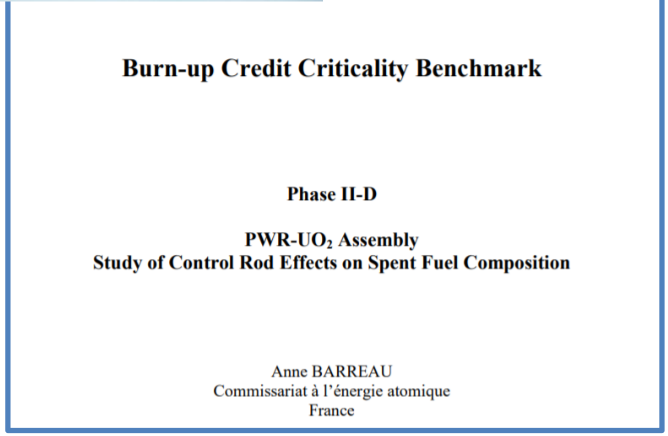
IAEA TECDOC SERIES



IAEA-TECDOC-1742

Benchmark Analyses on the Control Rod Withdrawal Tests Performed during the PHÉNIX End-of-Life Experiments

ISBN 92-64-02316-X



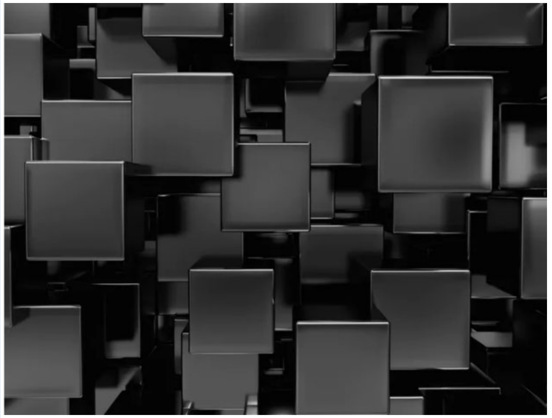
Burn-up Credit Criticality Benchmark

Phase II-D

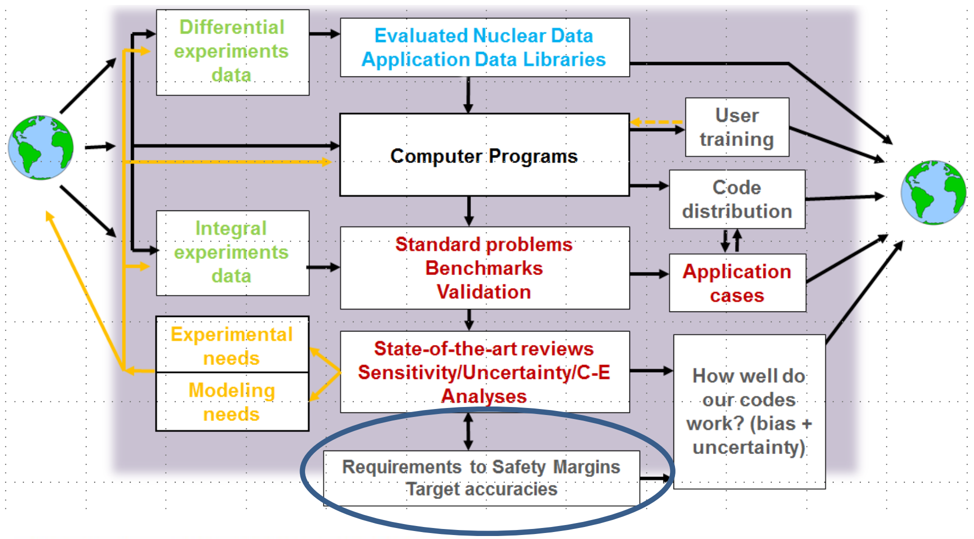
PWR-UO$_2$ Assembly
Study of Control Rod Effects on Spent Fuel Composition

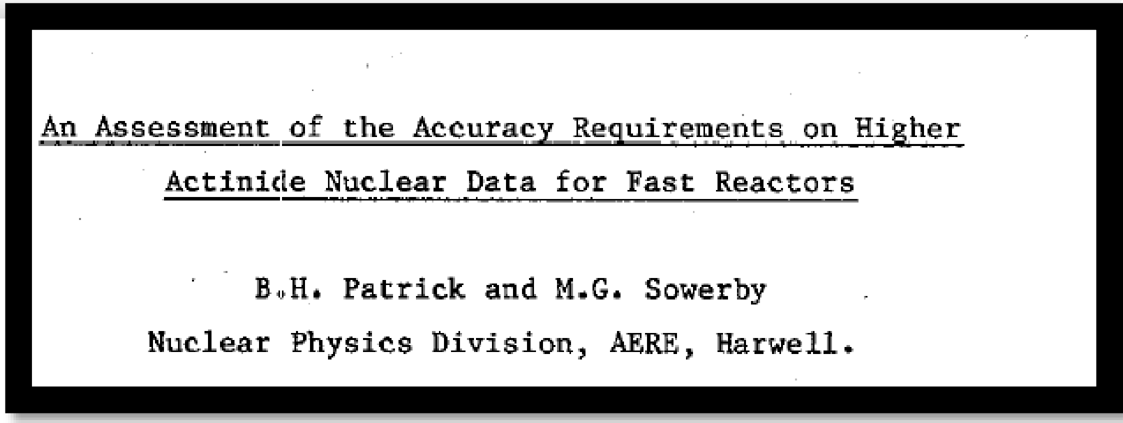
Anne BARREAU
Commissariat à l'énergie atomique
France

Industry surrogate models/response functions



What do we need?





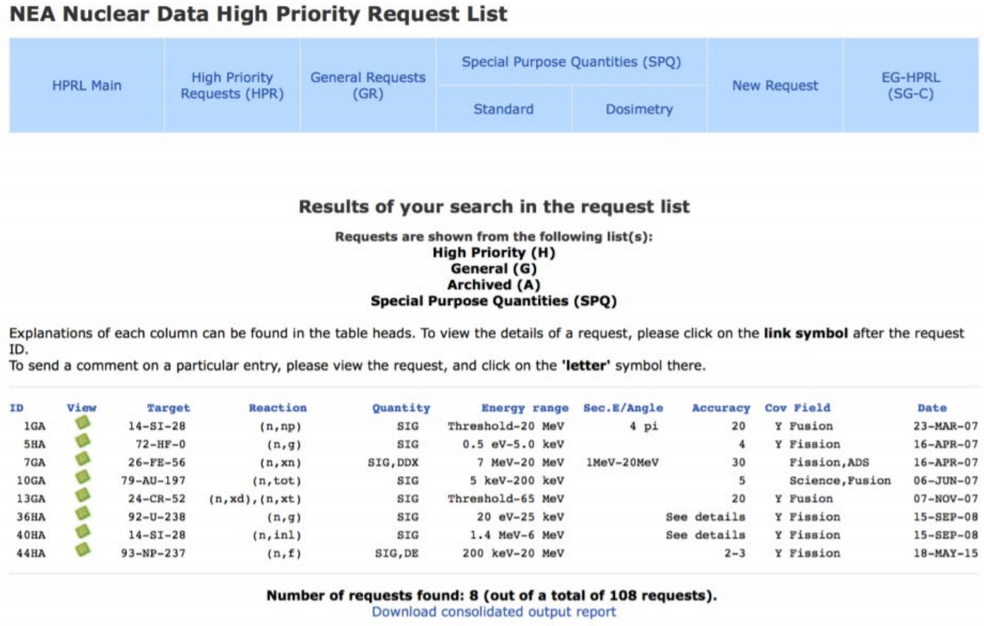
An Assessment of the Accuracy Requirements on Higher Actinide Nuclear Data for Fast Reactors

B.H. Patrick and M.G. Sowerby

Nuclear Physics Division, AERE, Harwell.

Needs for design

Needs for licensing(!)



NEA Nuclear Data High Priority Request List

Results of your search in the request list

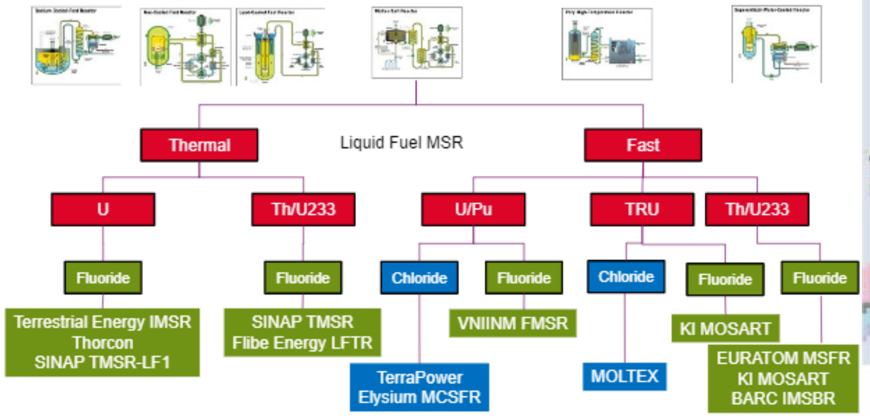
Requests are shown from the following list(s):
High Priority (H)
General (G)
Archived (A)
Special Purpose Quantities (SPQ)

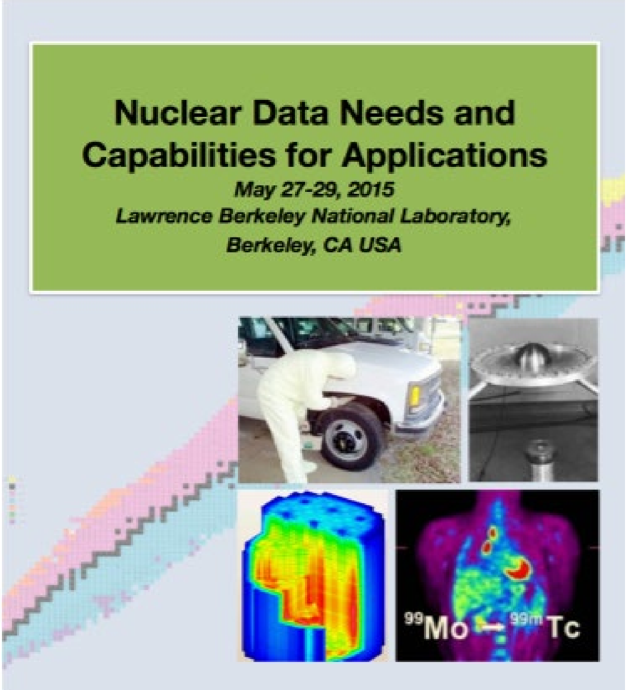
Explanations of each column can be found in the table heads. To view the details of a request, please click on the **link symbol** after the request ID.
To send a comment on a particular entry, please view the request, and click on the **'letter'** symbol there.

ID	View	Target	Reaction	Quantity	Energy range	Sec.E/Angle	Accuracy	Cov	Field	Date
1GA	◆	14-SI-28	(n,np)	SIG	Threshold-20 MeV	4 pi	20	Y	Fusion	23-MAR-07
5HA	◆	72-HF-0	(n,g)	SIG	0.5 eV-5.0 keV		4	Y	Fission	16-APR-07
7GA	◆	26-FE-56	(n,xn)	SIG,DDX	7 MeV-20 MeV	1MeV-20MeV	30		Fission,ADS	16-APR-07
10GA	◆	79-AU-197	(n,tot)	SIG	5 keV-200 keV		5		Science,Fusion	06-JUN-07
13GA	◆	24-CR-52	(n,xd),(n,xt)	SIG	Threshold-65 MeV		20	Y	Fusion	07-NOV-07
36HA	◆	92-U-238	(n,g)	SIG	20 eV-25 keV		See details	Y	Fission	15-SEP-08
40HA	◆	14-SI-28	(n,inl)	SIG	1.4 MeV-6 MeV		See details	Y	Fission	15-SEP-08
44HA	◆	93-NP-237	(n,f)	SIG,DE	200 keV-20 MeV		2-3	Y	Fission	18-MAY-15

Number of requests found: 8 (out of a total of 108 requests).
Download consolidated output report

The challenge faced by the GEN IV MSR systems





Nuclear Data Needs and Capabilities for Applications

May 27-29, 2015
Lawrence Berkeley National Laboratory,
Berkeley, CA USA

U.S. DEPARTMENT OF ENERGY | Office of Science

Conclusions/Recommendations

1. Continue development of tools that give rapid or continuous performance assessments of new libraries.
2. Make serious efforts to address lack of experimental correlations.
3. Reactor physics: create models, compute response functions, apply machine learning; incorporate into testing.
4. Improve response functions computational capability, share response functions.
5. Incorporate legacy experiments (and proprietary data) that underpinned past validation campaigns.
6. Improve usability, uncertainty analysis, trust of other benchmark data (SINBAD, SFCOMPO).
7. Track performance over time.
8. Verification exercises exist for most applications, incorporate these into testing.
9. Collect the needs of new applications and safety community, emphasise the value to industry to provide response functions to the nuclear data community.

Many aspects will be discussed in other talks. I'm looking forward to them!

Fission Experiments at University of Michigan

Sara A. Pozzi, Ph. D.

Professor

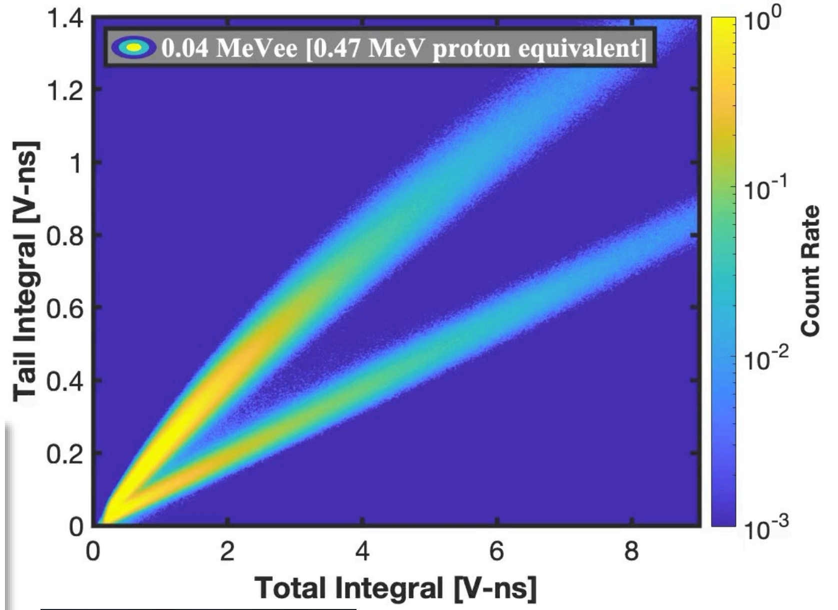
Department of Nuclear Engineering & Radiological Sciences
University of Michigan, Ann Arbor MI, USA

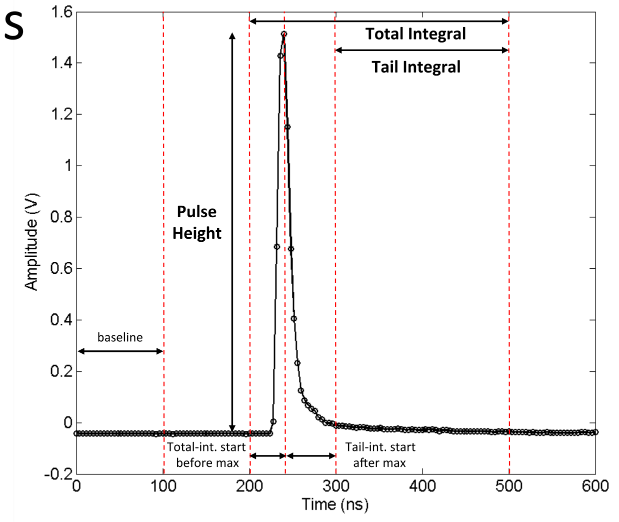
Organic Scintillation Detectors

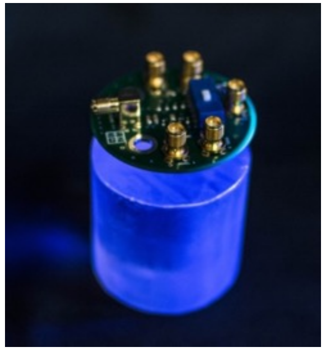
General Characteristics

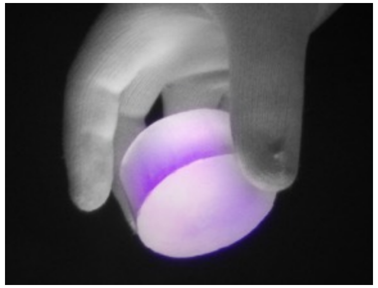
- Benchmark experiments based on organic scintillator systems could provide data in an expanded energy range
- Organic scintillators have several advantages for detecting neutrons and gamma rays
  - Nanosecond-scale response times
  - Response is proportional to the energy deposited
  - Good intrinsic efficiency
  - Pulse shape discrimination
  - Good scalability and low cost

Shielded ^{252}Cf source measured with a 2”x2” stilbene



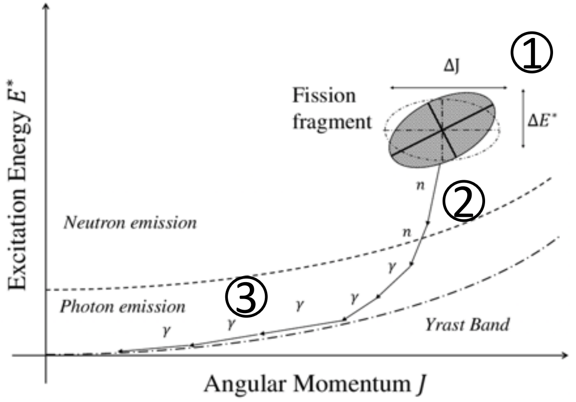




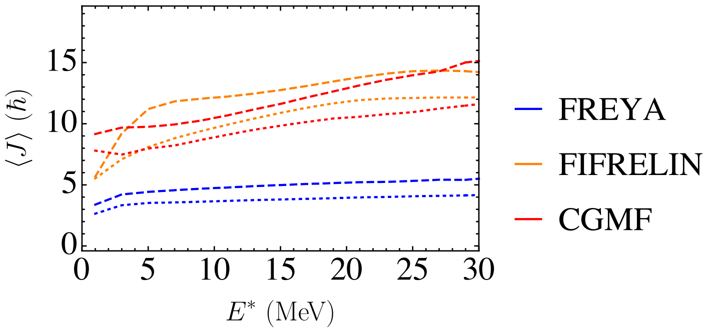


Experiments for Improved Fission Data

Fission fragment physics

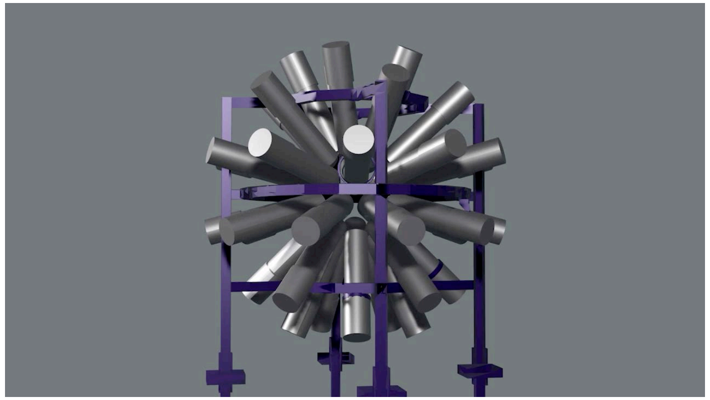


The three stages of fission emission: (1) initial excitation, (2) neutron evaporation, (3) gamma decay.

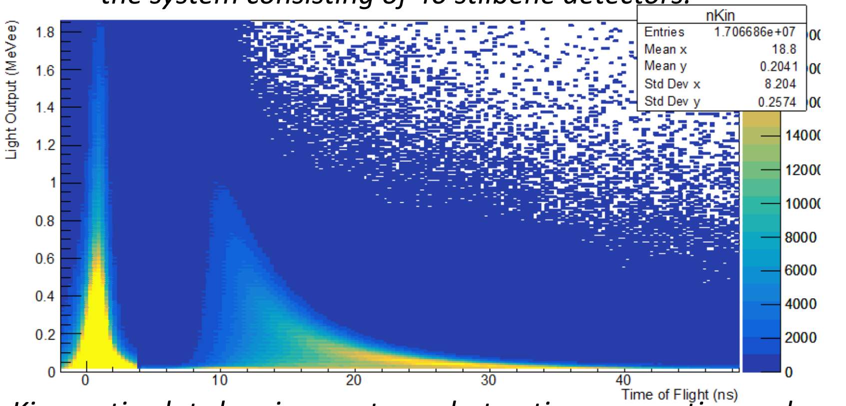


A fragment angular momentum and excitation energy determine the neutron-photon correlations (dotted/dashed: light/heavy fragment).

Low energy neutron emission in ^{252}Cf(sf) at University of Michigan

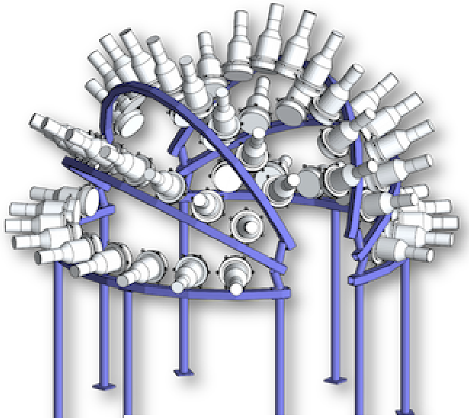


Animation of the FS3 system at Michigan showing the system consisting of 40 stilbene detectors.

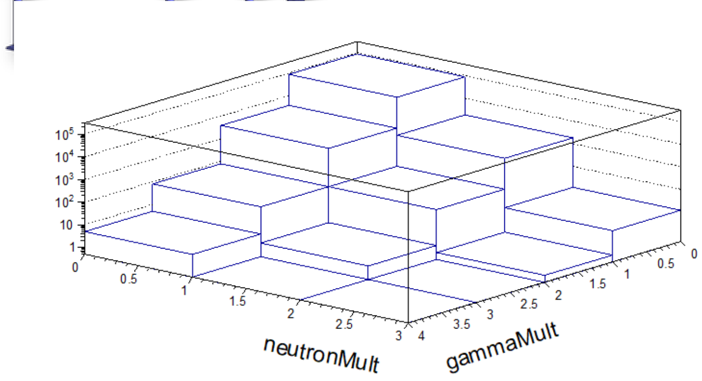


Kinematic plot showing neutron-photon time separation and light output collected with ORNL fission chamber and a 30 keVee (~300 keV proton) detection threshold.

Event-by-event neutron-photon correlations in ^{242}Pu(sf) fission chamber using Chi-Nu at LANL



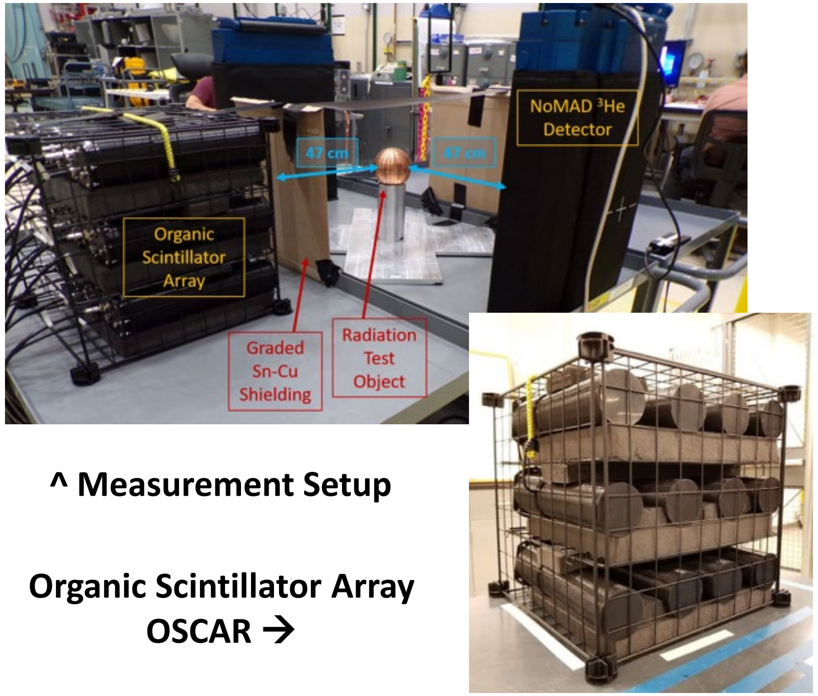
The Chi-Nu spectrometer at LANL-LANSCE, consisting of 54 EJ309 detectors.



Neutron-photon measured multiplicity distribution in ^{242}Pu(sf). Neutron-photon correlations can be determined from this distribution

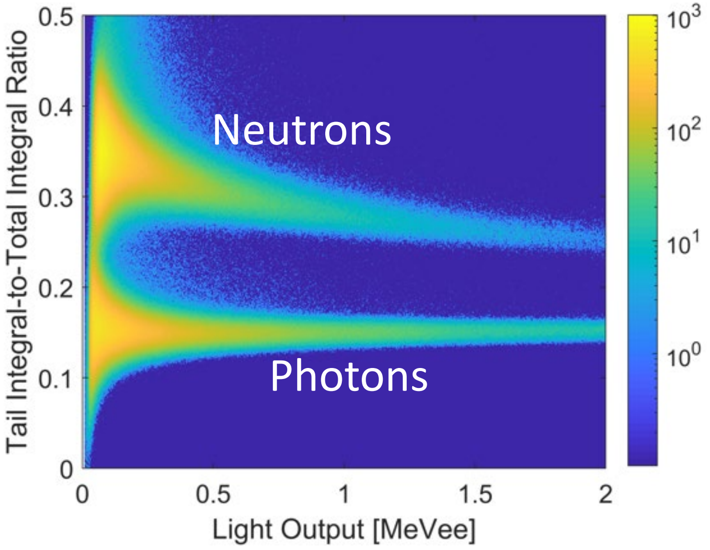
1. M. J. Marcath, R. C. Haight, R. Vogt, M. Devlin, P. Talou, I. Stetcu, J. Randrup, P. F. Schuster, S. D. Clarke, S. A. Pozzi, “Measured and simulated ^{252}Cf(sf) prompt neutron-photon competition”, *Phys. Rev. C 97*, 044622, 2018.
2. S. Marin, V. A. Protopopescu, R. Vogt, M. J. Marcath, S. Okar, M. Y. Hua, P. Talou, P. F. Schuster, S. D. Clarke, S. A. Pozzi, “Event-by-event neutron–photon multiplicity correlations in ^{252}Cf(sf)”, *Nucl. Instr. Meth. A 968*, 163907, 2020.

Subcritical Copper-Reflected Alpha-Phase Plutonium Benchmark using Organic Scintillators

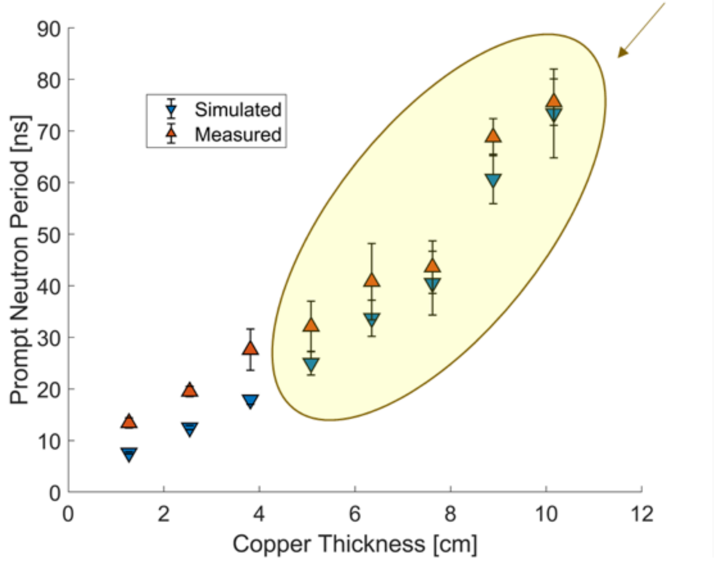


^ Measurement Setup

Organic Scintillator Array OSCAR →



Pulse shape discrimination, 35 keVee (~400 keV proton) detection threshold



Rossi-alpha results.

- SCRαP Benchmark: 4.5 kg of weapons-grade, alpha-phase plutonium reflected by copper (1.27 cm – 10.16 cm)
- Rossi-alpha and Feynman-alpha neutron measurements were performed and independently simulated prompt neutron period
- A rigorous quantification and propagation of measurement uncertainty was developed and validated
- Organic scintillator estimates of the prompt neutron period agree within one-standard-deviation error bars

1. T. Cutler, J. Arthur, J. Hutchinson, S. Walston, G. Keefer, W. Monage, "Copper- and Polyethylene-Reflected Plutonium-Metal-Sphere Subcritical Measurements," NEA/NSC/DOC(95)03/IX, FUND-NCERC-PU-HE3-MULT-003, 2019.
2. M.Y. Hua, J.D. Hutchinson, G.E. McKenzie, B.C. Kiedrowski, M.W. Liemohn, S.D. Clarke, S.A. Pozzi, “Measurement Uncertainty of Rossi-alpha Neutron Experiments,” *Annals of Nuclear Energy 147*, 107672, 2020.

NAVAL NUCLEAR
LABORATORY

Pulsed-Neutron Die-Away (PNDA) Benchmark for Light Water Thermal Scattering

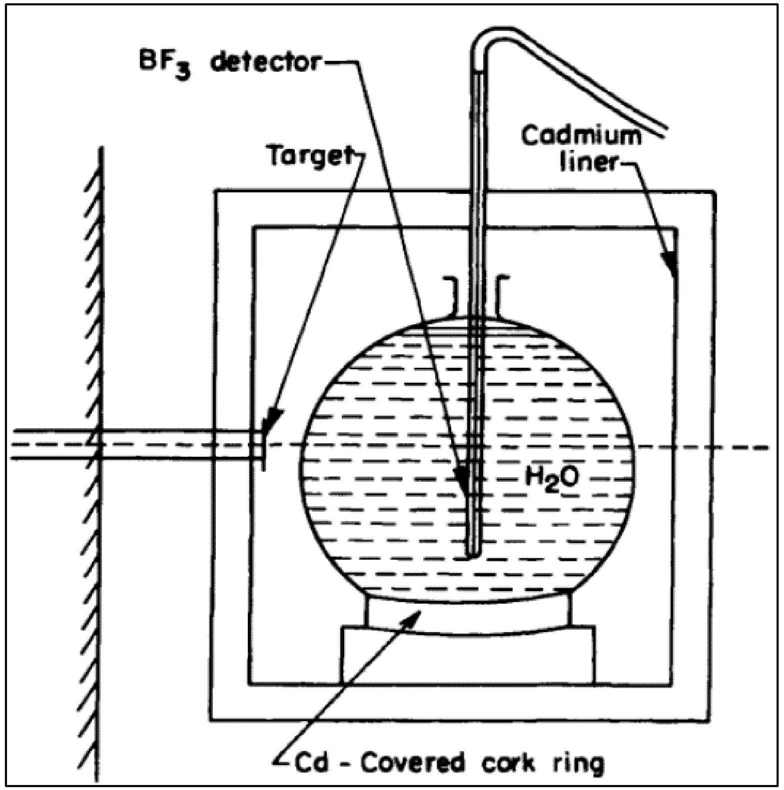
Jesse Holmes

WANDA 2021
January 25 – February 3

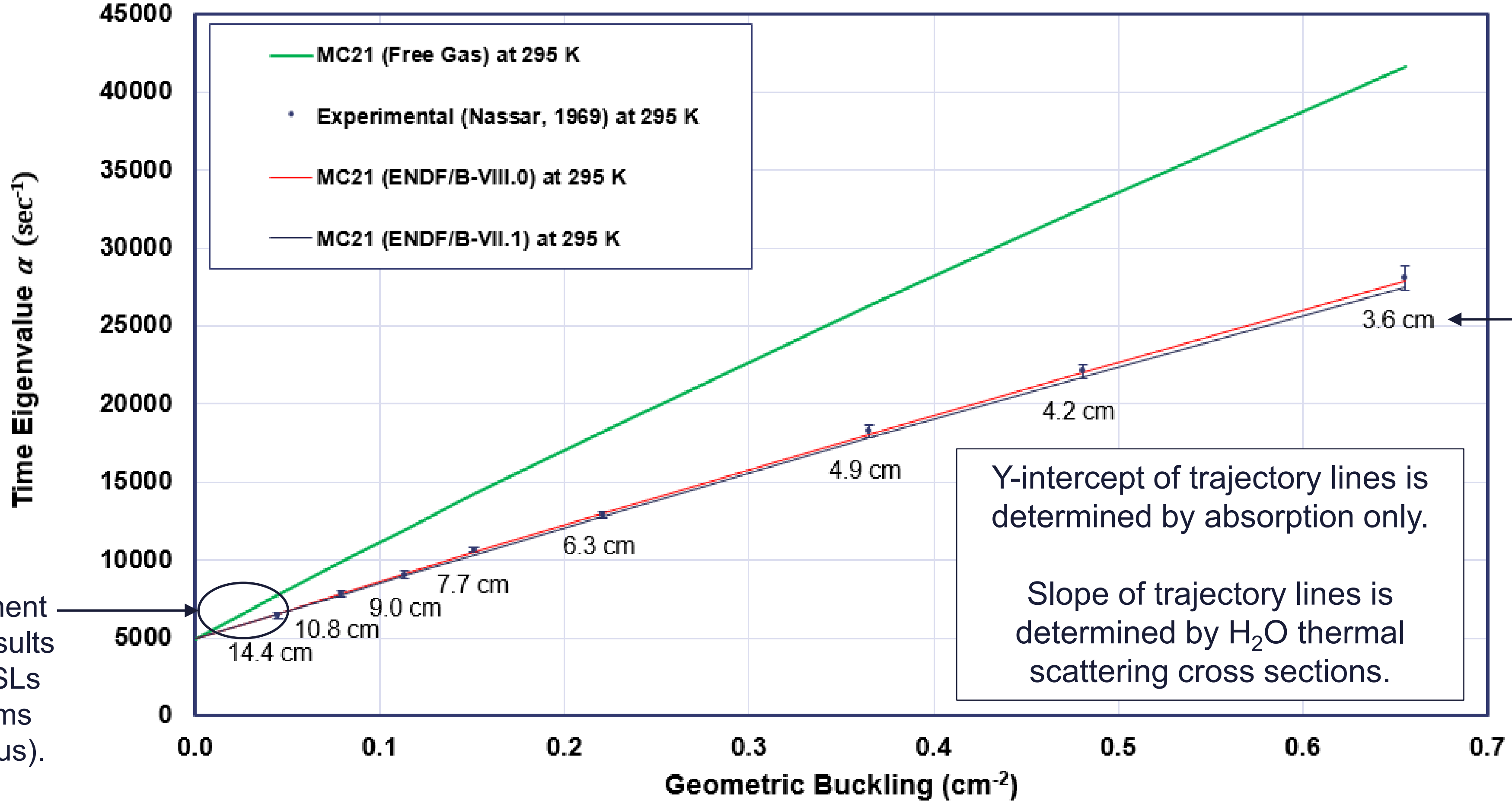
Proposed ICSBEP Volume IX Fundamental Physics Experiment

PNDA Experimental Description
(Nassar and Murphy, *NSE*, Vol. 35, 1969)

- Pulse of 14 MeV neutrons (D+T generator) incident upon 295 K H_2O in spherical Pyrex flasks of various radii, surrounded by cadmium.
- Thermal neutron count rate was recorded as a function of time.
- Once thermal and spatial equilibrium is established, the neutron flux follows the form $\varphi(\boldsymbol{r},t) = \varphi_0(\boldsymbol{r})e^{-\alpha t}$, where α is the fundamental mode time eigenvalue calculated from the recorded count rate data.
- Measured α is a function of radius (geometric buckling), absorption, and integral and differential thermal scattering cross sections.
- Sensitivity to thermal scattering in H_2O, as well as differential scattering cross sections, increases with decreasing radius.
- The primary source of experimental uncertainty is counting statistics. The experiment is simple to model and the α results depend only the absorption and thermal scattering characteristics of H_2O.
- PNDA experiments of this type can be an inexpensive alternative to critical experiments for validation of TSL data.



MC21 PNDA Modeling Results vs. Nassar and Murphy Experiment



Radii of spheres

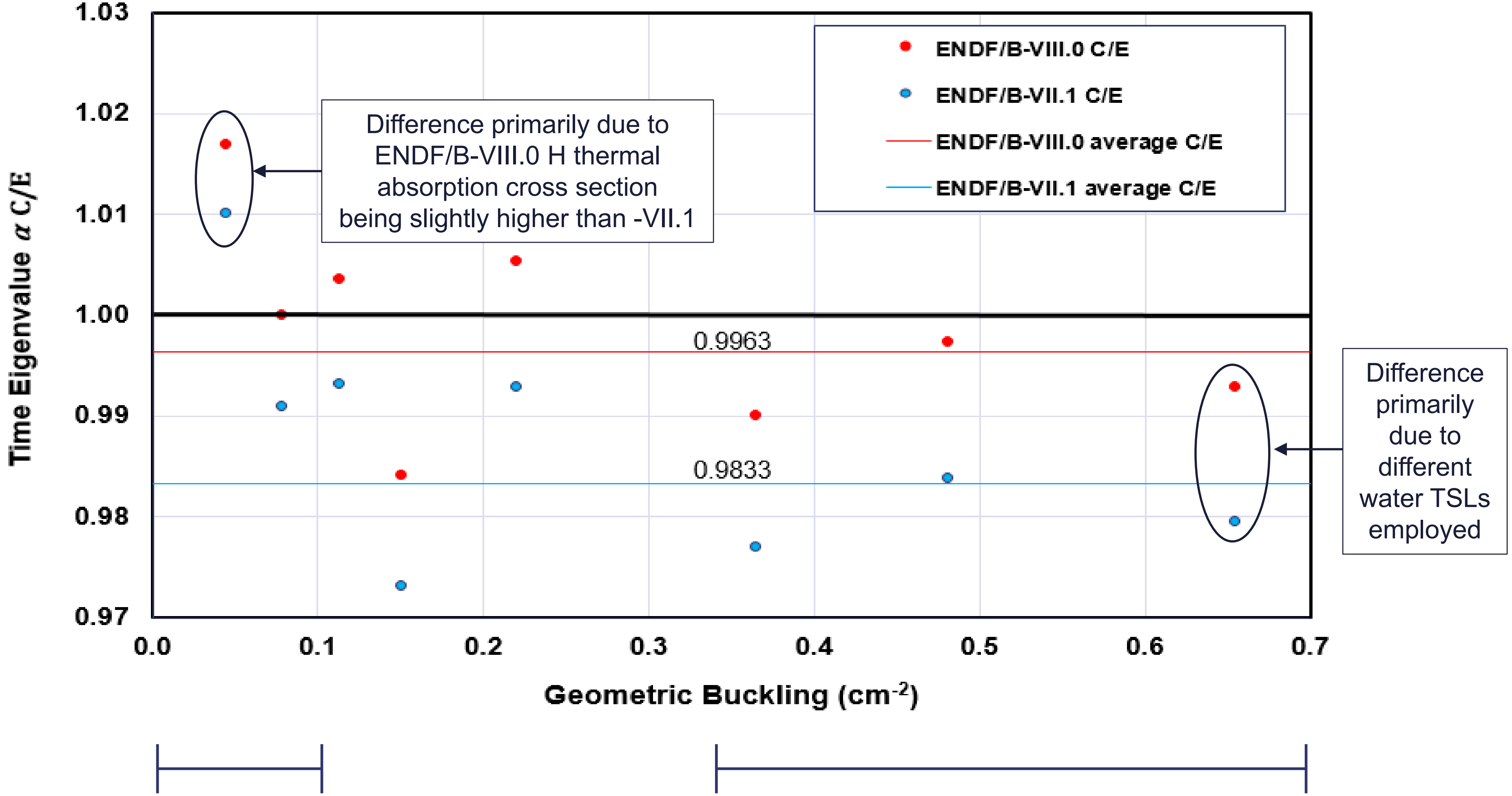
Free gas treatment gives similar results to using H_2O TSLs for larger systems (> ~10 cm radius).

Y-intercept of trajectory lines is determined by absorption only.

Slope of trajectory lines is determined by H_2O thermal scattering cross sections.

Uncertainty bars shown are experimental. MC21 statistical uncertainty is negligible.

MC21 PNDA Modeling Results vs. Nassar and Murphy Experiment



Difference primarily due to ENDF/B-VIII.0 H thermal absorption cross section being slightly higher than -VII.1

Difference primarily due to different water TSLs employed

Insensitive to thermal scattering

Very sensitive to thermal scattering

Experiments with Neutron Induced Neutron Emission

Y. DANON on behalf or the RPI/NNL cross section group

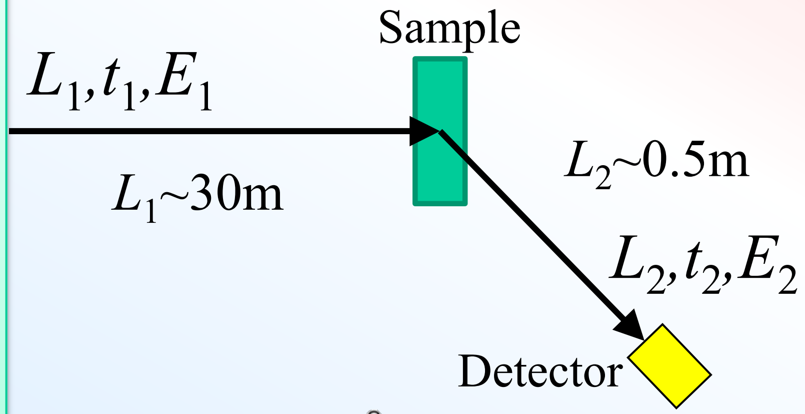
Professor and Director Gaerttner LINAC Center
Nuclear Engineering Program Director
Department of Mechanical, Aerospace and Nuclear Engineering
Rensselaer Polytechnic Institute, Troy, NY, 12180

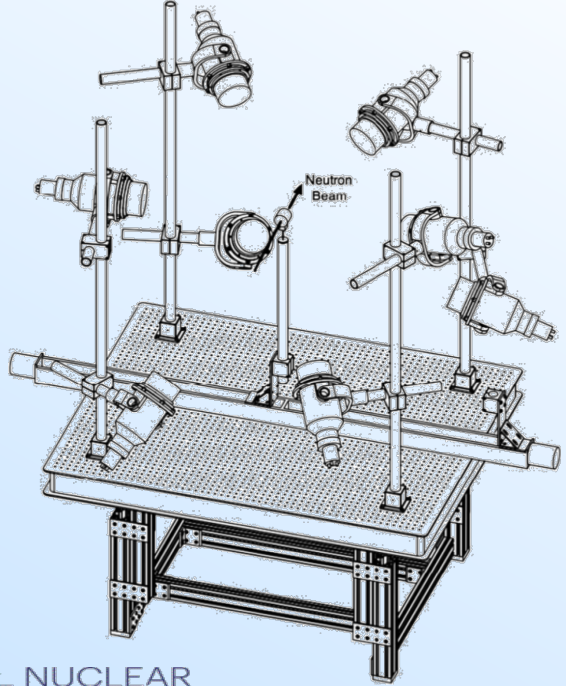
WANDA 2021, January 25 - February 3, 2021, online

Neutron Induced Neutron Emission

How is it done:

1. Use a pulsed “white” neutron beam with a neutron time of flight setup and sample to source distance L_1
2. Position multiple neutron detectors at different angles around the sample at distance L_2
3. Measure neutrons emission from the sample using surrounding detectors
4. Compare the measurements to detailed simulations (use a carbon reference sample)



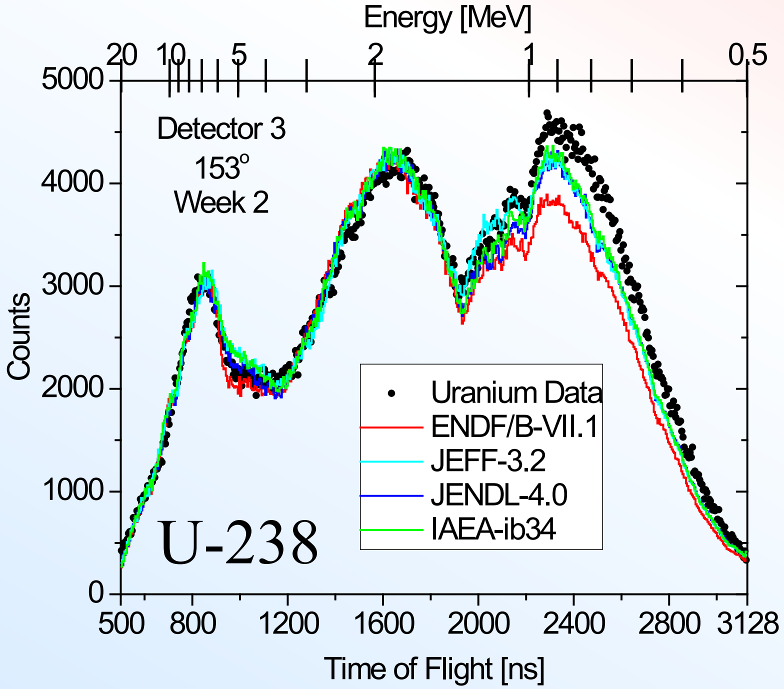


Keep it simple

- Relatively simple experiment
- Can use thick samples to induce more collisions
- Can use different sample geometries
- Use fast or keV neutron detectors

Nuclear Data

- Requires time dependent simulation codes
- Sensitive to the scattering (or fission) cross sections and angular distributions
- Requires good physics in the transport code. (currently fission neutron angular distributions are missing from MCNP)
- Was used to improve U-238 angular distributions and cross section in ENDF/B-8.0



Detector Efficiency Prob. to Interact Prob. to scatter/fission

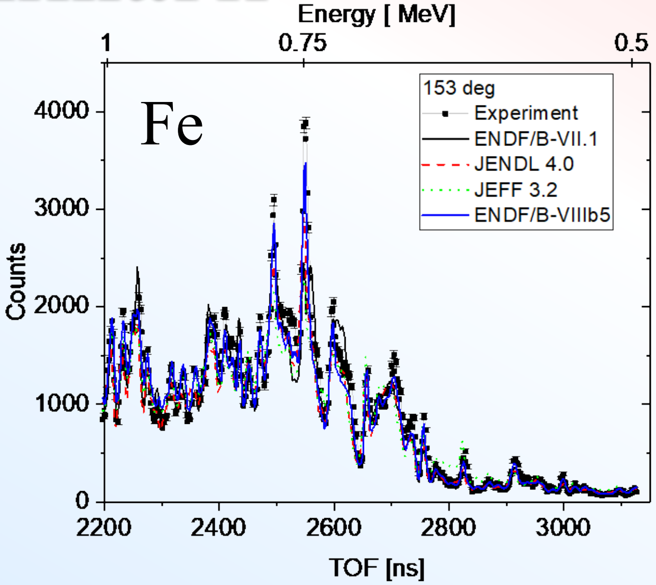
$$Y(E,\varphi) \propto \eta(E')\Phi(E)\left(1-e^{\Sigma_t(E)L}\right)\frac{\sigma_{s,f}}{\sigma_t}\frac{f(E,\varphi)}{2\pi}+Y_{MS}(E)+B(E)$$

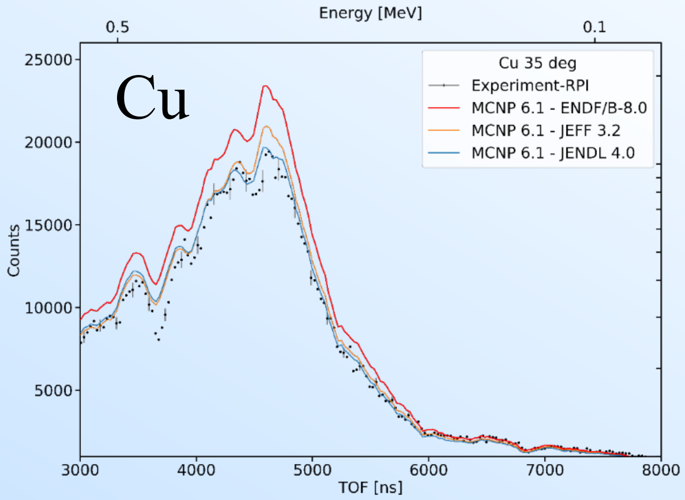
Contributions from:
Multiple scattering
Background and room return

Incident Flux Probability to Scatter in direction φ

Making it a benchmark

- The experimental uncertainty is in the interpretation of the experiment:
  - Neutron flux shape
  - Detector efficiency shape
  - Documentation of geometry
  - Background and room return
  - Gamma contamination
  - Accuracy of carbon reference cross sections
- **Typical systematic uncertainty is of the order of 5%**
- Can be compiled to Shielding Integral Benchmark Archive and Database (SINBAD) or International Criticality Safety Benchmark Evaluation Project (ICSBEP)
- Experiments were performed for Be, Mo, Fe, Pb, Cu, Zr, U-238, U-235, Pu-239





Scattering Related Group Publications

- **Journal**
  - A. M. Daskalakis, E. J. Blain, B. J. McDermott, R. M. Bahran, Y. Danon, D. P. Barry, R. C. Block, M. J. Rapp, B. E. Epping and G. Leinweber, **"Quasi-differential elastic and inelastic neutron scattering from iron in the MeV energy range"**, Annals of Nuclear Energy, vol. 110, pp. 603 - 612, 2017.
  - E. Blain, A. Daskalakis, R.C. Block, D. Barry, Y. Danon, "***A method to measure prompt fission neutron spectrum using gamma multiplicity tagging***", Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 805, Pages 95-100, 1 January 2016, (invited: Special Issue in memory of Glenn F. Knoll).
  - A.M. Daskalakis, R.M. Bahran, E.J. Blain, B.J. McDermott, S. Piela, Y. Danon, D.P. Barry, G. Leinweber, R.C. Block, M.J. Rapp, R. Capote, A. Trkov, "***Quasi-differential neutron scattering from 238U from 0.5 to 20 MeV***", Annals of Nuclear Energy, Volume 73, Pages 455-464, November 2014.
  - R. Capote, A. Trkov, M. Sin M. Herman, A. Daskalakis, and Y. Danon, "***Physics of Neutron Interactions with ^{238}U: New Developments and Challenges***", Nuclear Data Sheets 118, 26–31, (2014).
  - D. P. Barry, G. Leinweber, R. C. Block, and T. J. Donovan, Y. Danon, F. J. Saglime, A. M. Daskalakis, M. J. Rapp, and R. M. Bahran, "***Quasi-differential Neutron Scattering in Zirconium from 0.5 MeV to 20 MeV***", Nuclear Science and Engineering, 174, 188–201, (2013).
  - R.Dagan, B. Becker, Y. Danon, "***A complementary Doppler Broadening formalism and its impact on nuclear reactor simulation***", Kerntechnik 3, Page 185-189, (2011).
  - Frank J. Saglime III, Yaron Danon, Robert C. Block, Michael J. Rapp, Rian M. Bahran, Greg Leinweber, Devin P. Barry, Noel J. Drindak, and Jeffrey G. Hoole, "***A system for differential neutron scattering experiments in the energy range from 0.5 to 20 MeV***", Nuclear Instruments and Methods in Physics Research Section A, 620, Issues 2-3, Pages 401-409, (2010).
- **Conference Proceedings**
  - Y. Danon, "**Experiments with Neutron Induced Neutron Emission from U-235, Pu-239, and Graphite**", 2019 International Conference on Nuclear Data for Science and Technology (ND2019), Beijing China, May 2019.
  - Daskalakis, Adam, Blain, Ezekiel, Leinweber, Gregory, Rapp, Michael, Barry, Devin, Block, Robert and Danon, Yaron, "**Assessment of beryllium and molybdenum nuclear data files with the RPI neutron scattering system in the energy region from 0.5 to 20 MeV**", EPJ Web Conf., vol. 146, pp. 11037, 2017
  - R. Capote, A. Trkov, M. Sin, M. W. Herman, P. Schillebeeckx, I. Sirakov, S. Kopecky, D. Bernard, G. Noguere, A. Daskalakis and Y. Danon, "**U-238 evaluation and validation of the neutron induced reactions up to 20 MeV**", ND 2016 International Conference on Nuclear Data for Science and Technology, Bruges, Belgium,, 11-16, September 2016
  - K. Mohindroo, E. Blain, Y. Danon, S. Mosby and M. Devlin, "**Quasi-differential neutron induced neutron emission reaction measurements at WNR**", Transactions of the American Nuclear Society, vol. 115, pp. 701-703, 2016
  - A. M. Daskalakis, E. J. Blain, B. J. McDermott, R. M. Bahran, Y. Danon, D. P. Barry, G. Leinweber, M. J. Rapp, R. C. Block, "***Separation of Neutron Inelastic and Elastic Scattering Contribution from Natural Iron using Detector Response Functions***", 12th International Topical Meeting on Nuclear Applications of Accelerators (AccApp '15), Washington D.C., November 2015.
  - Amanda E. Youmans, J. Brown, A. Daskalakis, N. Thompson, A. Welz, Y. Danon, B. McDermott, G. Leinweber, M. Rapp, "***Fast Neutron Scattering Measurements with Lead***", 12th International Topical Meeting on Nuclear Applications of Accelerators (AccApp '15), Washington D.C., November 2015
  - Y. Danon, L. Liu, E.J. Blain, A.M. Daskalakis, B.J. McDermott, K. Ramic, C.R. Wendorff, D.P. Barry, R.C. Block, B.E. Epping, G. Leinweber, M.J. Rapp, T.J. Donovan, "***Neutron Transmission, Capture, and Scattering Measurements at the Gaerttner LINAC Center***", Transactions of the American Nuclear Society, Vol. 109, p. 897-900, Washington, D.C., November 10–14, 2013
  - Adam M. Daskalakis, Rian M. Bahran, Ezekial J. Blain, Brian J. McDermott, Sean Piela, Yaron Danon, Devin P. Barry, Greg Leinweber, Robert C. Block, Michael J. Rapp, "***Quasi-Differential Neutron Scattering Measurements of ^{238}U***", ANS Winter Meeting and Nuclear Technology Expo, American Nuclear Society, San Diego CA. November 11-15, 2012.
  - Frank J. Saglime III, Yaron Danon, Robert C. Block, Michael J.Rapp, and Rian M. Bahran, Devin P. Barry, Greg Leinweber, and Noel J. Drindak, "***High Energy Neutron Scattering Benchmark of Monte Carlo Computations***", International Conference on Mathematics, Computational Methods & Reactor Physics (M&C 2009), Saratoga Springs, New York, May 3-7, 2009, on CD-ROM, American Nuclear Society, LaGrange Park, IL (2009).
  - Frank J. Saglime III, Yaron Danon, Robert Block, "***Digital Data Acquisition System for Time of Flight Neutron Beam Measurements***", The American Nuclear Society's 14th Biennial Topical Meeting of the Radiation Protection and Shielding Division, p. 368, Carlsbad New Mexico, USA. April 3-6, 2006.

NAVAL NUCLEAR
LABORATORY

The Atlas of Gamma-ray Spectra from the Inelastic Scattering of Reactor Fast Neutrons

Amanda Lewis[1], Lee Bernstein[2,3], Aaron Hurst[3]

[1] Naval Nuclear Laboratory
[2] Lawrence Berkeley National Laboratory
[3] University of California, Berkeley

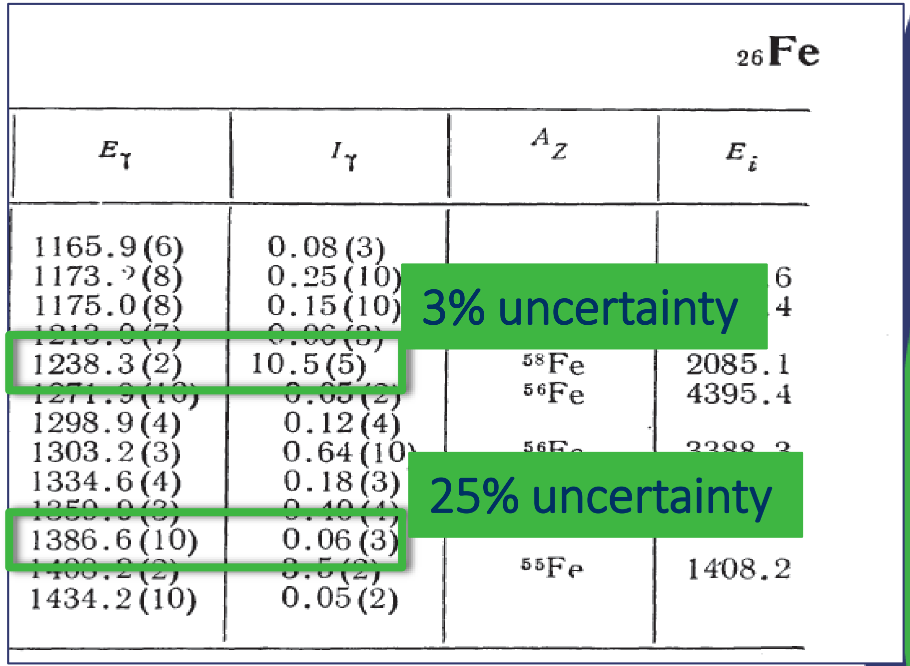
The “Baghdad Atlas” [1] is a large compilation of identified gamma-ray intensities from a fast reactor spectrum

- The neutron source was the Al-Tuwaitha research facility outside of Baghdad in the 1970s
  - A low-energy filter was used to simulate a fast reactor spectrum
- All intensities were measured in reference to the 847 keV gamma ray in ^{56}Fe
- A single Ge(Li) detector at 90° measured the gamma rays from 105 targets
- Uncertainties
  - Flux
  - Statistics
  - Detector efficiency
  - Non-linearity in energy
  - Gamma-ray self-absorption
  - Sample

Flux — No model of the reactor, so this is determined by fitting

Statistics, Detector efficiency, Non-linearity in energy, Gamma-ray self-absorption — Provided by the experimentalists (at 2-sigma)

Sample — Given with the normalization to ^{56}Fe



$_{26}$**Fe**

E_γ	I_γ	^AZ	E_i
1165.9(6)	0.08(3)		
1173.?(8)	0.25(10)	[illegible]	[illegible].6
1175.0(8)	0.15(10)	[illegible]	[illegible].4
[illegible]	[illegible]		
1238.3(2)	10.5(5)	^{58}Fe	2085.1
1271.9(10)	0.05(2)	^{56}Fe	4395.4
1298.9(4)	0.12(4)		
1303.2(3)	0.64(10)	^{56}Fe	3388.3
1334.6(4)	0.18(3)		
[illegible]	[illegible]		
1386.6(10)	0.06(3)		
1408.2(2)	3.5(2)	^{55}Fe	1408.2
1434.2(10)	0.05(2)		

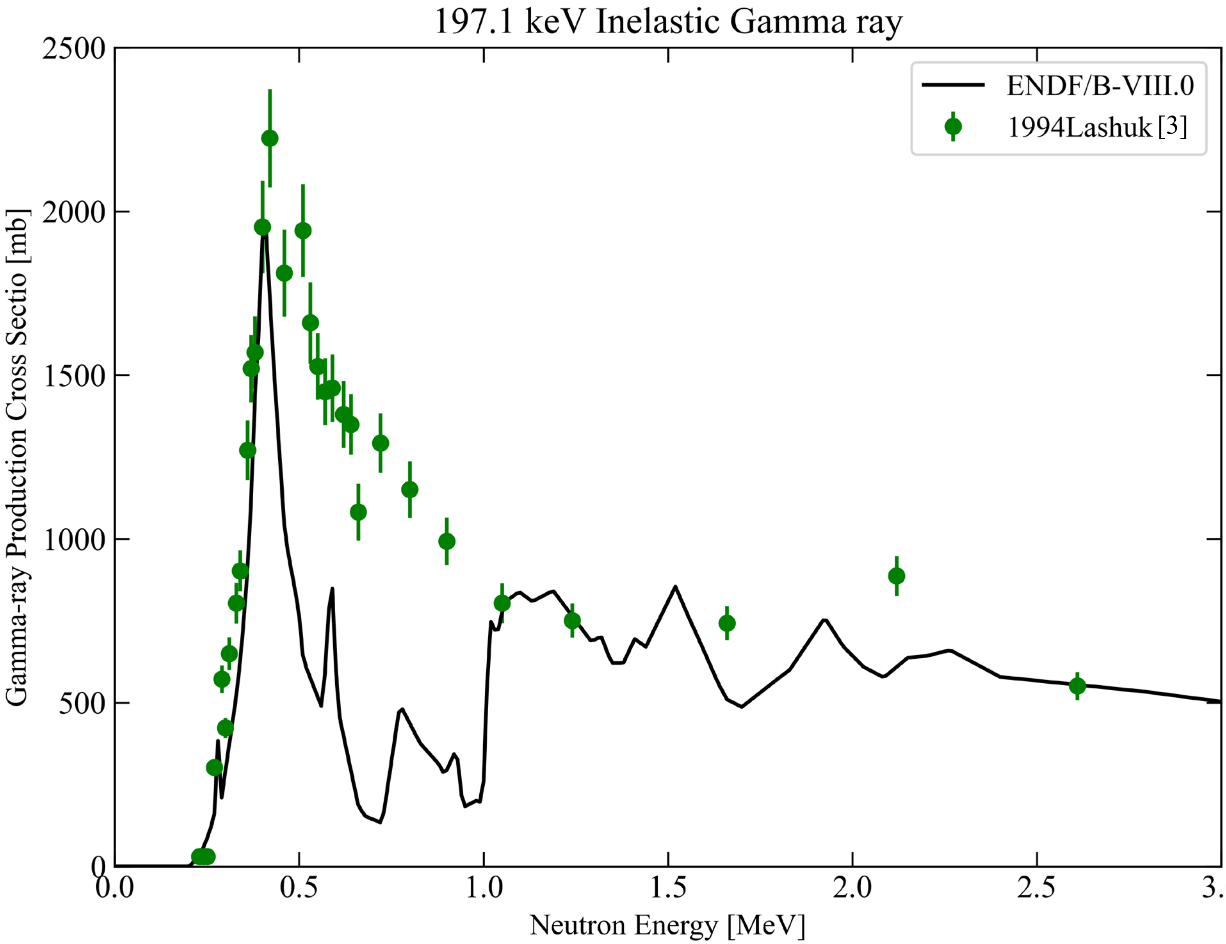
3% uncertainty

25% uncertainty

[1] A. M. Demidov, et. al., Atlas of Gamma-ray Spectra from the Inelastic Scattering of Reactor Fast Neutrons, Moscow, Atomizdat (1978)

The Baghdad Atlas provides a broad ability to uncover problems in evaluated inelastic cross sections

- The Atlas tests elastic and inelastic scattering and discrete and statistical structure
- ^{19}F inelastic scattering was shown to be problematic using machine learning on k_{eff} benchmarks [2]
- The Atlas can also find the problem, based on the 197.1 keV gamma:
  - With a preliminary flux shape, the ENDF/B-VIII.0 value is **around 50% lower** than the Atlas value.



[2] Neudecker, et. al., NDS 167 (2020)
[3] EXFOR entry 41186

The Atlas data tables are already available and the flux will be published soon

- A digitized version of the database is available at nucleardata.berkeley.edu/atlas

- A future publication will detail the flux shape that should be used
  - We don’t have an MCNP input – the setup is not well characterized
  - Instead, the flux shape is fit based on the ^{56}Fe values

- A new database should be developed for “quasi-differential” benchmarks
  - Differential in reaction, but integral in energy
  - More benchmarks like the Baghdad Atlas need to be created, with:
    - More modern technology
    - Well-characterized neutron sources and experimental setups
    - Neutron spectra that are directly relevant to applications
      - The ENDF format does not allow for direct calculation of gamma-ray cross sections to compare to the Atlas values for many isotopes

NC STATE UNIVERSITY

RADIANS

Subcritical Neutron Multiplicity Counting Experiments Applied to Nuclear Data Adjustment

John Mattingly

North Carolina State University

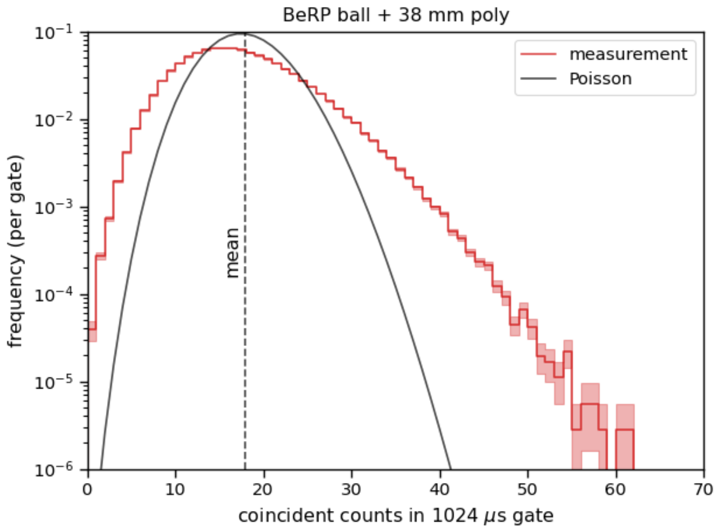
Subcritical neutron multiplicity counting

- Neutron multiplicity counting (NMC) accumulates the distribution of coincident neutron counts

- The example used in this talk is a measurement of the BeRP ball reflected by polyethylene
  - 4.4-kg weapons-grade plutonium (WGPu) metal
  - Bare and reflected by polyethylene up to 150 mm thick
  - Measured using LANL nPod ^{3}He neutron multiplicity counter
  - Available in the Shielding and Integral Benchmark Archive and Database (SINBAD package no. NEA-1517/92)

- The NMC distribution measured from a multiplying system is broader than a Poisson distribution
- The higher moments (variance, skewness, kurtosis…) are more sensitive than the mean to changes in the nuclear cross sections (σ_f, σ_c, and σ_s) and other parameters (χ, $\bar{\nu}$, $\nu(\nu-1)$, etc.)


Polyethylene-reflected WGPu metal sphere



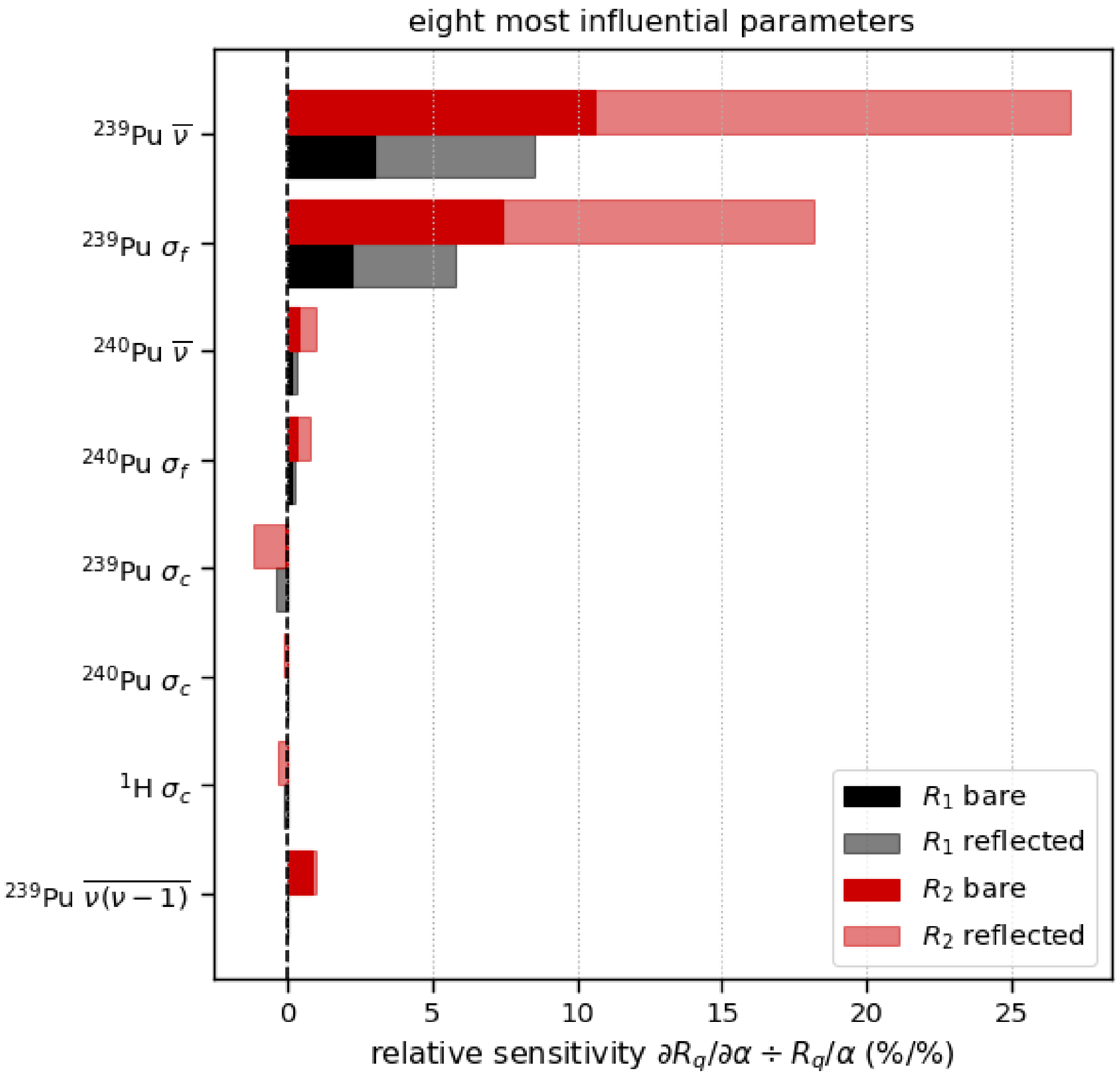
Adjoint sensitivity analysis

- NMC measurements have not been previously used for nuclear data evaluation because there was no efficient method to estimate their sensitivity to energy-dependent cross sections and other transport parameters

- Recently, NCSU developed a new adjoint-based first-order sensitivity analysis method to estimate sensitivities for higher-order NMC moments

- This also enables propagation of covariances in nuclear data onto uncertainties in the calculated moments

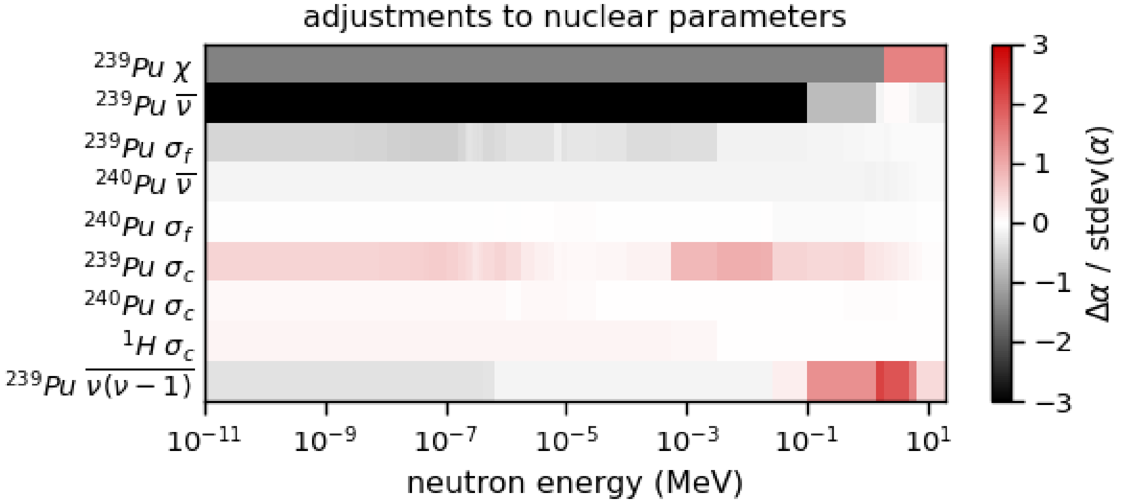
- Finally, it enables nuclear data adjustment using NMC measurements

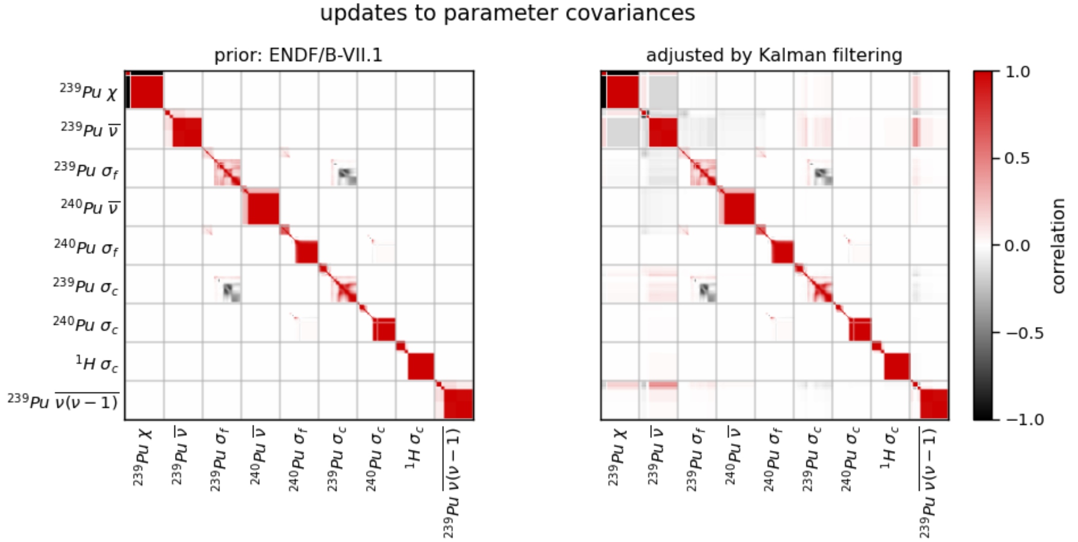


Nuclear data adjustment

- Bayesian methods can be used with NMC measurements for nuclear data adjustment
  - An existing nuclear data evaluation is treated as a prior estimate of the mean value and covariance of the transport parameters
  - A Bayesian method updates the parameter values and covariances to minimize the error between the measured and calculated NMC moments

- The example shown at right used extended Kalman filtering (EKF), but there are many alternative methods for data adjustment





Summary

- Subcritical NMC measurements accumulate the frequency distribution of coincident neutron counts
- Their higher-order moments are more sensitive than the mean count rate to variations in nuclear cross sections and other transport parameters

- It is now possible to estimate the moments’ sensitivity to energy-dependent nuclear data using first-order adjoint sensitivity analysis
- Nuclear data values and covariances can be adjusted using Bayesian inference to minimize error between measured and calculated NMC moments

- Existing subcritical NMC benchmark measurements are plentiful, and new benchmarks are relatively simpler than critical benchmarks to plan and execute
- The benchmarks do not easily fit into the International Criticality Safety Benchmark Experiment Program (ICSBEP) framework, which is principally structured to evaluate uncertainties in k_{eff}

THE CENTRALITY OF VALIDATION

“Validation as a Three-Body Problem”

Dr. Jerry N. McKamy
DOE Nuclear Criticality Safety Program Manager, Retired
Spectra Tech Senior Criticality Safety Consultant

OUTLINE

- Validation as a Three Body Problem
- History/Background of Validation: Transforming from “prototype” to tests of underlying nuclear data.
- Rise of and importance of S/U; Transitioning from qualitative to quantitative area of applicability
- CeDT Process Developed and Applied To Ensure Which of the Underlying Problems are Targeted with Sufficient Precision and Accuracy to be effective
- Wrap Up/Summary

VALIDATION AS A THREE BODY PROBLEM

- The calculated observables coming out of a Monte-Carlo code depend upon:
  - The physics and calculations of the code being accurate with no errors;
  - Having all needed differential nuclear data measured with known precision; and,
  - The evaluated nuclear data files used by the code accurately representing the differential nuclear data.
- Every application of Monte-Carlo to a nuclear observable MUST have a validation system that verifies all the necessary conditions above are met and can produce a result of the desired precision and accuracy.
- Evaluated nuclear data files contain compensating errors and these are reaction channel and energy dependent. Slight changes in the neutron energies can remove the undetected compensating error.
- Flying blind can produce unacceptably large and unquantified errors in calculated observables.

A BRIEF HISTORY OF VALIDATION

- ANSI/ANS-8.1 requires that criticality safety limits be based on direct comparison to experiment data or on computational methods validated by experiment data.
- 1943-1969 Era: Direct comparison to prototype integral experiment dominates (e.g. underground nuclear weapons testing, Pajarito Site at LANL, etc.).
- 1969-1985 Era: Prototype integral experiments and Monte-Carlo co-equal. Every nuclear weapons site had a critical mass lab (Hanford, LLNL, LANL, ORNL, and Rocky Flats).
- 1985-Present Era: Monte-Carlo dominates with validation focused on precision and accuracy of underpinning basic and evaluated nuclear data (last underground nuclear test was in 1992; last critical mass lab standing was Pajarito Site by 1994).
- 1990’s brings the end of nuclear structure investigations as active university research areas. Basic differential nuclear physics data frozen in time as is nuclear theory. Everything has NOT been measured and what has been measured was NOT driven to the accuracy and precision required to produce a given end uncertainty in a modern code-calculated observable.

THE REFORMATION OF VALIDATION

- 1985 – Anderson and McKamy at Rocky Flats make the following observations:
    - Criticality experiments for validation must focus on testing the energy dependent neutron cross-sections in the application.
    - All extant validation experiments can be characterized as either purely thermal, purely fast, or a coupled fast-slow system. No tests of the intermediate energies exist.
    - Experimental uncertainties of existing integral data are at least 2% in k_{eff} and must be reduced to produce meaningful tests of underlying nuclear data.
    - Propose true intermediate energy integral experiments (NESVEX)
- 1992 Rocky Flats Organizes the "Area(s) of Applicability Workshop" under the leadership of Dr. Paul Felsher and Dr. Sean Monahan
- 1992 DOE Defense Programs (Chung) establishes the ICSBEP.

THE CASE FOR INTERMEDIATE ENERGY EXPERIMENTS

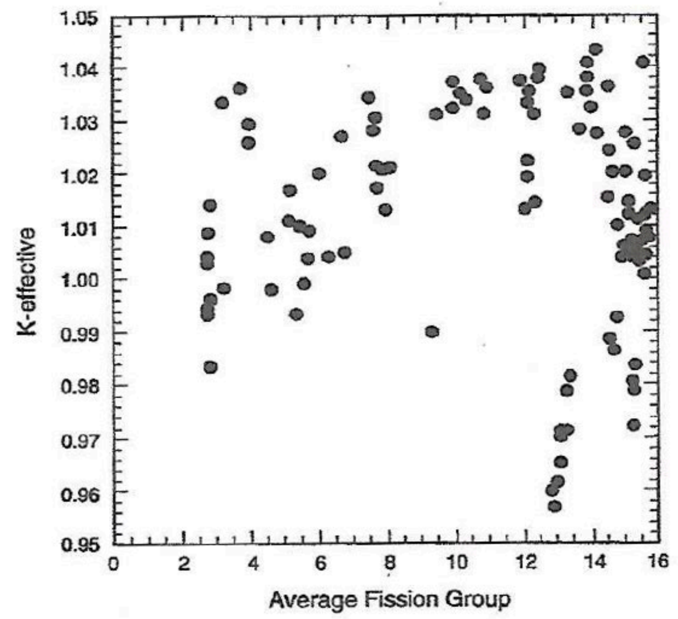


Figure 3 - Results for 110 plutonium critical experiments, with the average energy causing fission calculated as defined in the text. Identified results are observed for uranium critical experiments.

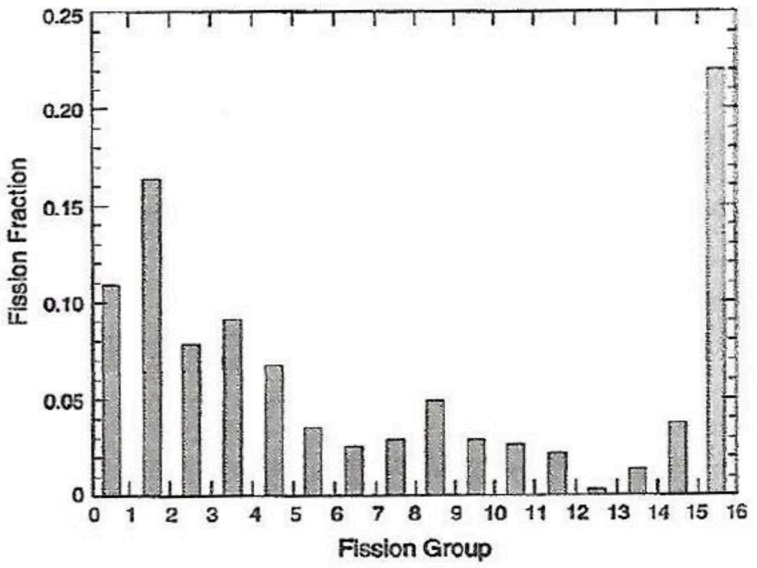


Figure 4 - Fission-causing spectrum for a plutonium critical experiment with an average energy of 7.7. The fission-causing spectrum is dominated by groups 1 through 5 and groups 15 and 16, where 78% of the fissions occur.

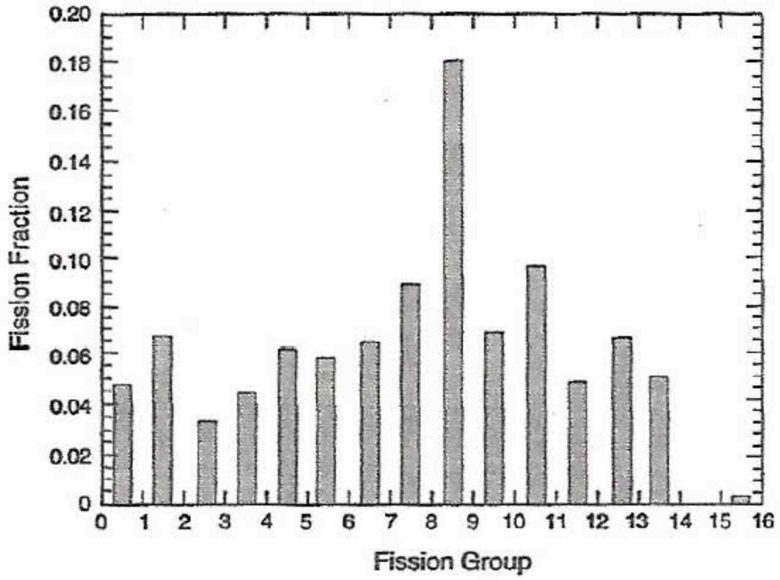
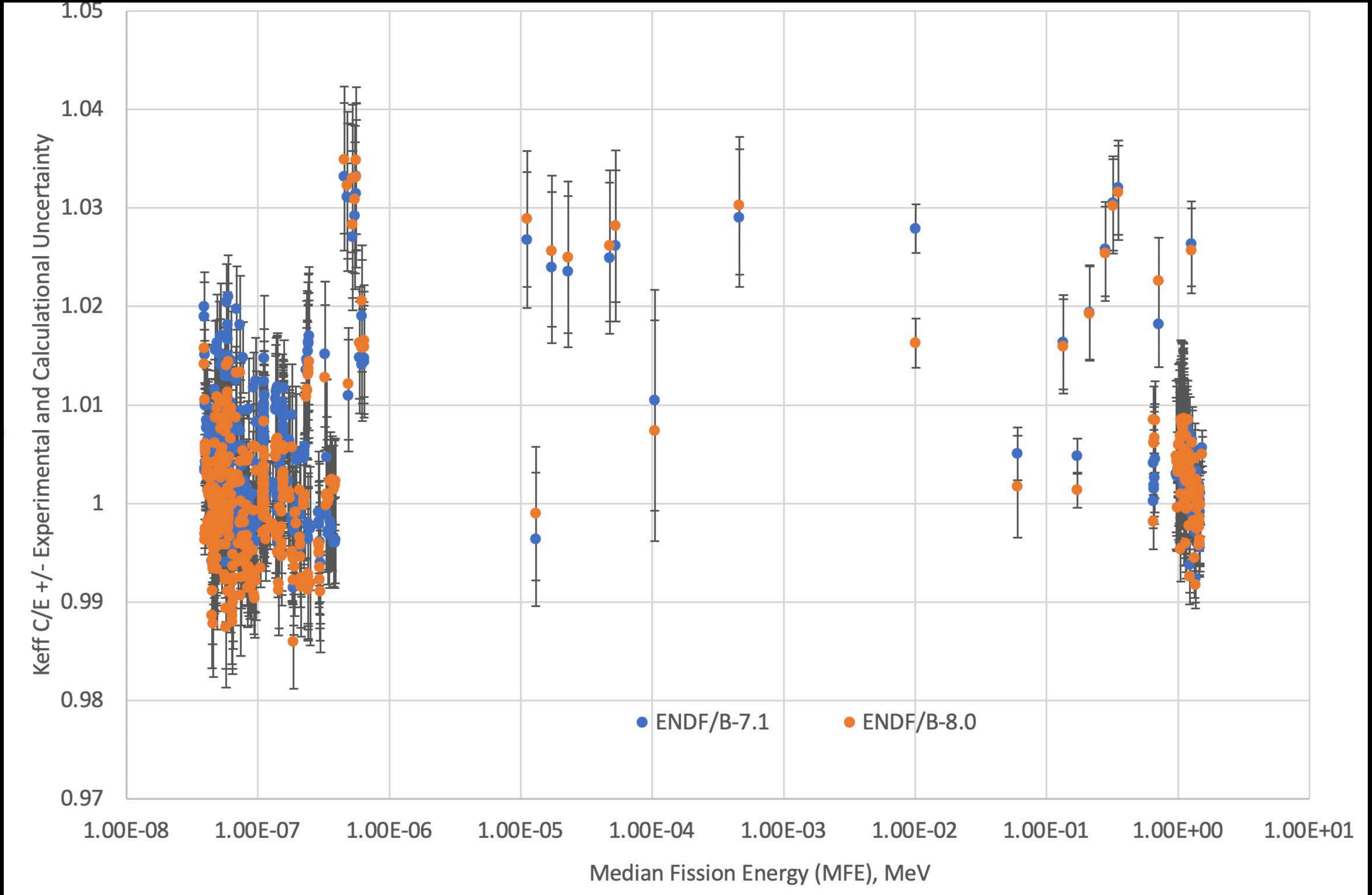


Figure 7 - A typical fission-causing spectrum for a proposed plutonium experiment with an average energy of 8.1. In this example, 74% of the fissions take place in groups 6 through 14.

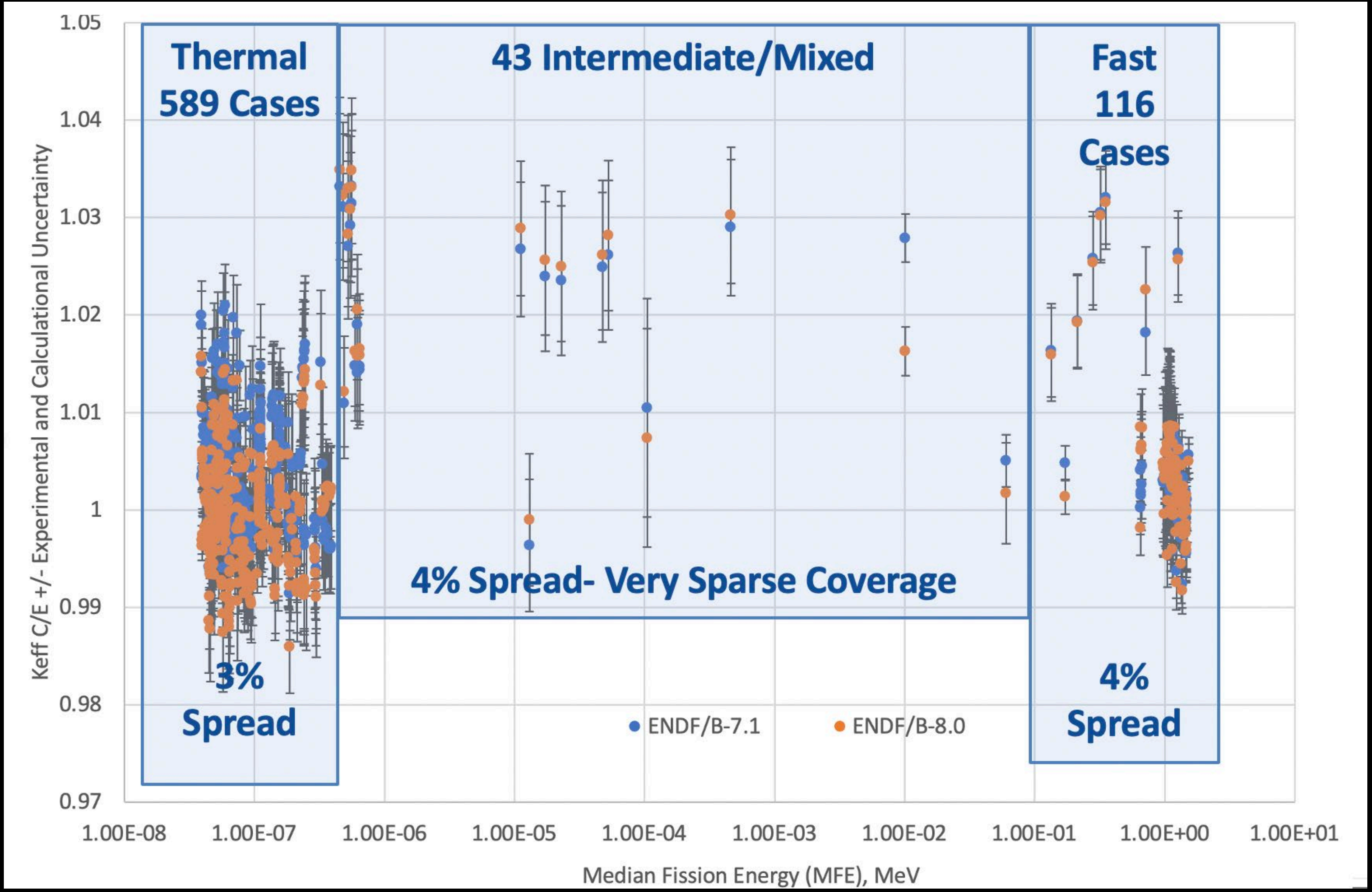
"Validation Experiments In Nuclear Criticality Safety," R.E. Anderson & J.N. McKamy, Proceedings of the Topical Meeting on Physics and Methods in Criticality Safety, 1993

INTERNATIONAL CRITICALITY SAFETY BENCHMARK EVALUATION PROJECT- 748 PLUTONIUM BENCHMARKS



Benchmarks calculated with COG10 in 2019 by LLNL, C/E plotted versus Median Fission Energy (MFE)

INTERNATIONAL CRITICALITY SAFETY BENCHMARK EVALUATION PROJECT- 748 PLUTONIUM BENCHMARKS



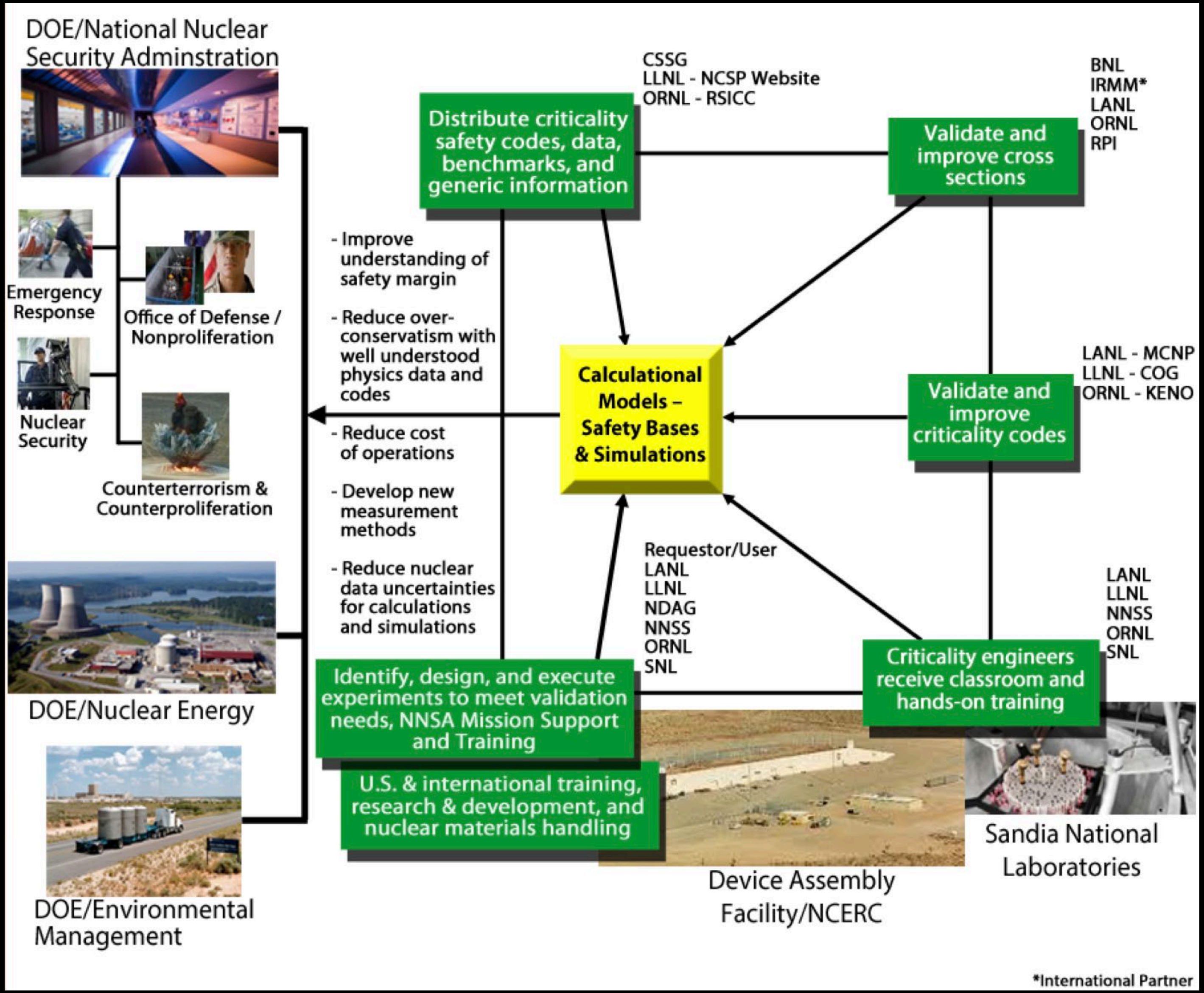
Benchmarks calculated with COG10 in 2019 by LLNL, C/E plotted versus Median Fission Energy (MFE)

FROM QUALITATIVE TO QUANTITATIVE

- 1993 – DNFSB Recommendation 93-2 preserves Pajarito Site and prevents DOE from eliminating integral critical experiment capability. Thank you Dr. Herb Kouts!!
- 1997 – DNFSB Recommendation 97-2 broadens 93-2 to include the overall infrastructure and pipeline supporting criticality safety including one specific recommendation to develop a capability to develop and share data that are not plant/site/process specific.
- DOE developed the AROBCAD (AReas Of Bounding Curves And Data) initiative at ORNL under the leadership of Calvin Hopper. This gave birth to quantitative sensitivity and uncertainty analysis by reaction channel and neutron energy for characterizing applications and corresponding benchmark experiments. This evolved into what we know as TSUNAMI for SCALE and later on, WHISPER for MCNP.
- 2004 - DOE NCSP developed and instituted a process to design critical experiments focused on the quantitative match between S/U analysis of the application and the benchmark experiment and including quantitative estimates of experimental uncertainty to test specific reaction channels in specific energy regimes. This is called the "Critical/Sub-Critical Design Team" (C_edT) approach.

THE INTEGRATED NUCLEAR CRITICALITY SAFETY PROGRAM

The DOE Nuclear Criticality Safety Program is designed precisely to maintain and improve the surety of the calculational tools used by nuclear data practitioners with an emphasis on nuclear criticality safety applications. Every element of the Validation Three Body Problem is addressed.



- Improve understanding of safety margin
- Reduce over-conservatism with well understood physics data and codes
- Reduce cost of operations
- Develop new measurement methods
- Reduce nuclear data uncertainties for calculations and simulations

WRAP UP

- The NCSP nuclear data and methods infrastructure has been utilized to solve real world application problems such as U233 down-blending at ORNL.
- Any program that relies on Monte-Carlo calculated observables based on evaluated nuclear data sets MUST ensure the surety of their Validation Three Body Problem to:
  - Understand the specific nuclear physics of their application,
  - Validate the applicability of the code/method and underlying evaluated nuclear data sets for their specific application (inter-code comparison, vary cross-section sets used, use S/U methods to select applicable existing benchmarks, etc.),
  - If the bias and uncertainty in the bias of the available validation result is unacceptably large, use C_edT methodology to design tailored physics benchmarks to reduce the bias and uncertainty in the bias targeted at specific nuclear reactions driving the final result, and
  - Use all this insight to drive either new differential measurements or new evaluations of the nuclear data (feedback and improvement).
- You don’t know what you don’t know! Theory must always be tested by experiment.

Secondary Gamma Production

Thomas M. Miller

Spallation Neutron Source Second Target Station

Oak Ridge National Laboratory

What problems am I solving? What data am I using?

- Applications
  - Shielding for high energy accelerators
    - Shielding around a spallation target and along neutron beamlines
    - Shielding along a proton accelerator
  - Shielding for criticality safety
    - Shielding at fissile material facilities
    - Detector response to criticality accidents

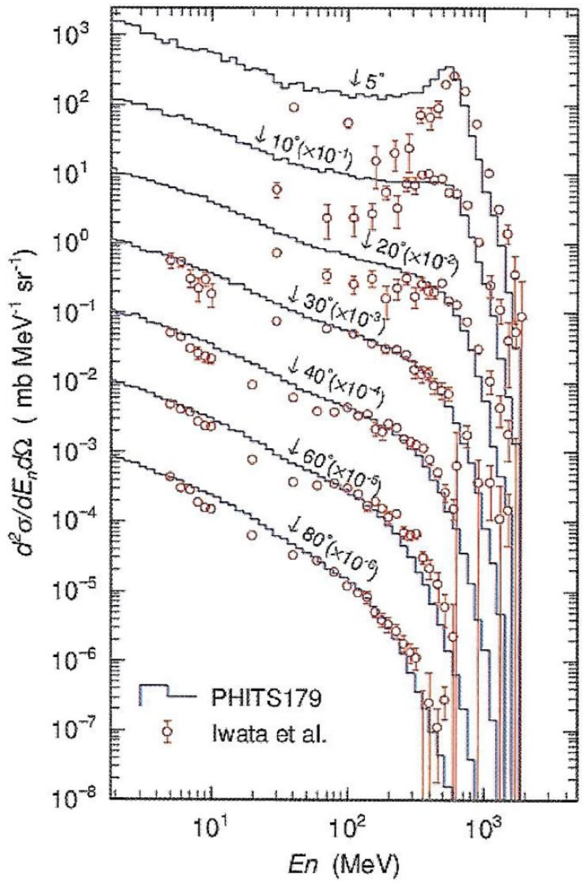
Installing bunker shielding blocks at ESS

- Cross sections
  - Less than 20 MeV
    - ENDF/B, including thermal scattering kernels
    - Usually processed by NJOY (MCNP) or AMPX (SCALE)
  - Greater than 20 MeV
    - Some ENDF/B
    - A little TENDL (currently 2019)
    - Mostly nuclear models (CEM, Bertini, and associated evaporation models)

ESS open shielding monolith

How do I validate data / codes

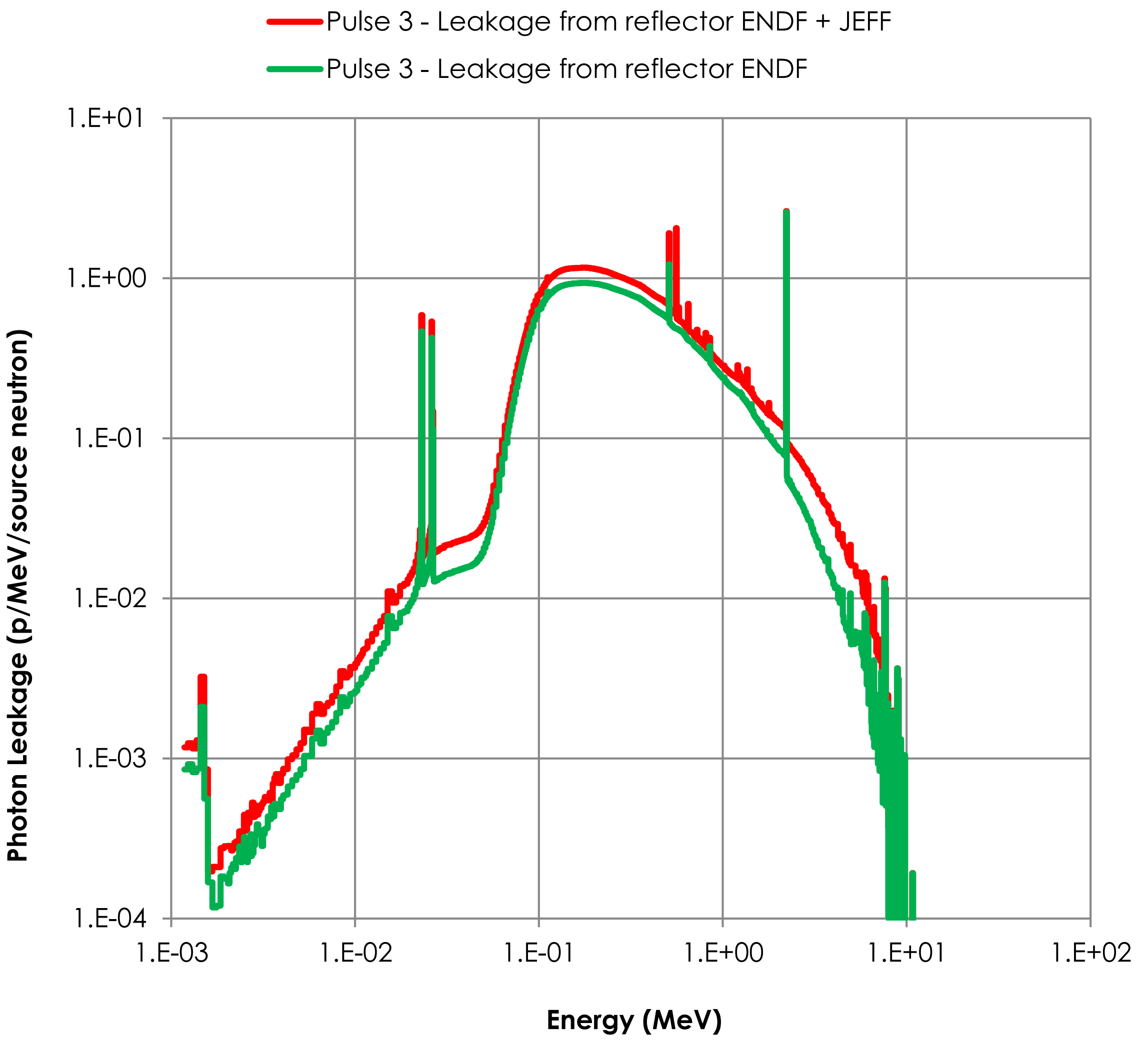
- In my experience, validation like that done by criticality safety practitioners is not common in the shielding community
- At fission / fusion facilities the benchmarks in SINBAD and the alarm / shielding portion of the ICSBEP handbook are useful
- SINBAD and the text by Nakamura and Heilbronn (*Handbook on Secondary Particle Production…*) have benchmarks relevant to accelerator facilities
- Otherwise, there are many individual conference papers and journal articles, but these descriptions are not always complete enough for benchmarking
- Rather than perform validation and determine a bias, most facilities requiring shielding analysis specify a “safety factor”
  - I have seen safety factors range from 20% to 5



Comparison of double differential neutron production cross sections for 600 MeV/A Ne on Pb (Nakamura and Heilbronn)

Data Problem: missing gamma production data

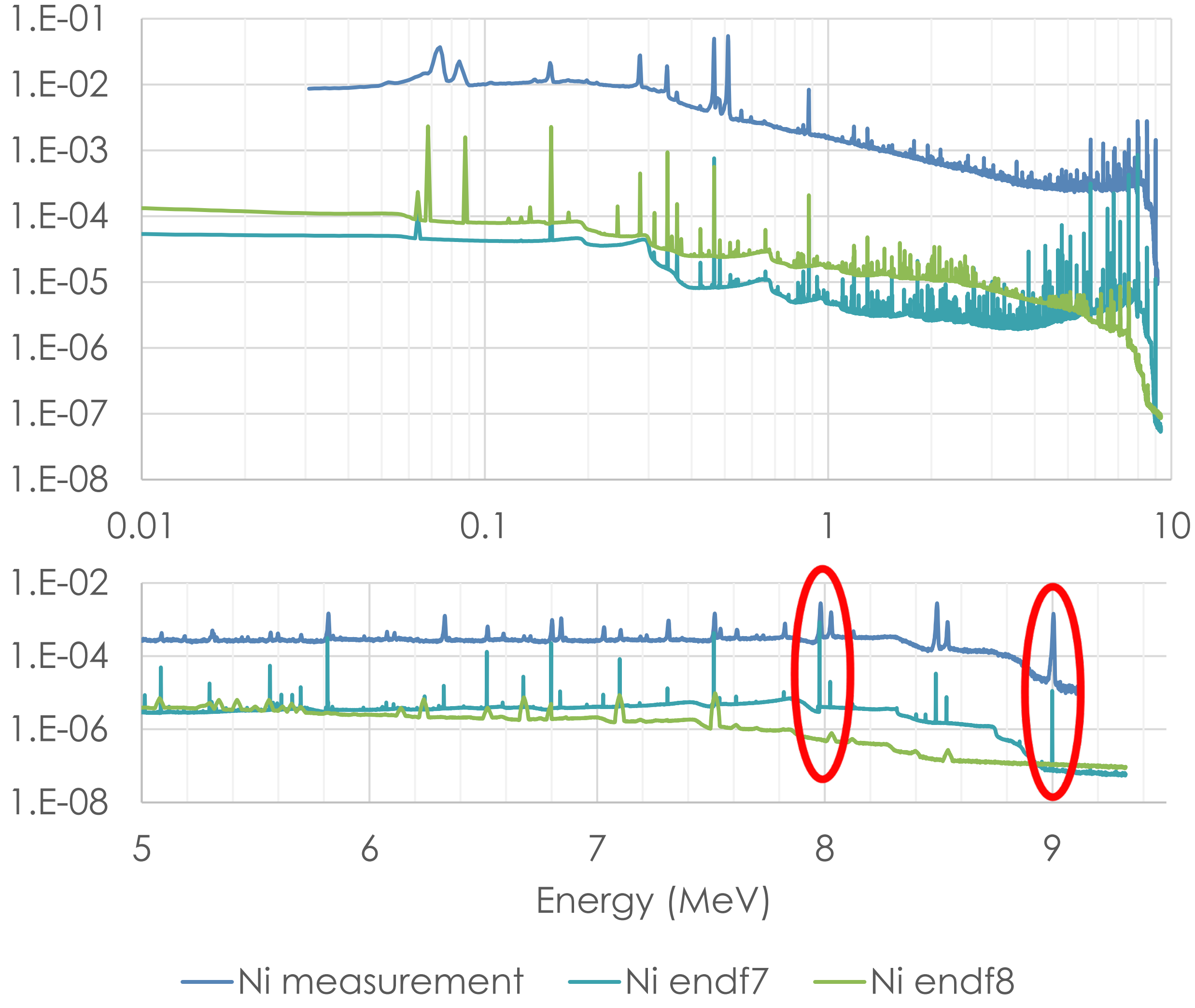
- ENDF (7 and 8) only has gamma production data for Cd-106 & 111. JEFF has these plus 110 and 113.
  - Cd-113 is a well know strong thermal absorber
- ALARM-TRAN-CH2-SHIELD-001 (ICSBEP) compares gamma dose measurements (TLD) and simulations
  - Simulations with ENDF underestimate the dose 30-40%
  - Simulations with JEFF underestimate the dose 10-20%
  - One sigma uncertainties for the dose measurements are 7-9%



Data Problem: inconsistent gamma production data

- Shielding around an instrument at the end of a neutron beamline is often dominated by gamma production in the neutron supermirrors (Ni, Ti, Mo, etc.)
- Measurements were performed by ESS at ILL in France to benchmark simulations of gamma production in neutron supermirrors
  - The gamma production in Ni is very different between ENDF 7 and 8
  - Important characteristic lines present in ENDF 7 are not in 8 (IAEA STI/PUB/1263)
  - The overall energy release by capture gammas is the same
- You might be able to calculate an integral quantity (e.g., dose) correctly, but most likely one cannot reproduce spectra

Comparison between measurement and simulation with ENDF/B-VII.1 and VIII.0 (Normalization: simulations per source neutron, measurement arbitrary



Concluding Remarks

- Cross sections for gammas are mostly analytic, but cross sections to produce secondary gammas rely on neutron evaluations
- Benchmarks measuring integral quantities like gamma dose are helpful and needed
- Benchmarks that measure gamma spectra would be ideal
  - Be sure one can identify the element/isotope producing the gammas
  - Be sure the neutron energy is well defined

Nuclear Data, Validation Methods, and Integral Needs

Dr. Bradley T. Rearden
Director of Engineering, Xe-Mobile

January 27, 2021

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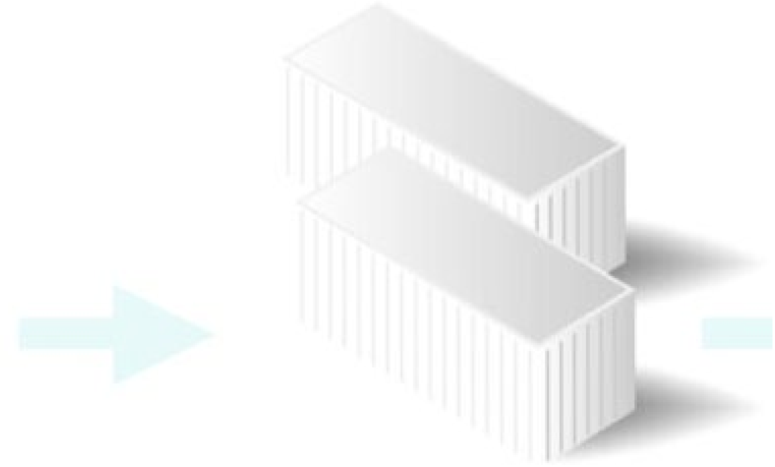
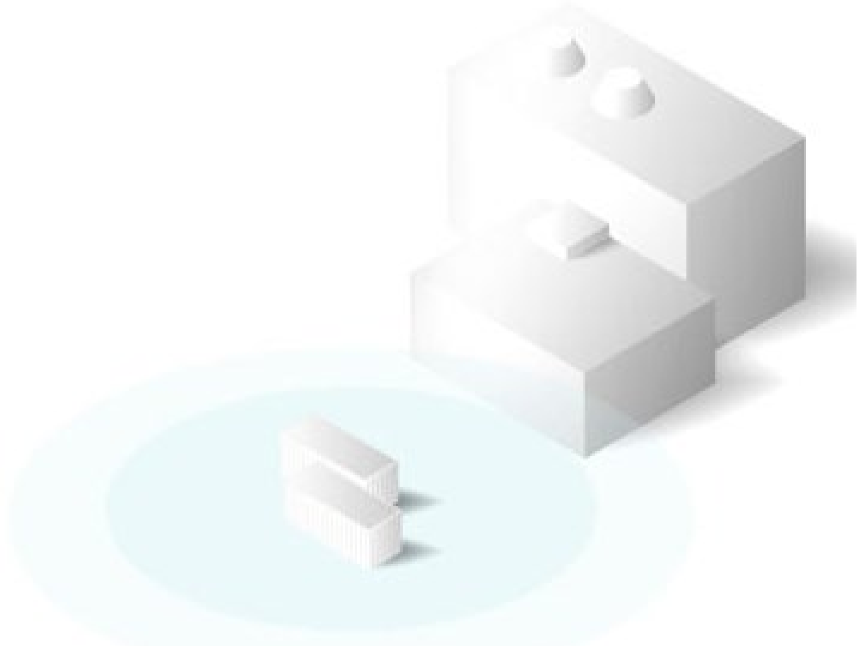
Novel Applications of Microreactors



Defense & forward bases

As the US Military prepares for “near-peer” adversaries of the future, highly portable power with a high energy density will be a game-changing technology.

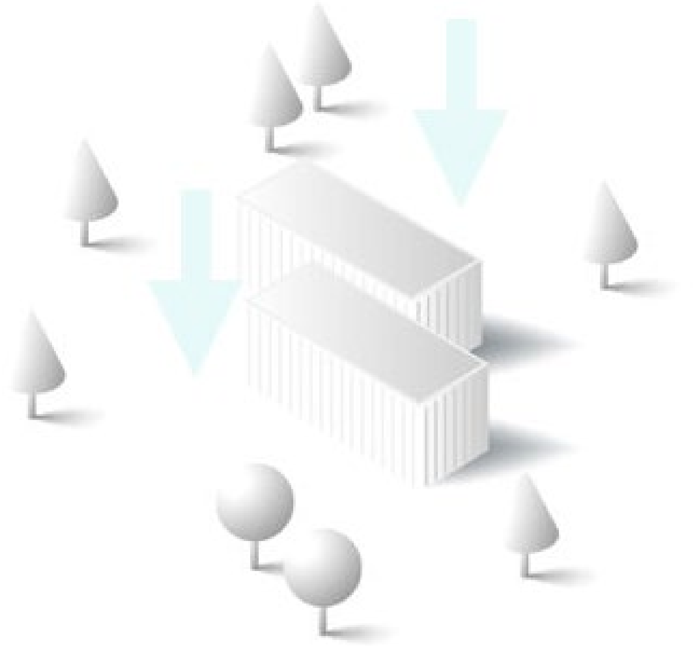
Highly Portable Power



Disaster Relief

The ability to transport flexible electricity solutions that do not require fueling for months or years provides critical infrastructure to get railroads, water purification facilities, and hospitals powered again – within one week.

Be powered again – within one week



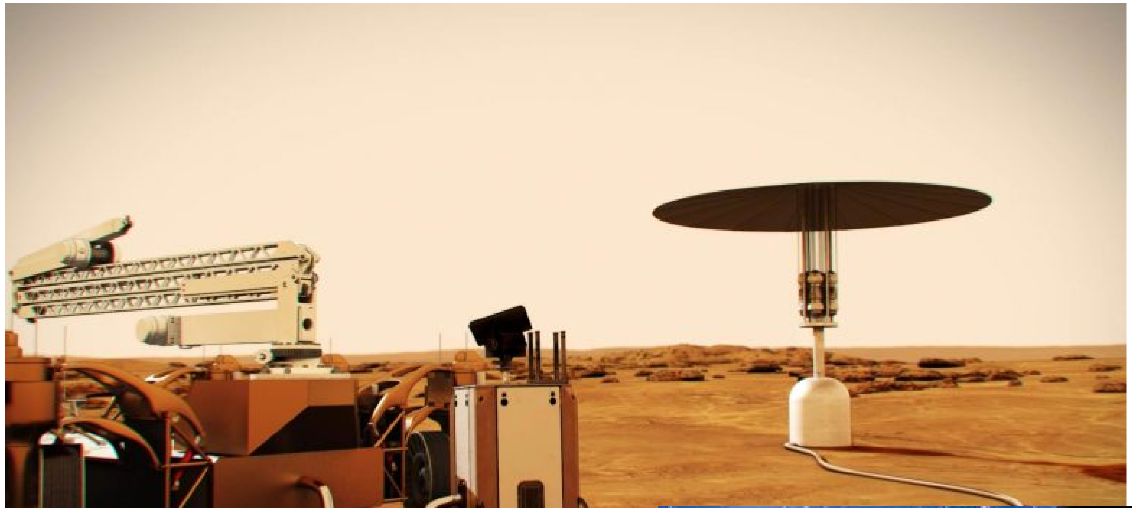
Remote Communities

Arid, Island and Alaskan/Canadian communities often use government-subsidized petroleum fuel deliveries to maintain their power. If their deliveries are disrupted, the impact can be significant.

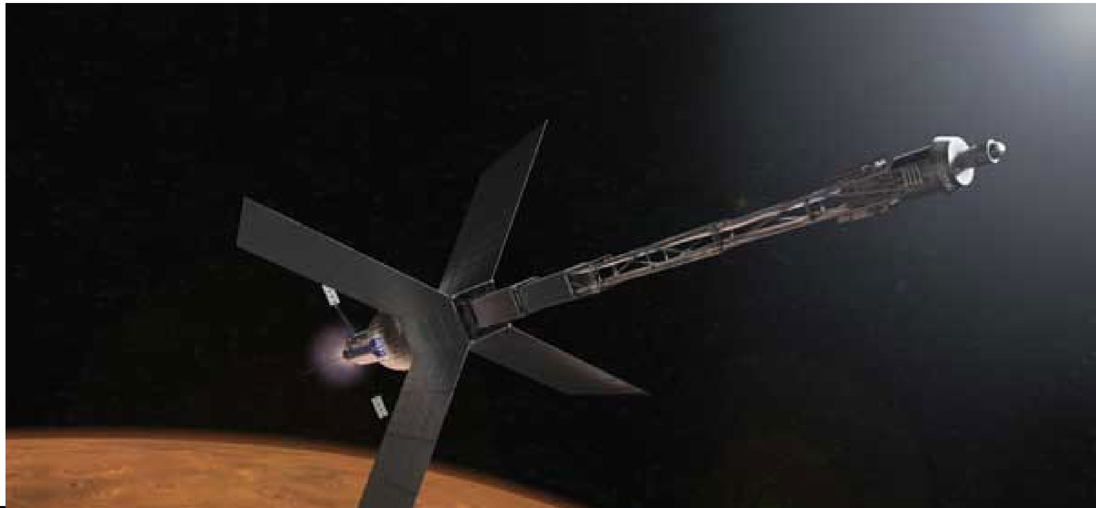
Maintain Power

Space Nuclear Applications

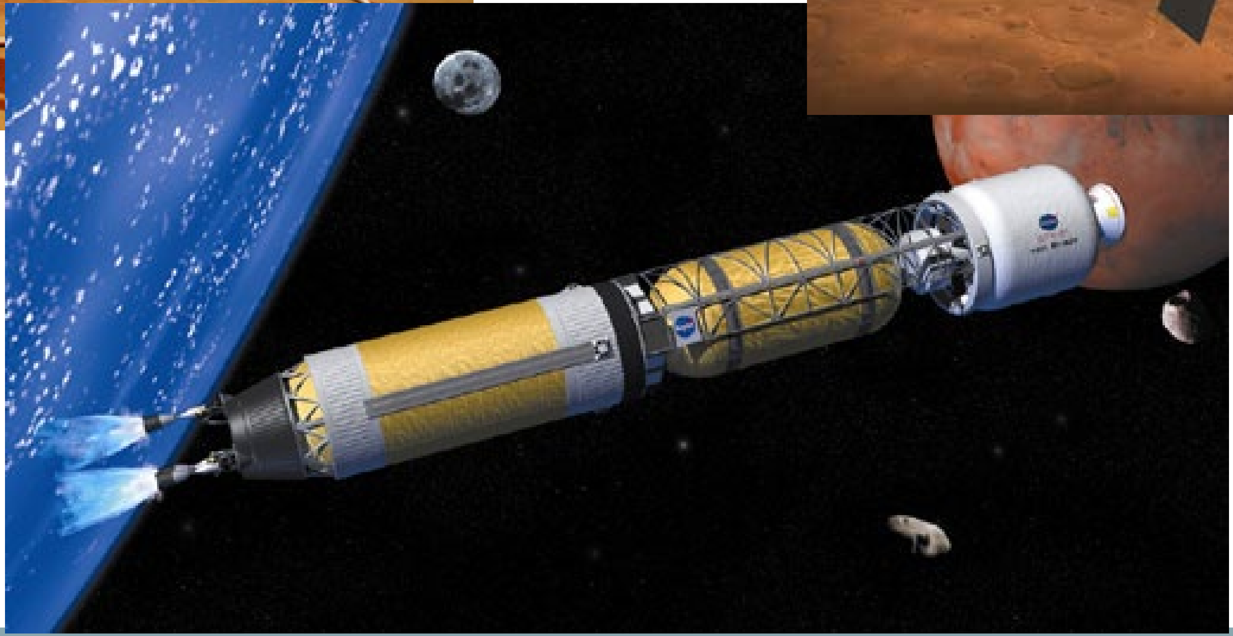
Fission Surface Power System



Nuclear Electric Propulsion



Nuclear Thermal Propulsion



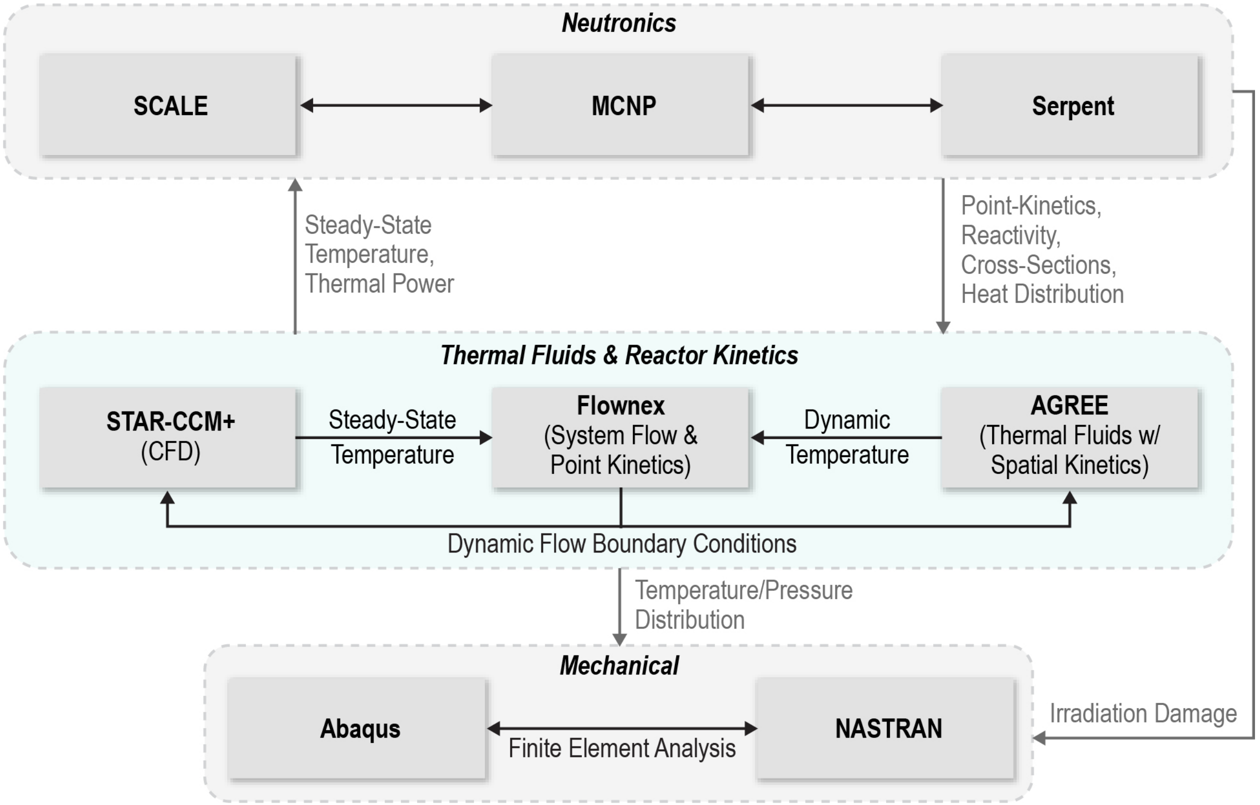
Images: NASA

Executive Actions and Appropriations

- **Promoting Small Modular Reactors for National Defense and Space Exploration (**Executive Order 13972, January 2021)
  - Demonstration of Commercial Reactors to Enhance Energy Flexibility at a Defense Installation
  - Defense Capabilities
  - Space Exploration
  - Domestic Fuel Supply
  - Common Technology Roadmap
- **Launch of Spacecraft Containing Space Nuclear Systems (**National Security Presidential Memorandum-20, August 2017)
  - Safety prescribed in terms of Total Effective Dose to population

- **DOE-NE** Advanced Reactor Demonstration Program ~$200M/yr, operational reactors 2027-2030s
- **DOD** Mobile Microreactor $70M FY21, demonstration unit in 2024
- **DARPA**/DRACO – ??
- **NASA NTP** ~$100M FY21
- **NASA FSP** – Launch ready 10 kWe, 10-year lifetime, 3500 kg power plant by 2026
- **NASA NEP** – Studies resuming in 2021

Nuclear data provide a foundation for performance and safety analysis



Neutronics

SCALE ↔ **MCNP** ↔ **Serpent**

Steady-State Temperature, Thermal Power

Point-Kinetics, Reactivity, Cross-Sections, Heat Distribution

Thermal Fluids & Reactor Kinetics

STAR-CCM+ (CFD)

Steady-State Temperature

Flownex (System Flow & Point Kinetics)

Dynamic Temperature

AGREE (Thermal Fluids w/ Spatial Kinetics)

Dynamic Flow Boundary Conditions

Temperature/Pressure Distribution

Mechanical

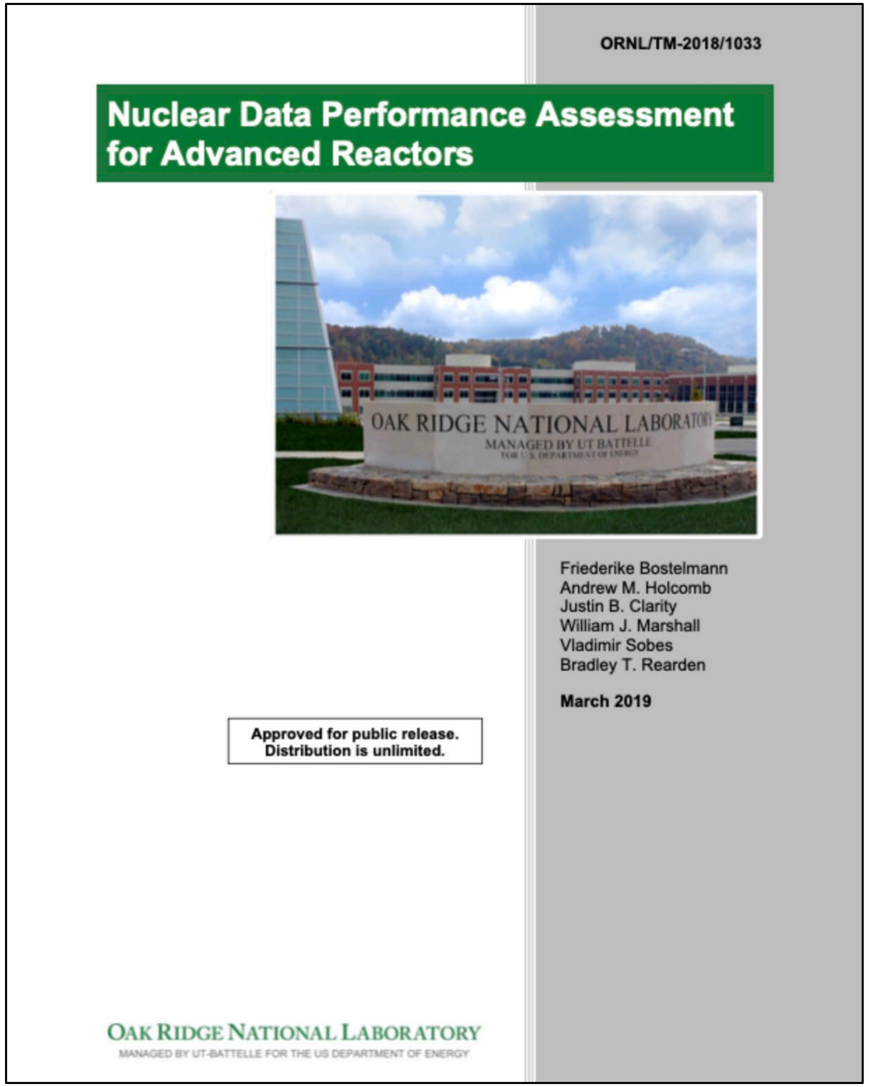
Abaqus ↔ **NASTRAN**

Finite Element Analysis

Irradiation Damage

Analysis	Tool/Model	Analysis Type	Outcome
Core neutronics	SCALE/ KENO/ORIGEN	Steady-state Monte Carlo neutron transport and transmutation	Power Profiles, Core life, Burnable poison design, Temperature and control element reactivity
Cross section generation	Serpent	Steady-state Monte Carlo neutron transport	Generated few-group cross sections for AGREE-Xe and verified reactivity results from SCALE and MCNP
Photon/Neutron Transport	MCNP	Steady-state Monte Carlo neutron and photon transport	Ex-core heating rates
Reactor Thermo-fluid Analysis	StarCCM+	High fidelity heat conduction and thermo-fluid dynamic behavior	Spatially resolved temperatures and coolant flow rates
Coupled neutronic-thermal fluid analysis	AGREE-Xe	Steady-state and time-dependent neutron diffusion/heat conduction/ subchannel fluid behavior	Peak and average temperatures of structures during transient scenarios
Plant Dynamics	Flownex	Steady-state and time-dependent analysis of plant-wide behavior	Plant/Reactor response to perturbations and fault conditions. Startup, shutdown, and critical power maneuvers
Shielding	SCALE/ MAVRIC/ ORIGEN	Steady-state neutron and gamma transport, activation, decay	Ex-vessel dose and activation rates
Structural Dynamics	NASTRAN	Dynamic Finite Element Analysis	Static-equivalent accelerations to be used for stress analysis, Load Isolation System evaluation
Mechanical and thermal stress	Abaqus	Steady-state Finite Element Analysis	FEA-calculated stresses, to be compared against material allowables to determine if the parts meet design requirements
Instrumentation & Controls	PSCAD	Simulation of electric power conversion	Power Balance of EPCS with a notional load bank at steady state response of system to various load transients, including abnormal loads and fault conditions
Hazards Analysis (Fire, chemical, mechanical, electrical, etc.)		Identification of hazards associated with assembly, transport, and disassembly operations	Design requirements for hazard mitigation systems (e.g., Fire Detection and Suppression)

Concerns with changes in ENDF/V-III.0 without consideration for reactor applications



ORNL/TM-2018/1033

Nuclear Data Performance Assessment for Advanced Reactors

Friederike Bostelmann
Andrew M. Holcomb
Justin B. Clarity
William J. Marshall
Vladimir Sobes
Bradley T. Rearden

March 2019

Approved for public release.
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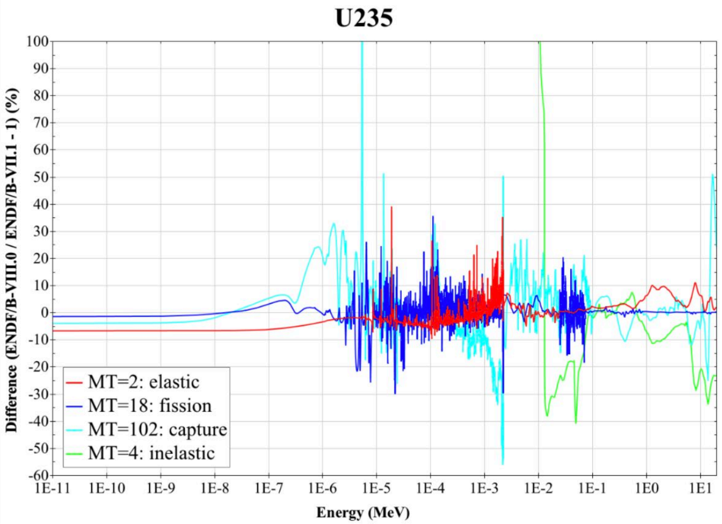
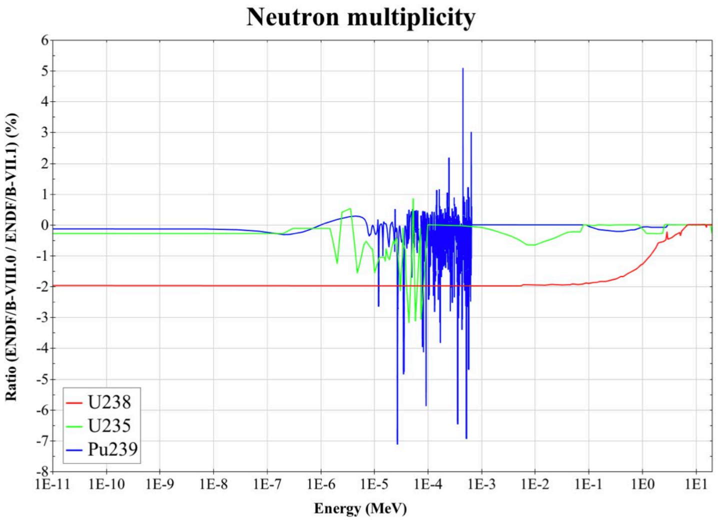
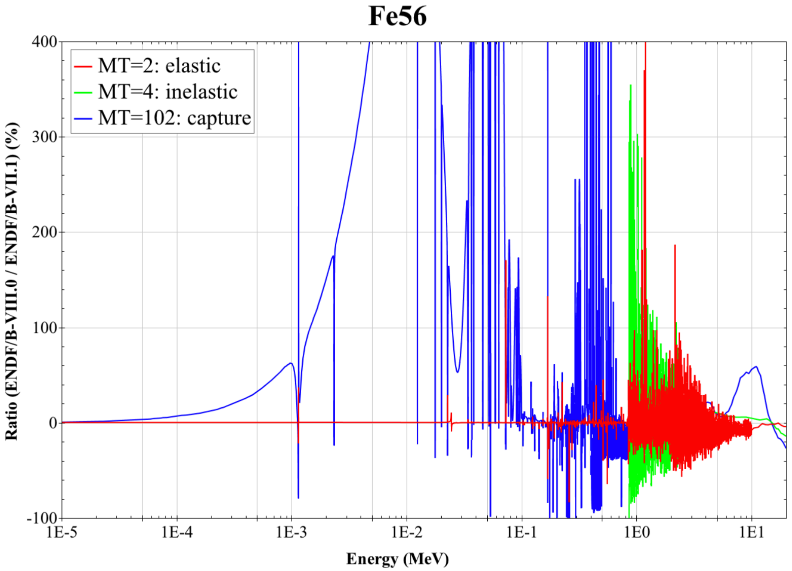
OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY







Validated Nuclear Data Needs

- **Small and precise reactors require optimized power and lifetime predictions**
  - Power distribution
  - Reactivity control and shutdown margin
  - Fission product inventories
- **Close proximity to public and need for low mass solutions require precise source term and shielding data**
  - Prompt neutrons and gammas from fission
  - Gamma emissions from fission product decay
  - Material activation and decay
  - Neutron and gamma attenuation
- **Thermal scattering law data**
  - Advanced moderators/reflectors are needed for small HA-LEU cores
  - YH_x is of interest for lower temperature applications
  - NTP systems approach 3000 K for fuel and structural materials with H_2 as internal propellant
- **Irradiation damage assessment is needed for wide range of materials**
  - Damage cross sections should be included in ENDF libraries

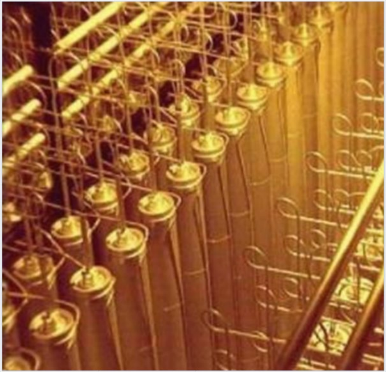
National Nuclear Security Administration

WANDA 2021: Nuclear Data for Defense Nuclear Nonproliferation Applications

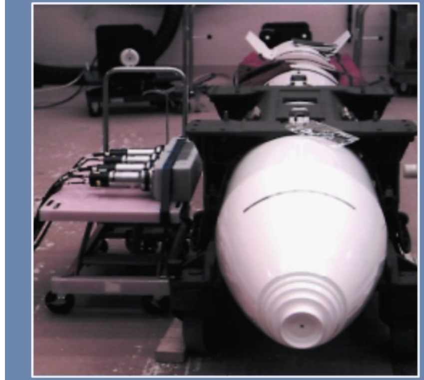
David Matters, NNSA/NA-221
DNN R&D, Office of Proliferation Detection
January 27, 2021

Defense Nuclear Nonproliferation (DNN) Research and Development (R&D)

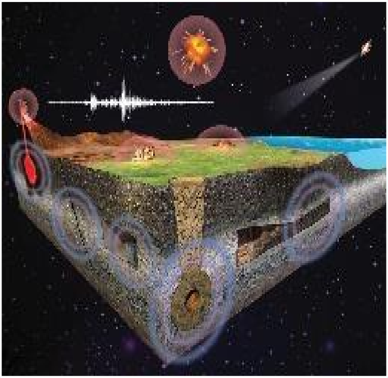
Advance U.S. nuclear security capabilities, in close coordination with mission Partners, using DOE National Laboratories, Universities, & Industry



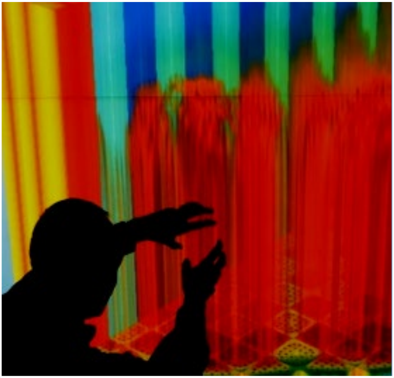
Detect Foreign Weapons Activities



Increase Nuclear Security



Detect Nuclear Explosions



Steward Nonproliferation Capabilities

Develop timely early proliferation detection capabilities

Develop high-confidence verification and monitoring capabilities

Capabilities to detect, locate & characterize foreign nuclear weapons development activities

Capabilities to detect presence, movement & diversion of SNM, including for interdiction, emergency response, safeguards

Capabilities for detecting & monitoring ground-, atmospheric-, & space-based nuclear detonations

Enabling infrastructure, science, and technology, and an expert workforce to meet future nonproliferation challenges

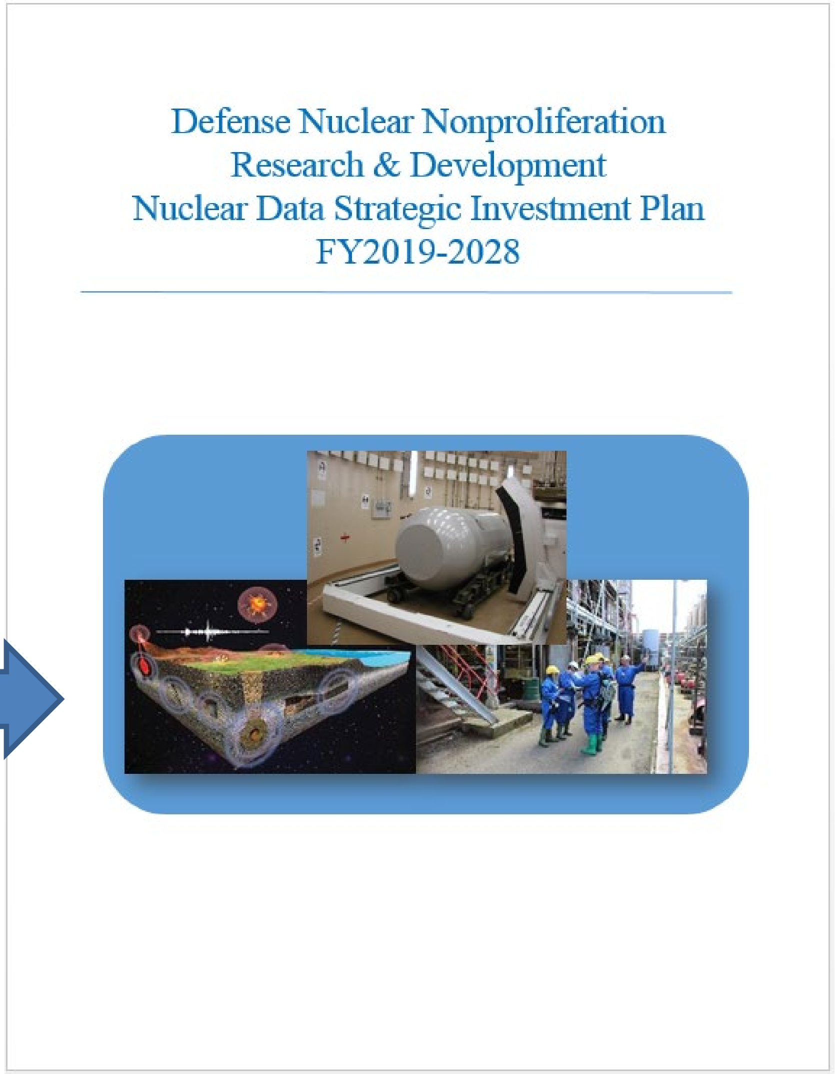
DNN R&D Support to Improve Nuclear Data

- Between FY09-FY21, experimental and theoretical investments to improve nuclear data capabilities total ~$75M

- Investments made by:
  - NA-221 - Emergency Response, Safeguards, Arms Control Monitoring & Verification, and Near-field Detection
  - NA-222 – Forensics

- NDREW (2018) provided input for DNN R&D collectively organize nuclear data efforts

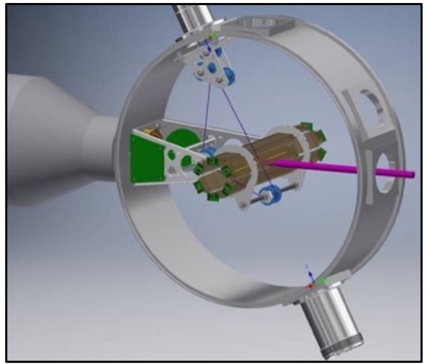
- Participation in the Office of Nuclear Physics Interagency FOA in FY18 through FY22 (including current FOA)



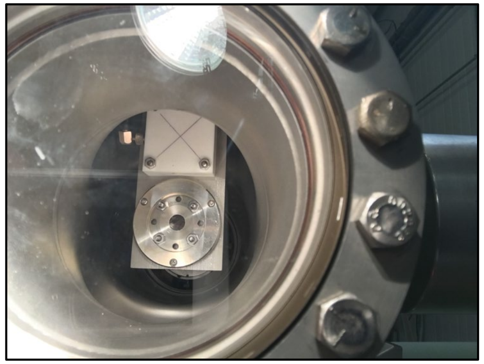
Defense Nuclear Nonproliferation
Research & Development
Nuclear Data Strategic Investment Plan
FY2019-2028

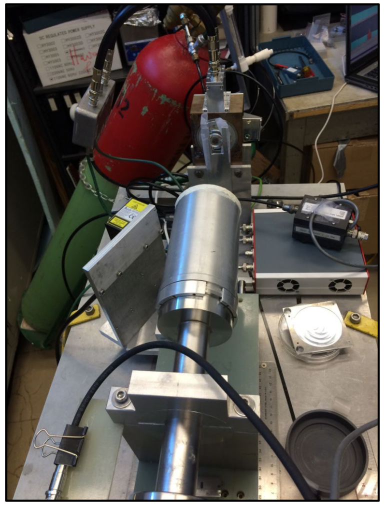
Current Nuclear Data Projects in DNN R&D

- **2017-2022, ANL:** Improving Antineutrino Spectra Predictions for Nonproliferation Applications
  - Nuclear data for fission products (FP) needed to reliably predict reactor antineutrino spectra
  - FP beams provided by the CARIBU facility, measurements w/Gammasphere
- **2018-2022, LLNL:** Fission Products decay measurements of selected isotopes for nonproliferation applications
  - Improving the Nuclear Data on Fission Product Decays at ANL's CARIBU
- **2019-2023, LANL:** Evaluation of Energy Dependent Fission Product Yields
  - FPY data for 235U, 238U, and 239Pu isotopes using monoenergetic and pulsed neutron beams with energies from 0.5 MeV to 15.0 MeV


Schematic of beta particle detector array


Target chamber for installation in the Gammasphere detector array


Sample harvested at CARIBU


β-γ coincidence measurement

Focus of Projects for FY22 Interagency FOA

Scoping studies on neutron-induced emission, (α,n) reaction data, secondary γ-ray emission, non-actinide reaction networks, etc. have informed NA-22's FOA input

- Reconcile discrete gamma-ray energies, multipolarities, and branching ratios and primary/secondary gamma-ray spectral data between the ENDF/B-VIII.0 and ENSDF libraries.
- Extend the Generalized Nuclear Database Structure format to include level density information and allow discrete levels in the continuum energy range. This extension enables primary-gamma triggered cascades (i.e., from neutron capture), including complete states up to the neutron separation energy and transitions from other unresolved states.
- Review identified existing gamma production cross-section data for validity, assess any unvalidated existing cross-section data for acceptability to correct existing cross-section data, or fill in missing cross-section data.
- **Perform new gamma production cross-section measurements for incident neutron energies spanning from thermal to 14 MeV for identified, specific instances of incorrect or missing cross-sections.**

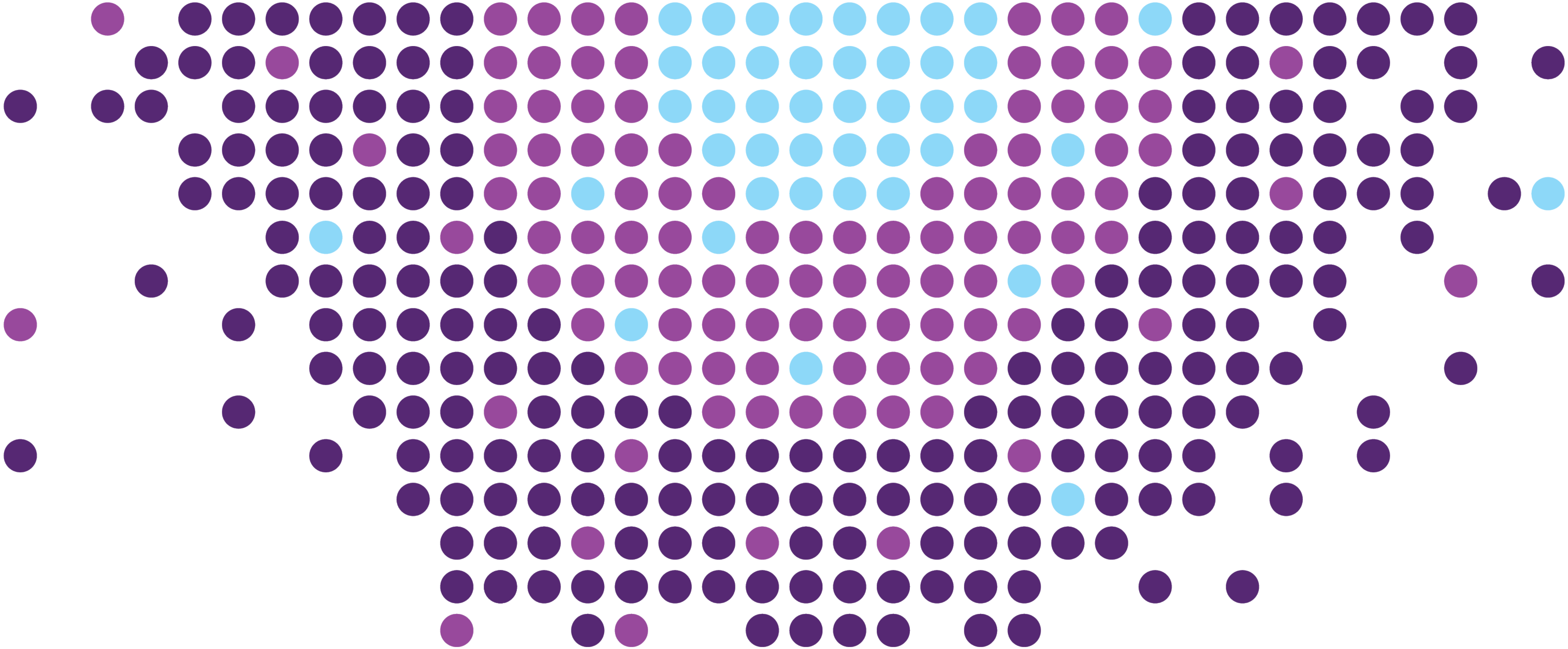
Benchmarks

Benchmark Data Needs

NA-22 has needs for improved benchmark data on a variety of elements that comprise structural and shielding materials, controlled or dangerous substances, and detector materials

- Active neutron interrogation techniques are employed in a variety of nonproliferation applications
- Modeling of secondary γ-ray emission from active neutron interrogation would benefit greatly from quality assurance checks with benchmark datasets
- Improved γ-production cross sections are needed on priority elements
- Benchmark data are primarily required from radiative capture (n,γ) and inelastic scattering (n,n'γ), depending on which cross sections dominate γ-ray production

First Priority	Follow-up	Remaining	
H	He	F	Gd
C	Li	Mg	Bi
N	Be	P	Np
O	B	S	Am
Na	Cl	Ar	
Al	Cr	K	
Si	Mn	Ca	
Fe	Ni	Ti	
Cu	Ge	As	
Pb	Br	Kr	
W	Cd	Mo	
U	I	Sn	
Pu	Cs	Sb	
	La	Xe	

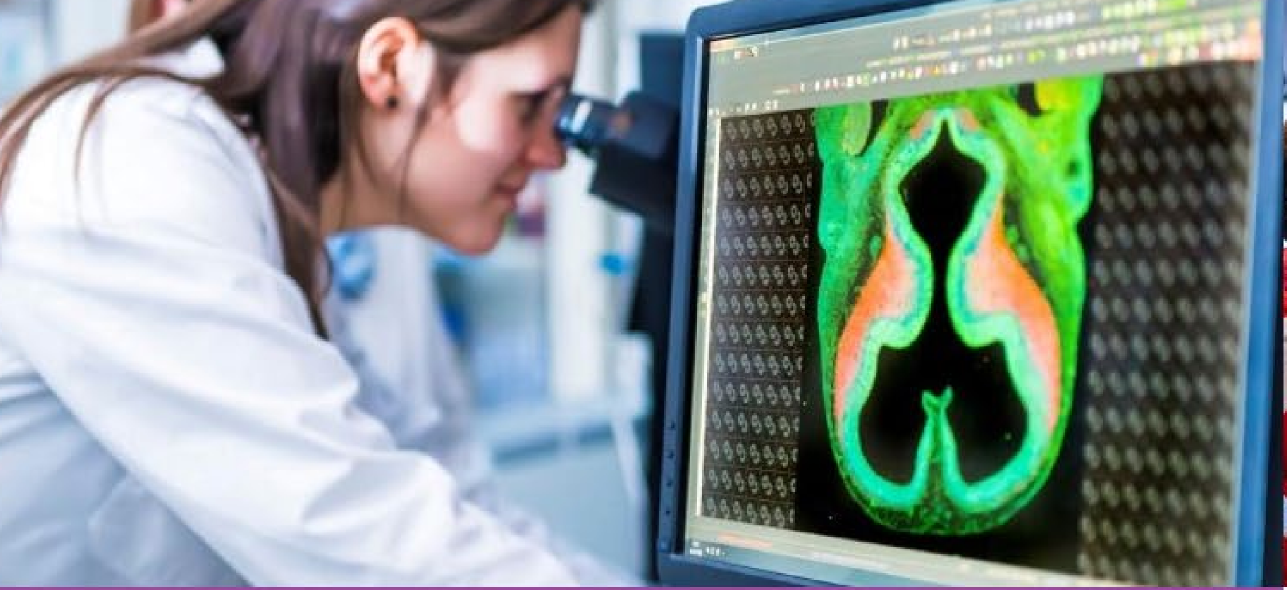


sck cen
Belgian Nuclear Research Centre

P. Romojaro, L. Fiorito, A. Stankovskiy and G. Van den Eynde - 27/01/2021

Nuclear Data for MYRRHA

Workshop for Applied Nuclear Data Activities (WANDA 2021)



NURA

With its **NURA** project, SCK CEN significantly increases its contribution to the fight against cancer. By pooling its knowledge and expertise in terms of radiopharmaceuticals, NURA contributes to the development of the next-generation radiopharmaceuticals. More specifically, NURA performs game-changing research into radiopharmaceuticals for treating different types of cancer in cooperation with clinical and industrial partners.

MYRRHA

SCK CEN works actively on the design and construction of a new multi-purpose research plant: MYRRHA, which stands for *Multi-purpose HYbrid Research Reactor for High-tech Applications*. MYRRHA is a versatile research infrastructure but above all unique. It is the world's first research reactor driven by a particle accelerator.

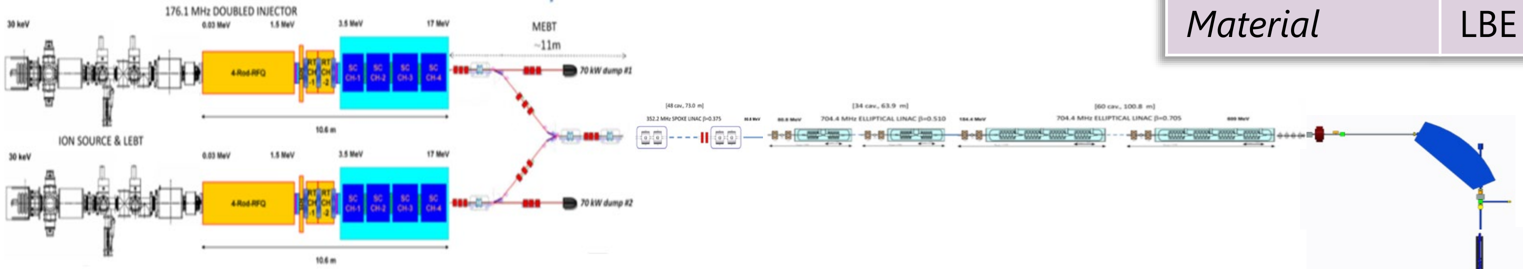
RECUMO

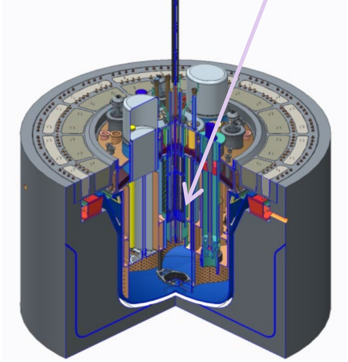
With the public-public partnership RECUMO, SCK CEN and the *National Institute for Radio Elements* (IRE) reach out to one another. SCK CEN will decontaminate the current and future highly radioactive residues and thus reduce the stock. In this way, RECUMO contributes to the security of supply of medical radio-isotopes, which are indispensable in the fight against cancer.

MYRRHA

- MYRRHA – An Accelerator Driven System
  - Demonstrate the ADS concept at pre-industrial scale
    - Can operate in critical and sub-critical modes
  - Demonstrate transmutation
  - Fast neutron source

Target	
Main reaction	spallation
Output	$2{\cdot}10^{17}$ n/s
Material	LBE (coolant)



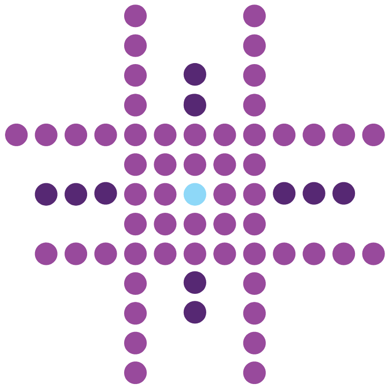


Accelerator	
Particles	protons
Beam energy	600 MeV
Beam current	2.4 to 4 mA

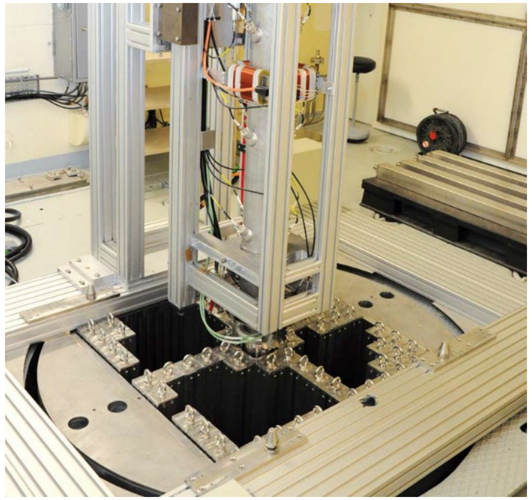
Reactor	
Power	65 to 100 MW_{th}
k_{eff}	0.95
Spectrum	fast
Coolant	LBE

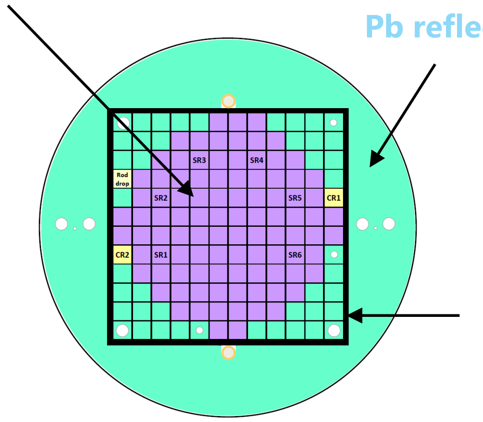
MYRRHA design

- Codes
  - Core
    - MCNP6.2
    - ALEPH2
  - Accelerator
    - MCNP6.2
    - ALEPH2
    - PHITS
- Nuclear data
  - JEFF-3.1.2, JEFF-3.2, JEFF-3.3 & JEFF-4T0
  - ENDF/B-VII.0, ENDF/B-VII.1 & ENDF/B-VIII.0
  - JENDL-4.0 & JENDL-5beta
  - TENDL-2014, TENDL-2015, TENDL-2017 & TENDL-2019



Nuclear Data Validation: VENUS-F

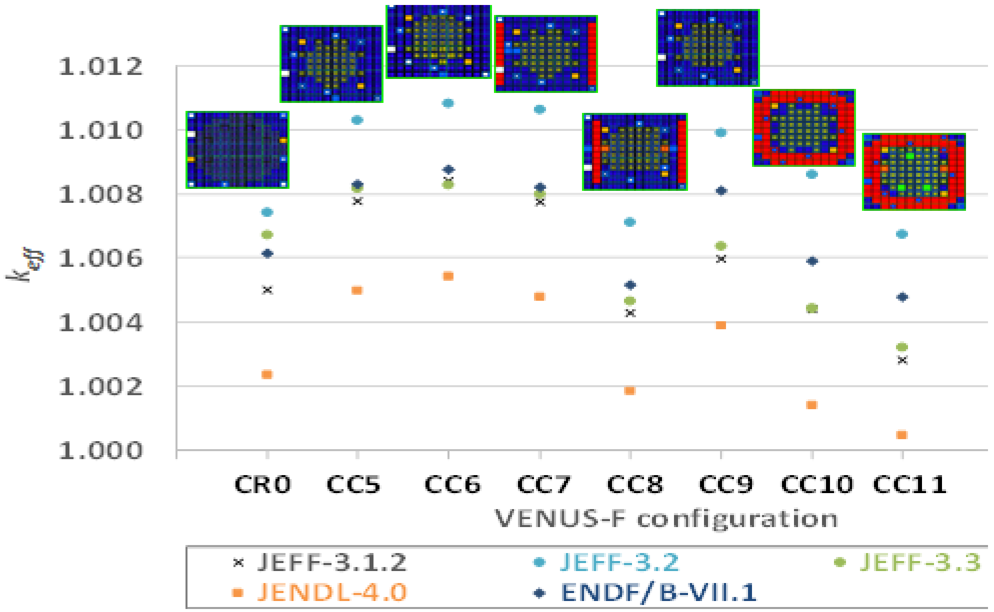




30% U metallic fuel + Pb "coolant" (solid Pb, alternatively Bi)

Pb reflector

SS



Core	#FAs	FA composition	Reflector	In-Pile Section
CR0	97	9 U+16 Pb	Pb	-
CC5	41	13 U+8 Pb+4 Al_2O_3	Pb	-
CC6	41	13 U+8 Pb+4 Al_2O_3	Pb	-
CC7	41	13 U+8 Pb+4 Al_2O_3	Pb+C	-
CC8	47	13 U+8 Pb+4 Al_2O_3	Pb+C	thermal spectrum
CC9	41	13 U+8 Bi+4 Al_2O_3	Pb	-
CC10	41	13 U+Pb+8 Bi+4 Al_2O_3	Pb+C	-
CC10b	47	13 U+Pb+8 Bi+4 Al_2O_3	Pb+C	thermal spectrum
CC11	50	13 U+Pb+8 Bi+4 Al_2O_3	Pb+C	thermal and fast spectrum

Source: A. Kochetkov and P. Baeten

Besides criticality, we have:

- Kinetic parameters
- CR curve
- Spectral indices
- Axial and radial traverses
- Pb-Bi void
- Fuel Doppler

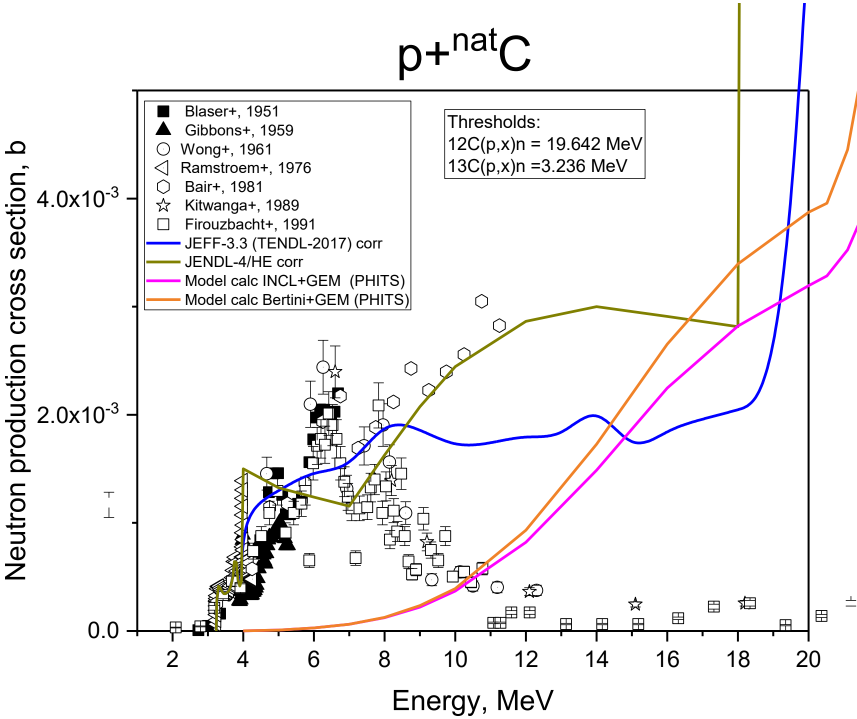
Extensive database for ND validation!

Nuclear Data Needs

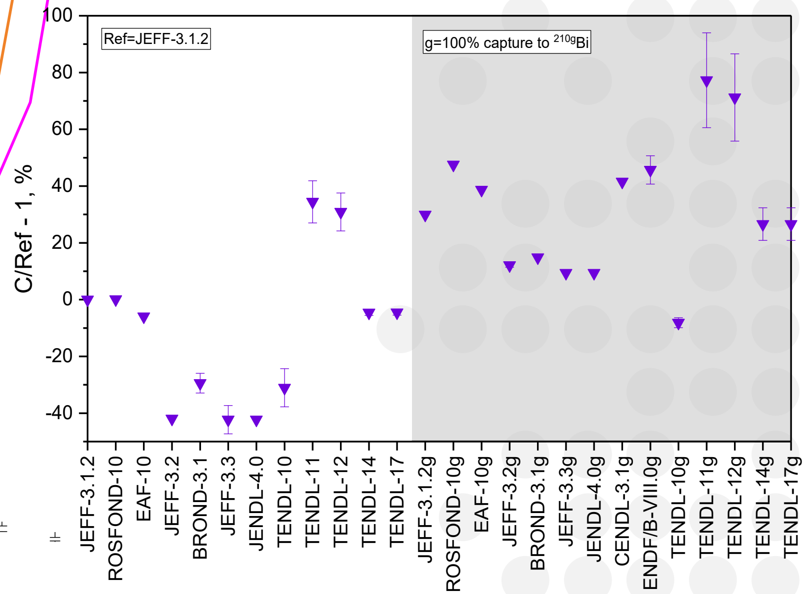
Nuclear data needs in JEFF-3.3 for MYRRHA:

- Adoption of JENDL-4.0 evaluation for ^{204}Pb or re-evaluation in the RRR and URR
- New evaluation ^{57}Fe(n,inel.) including missing resonances
- Re-evaluation ^{10}B(n,inel.) uncertainty
- Covariance evaluation for ^{209}Bi(n,n) and ^{209}Bi(n,γ)
- Covariance evaluation for ν_T, ν_p, ν_d ^{240}Pu & ν_d ^{235,238}U and ^{239,242}Pu
- Reduction of uncertainty ^{240}Pu(n,f)
- Reduction of uncertainty ^{54,57}Fe(n,n)
- Reduction of uncertainty ^{208}Pb(n,n)
- Reduction of uncertainty ^{238}U(n,inel.)

Criticality



Shielding



Radioactive source term and waste management

Source: JEFFDOC-1994, JEFFDOC-1956 and P. Baeten

Benchmarks

- Criticality
  - VENUS-F - MYRRHA mockup
  - Different configurations for nuclear data validation

- Shielding
  - Double-differential neutron yields experiments
  - Neutron transmission experiments

- Nuclear data adjustment
  - Simple configuration
  - Highly sensitive to a single nuclide and reaction channel

SCK CEN
Belgian Nuclear Research Centre
Studiecentrum voor Kernenergie
Centre d'Etude de l'Energie Nucléaire

Foundation of Public Utility
Stichting van Openbaar Nut
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Sensitivity Tool Needs for Modern Nuclear Data Validation

WANDA 2021

Expanded Benchmarks & Validation for Nuclear Data

Jan 27, 2021

Michael E. Rising

Monte Carlo Codes, XCP-3
Los Alamos National Laboratory

Acknowledgements: Research reported in this publication was supported by the U.S. Department of Energy LDRD program at Los Alamos National Laboratory.

LA-UR-21-20511

“Old School” Validation

- Validation

  Quantifying the ability of a **method** $(\boldsymbol{f})$, and the **input** $(\hat{\boldsymbol{x}})$, to accurately predict **reality** $(\boldsymbol{R})$.

$$\boldsymbol{R} \quad \cong \quad \boldsymbol{f}(\hat{\boldsymbol{x}}) \qquad ???$$

- This appears simple. It’s not.

- Consider $\boldsymbol{R}$ = benchmark experiment, $\boldsymbol{f}$ = `MCNP`, $\hat{\boldsymbol{x}}$ = nuclear data:

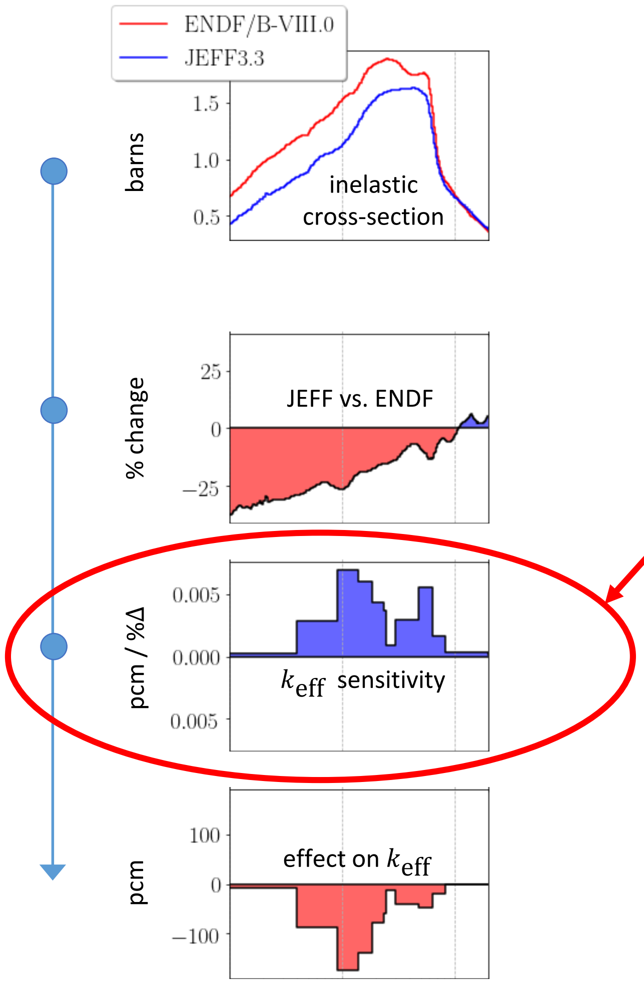
```
if ( Experiment == MCNP Simulation ) then
              ✓
else
              ?
end if
```

- **What about uncertainties?**
- **What about identifying problems in $\boldsymbol{R}$, $\boldsymbol{f}$, and $\hat{\boldsymbol{x}}$?**
- **To first order, sensitivity coefficients hold the key to connecting nuclear data and benchmark experiments**

- **Modern validation** is and should be at least as complex as each of the individual pieces, $\boldsymbol{R}$, $\boldsymbol{f}$, and $\hat{\boldsymbol{x}}$.

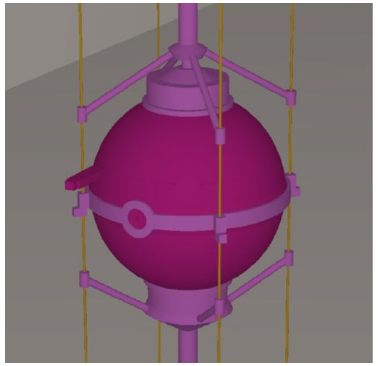
Decades of Experience in Validation of Nuclear Criticality Safety

Through differential and integral experiments alone, significant differences in evaluated nuclear data libraries **cannot be reconciled**

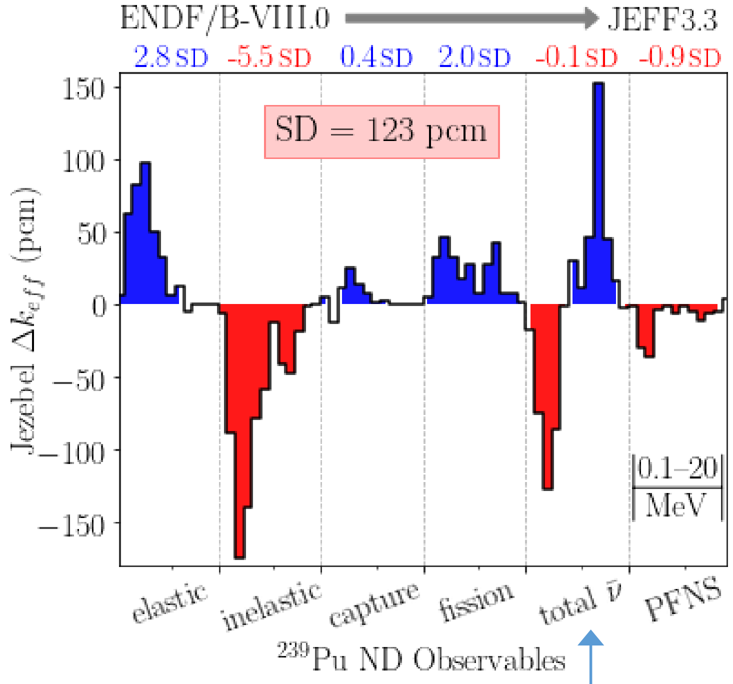


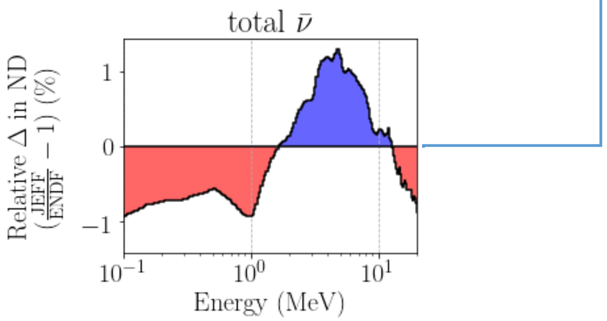
Differences in ENDF/B-VIII.0 and JEFF3.3 are representative of the uncertainty in the differential nuclear data measurements

MCNP® simulations with **sensitivity profile calculation** provide the link between nuclear data and predictive application simulations



Both ENDF/B-VIII.0 and JEFF3.3 **“predict”** Jezebel k_{eff} equally well





Sensitivity Methods and Tools are Key to Understanding and Reconciling Deficiencies in Nuclear Data

Sensitivity/perturbation methods and tools provide efficient uncertainty propagation to applications and efficient feedback to the nuclear data evaluation community.

Uncertainty Propagation to Applications: $\mathrm{Var}(A) = S_{A,\sigma}^{T} \boldsymbol{C}_{\boldsymbol{\sigma\sigma}} S_{A,\sigma}$

Feedback to Nuclear Data through Adjustment/Assimilation: $A, \sigma, \boldsymbol{C}_{\boldsymbol{\sigma\sigma}} \xrightarrow{\mathrm{GLLS}(S_{A,\sigma})} A', \sigma', \boldsymbol{C}'_{\boldsymbol{\sigma\sigma}}$

Just having benchmarks and simulated results isn’t sufficient!

High-fidelity sensitivity tools and methods are needed to perform **modern validation** for more diverse benchmarks and applications

- Criticality (k_{eff})
  - ICSBEP - criticality safety analyses
- Subcritical Multiplication
  - Singles/doubles rate, leakage multiplication
- Electron/photon physics
- High-energy physics (model physics)
- Reactor physics and kinetics
  - Reaction rates
  - Reactivity/void coefficients
  - Rossi-alpha, β_{eff}
- Shielding, fixed-source applications
  - SINBAD neutron/photon benchmarks

Slides for the WANDA session on “Expanded Benchmarks & Validation for Nuclear Data”

Denise Neudecker

WANDA, 1/27/2021

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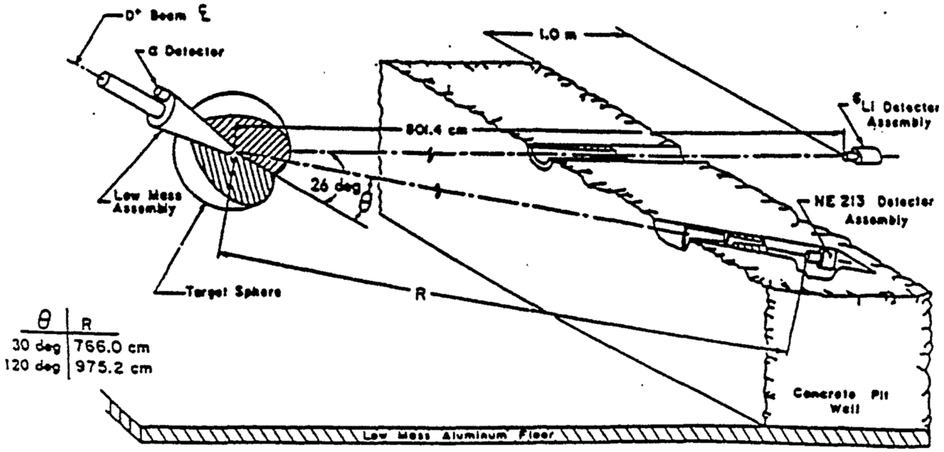
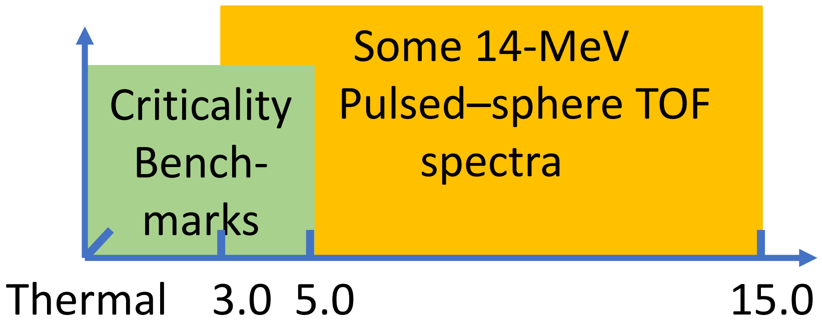
LA-UR-21-20322

Criticality on its own does not allow to validate conclusively pertinent nuclear data. TOF spectra can yield an important piece to the puzzle.

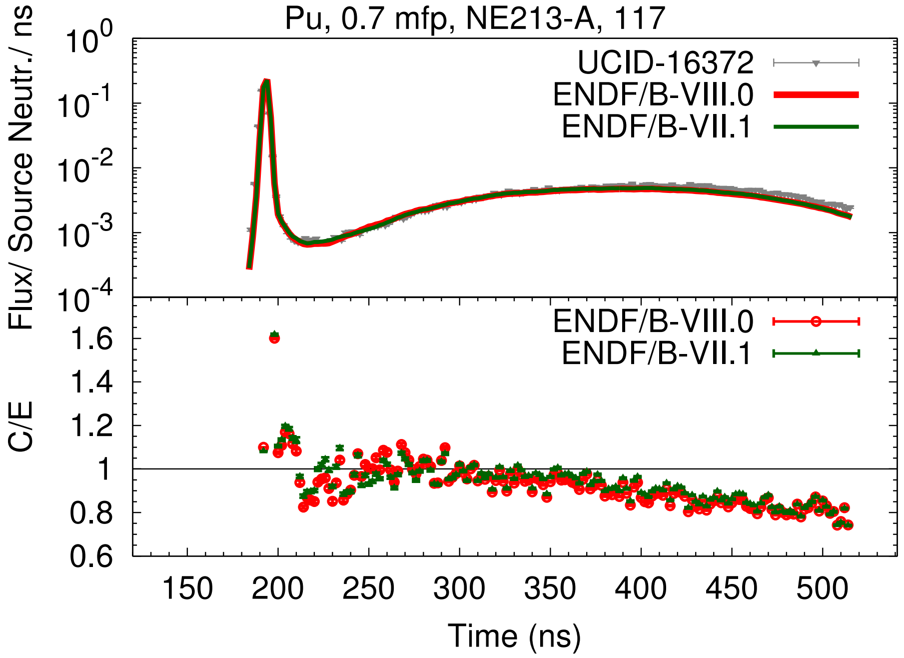



Criticality Bench-marks

Some 14-MeV Pulsed–sphere TOF spectra

Thermal 3.0 5.0 15.0

Nuclear-data energy range simulations are sensitive to (MeV)


Pu, 0.7 mfp, NE213-A, 117

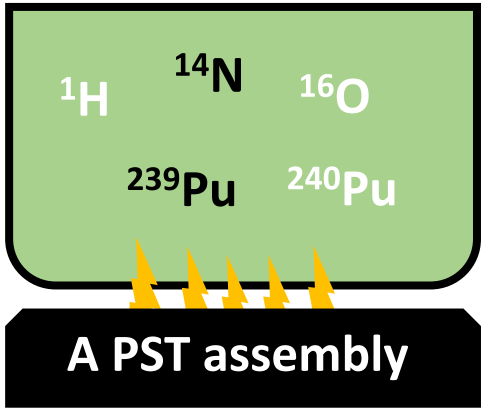
14-MeV LLNL pulsed-sphere TOF spectra extend validation of nuclear data from 5 to 15 MeV compared to criticality.

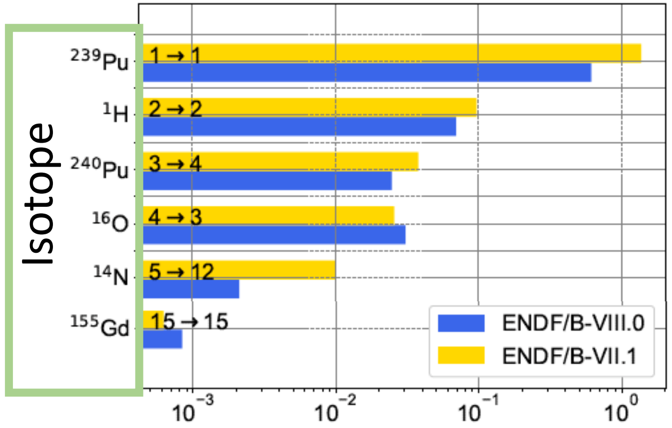
Caveat: currently experiments and uncertainties not as stringently quantified as criticality experiments BUT work is ongoing to include into SINBAD (WPEC SG-47).

Experiments: Wong et al., UCRL-51144, UCRL-ID-91774, Webster et al. UCID-17332.

Pulsed Sphere TOF spectra allow us to investigate the following nuclear data separately: light elements, structural isotopes, fuels.

Criticality Benchmarks

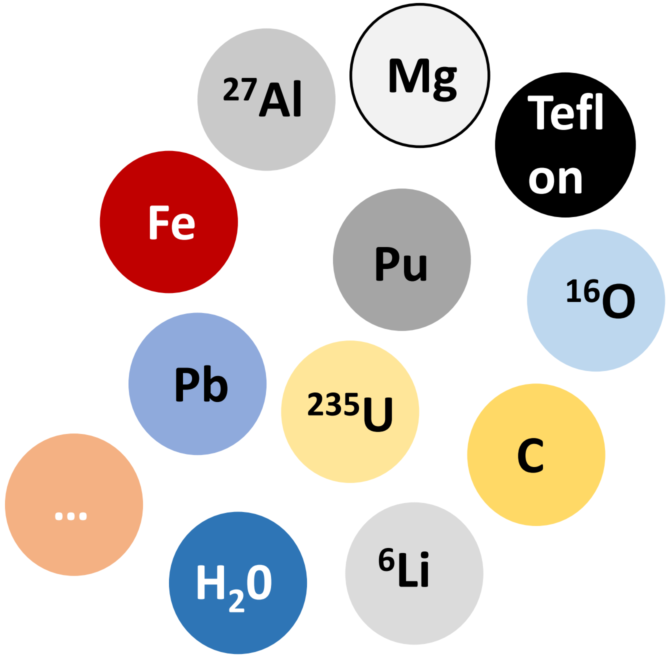




Importance of Nuclear Data for Bias

Neudecker et al., NDS 167, 36 (2020).

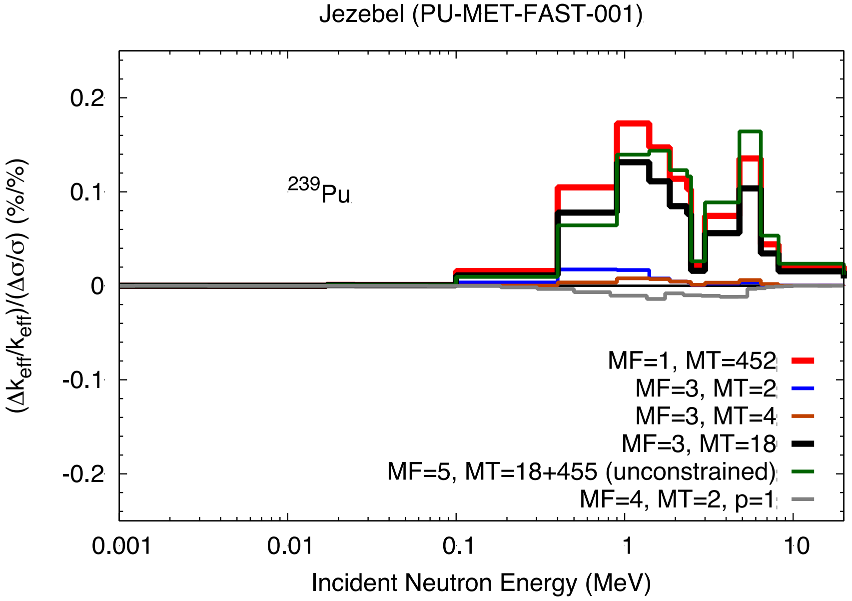
14-MeV LLNL pulsed spheres



Neudecker et al., LA-UR- 20-28636, submitted: “Issues could be in ^{6}Li, ^{12}C, ^{16}O, $^{24\text{-}26}$Mg, ^{27}Al, ^{48}Ti, ^{56}Fe, and ^{208}Pb nuclear data. Good agreement is found with ^{1,2}H, ^{7}Li, ^{9}Be, ^{14}N, ^{235,238}U, and ^{239}Pu nuclear data.”

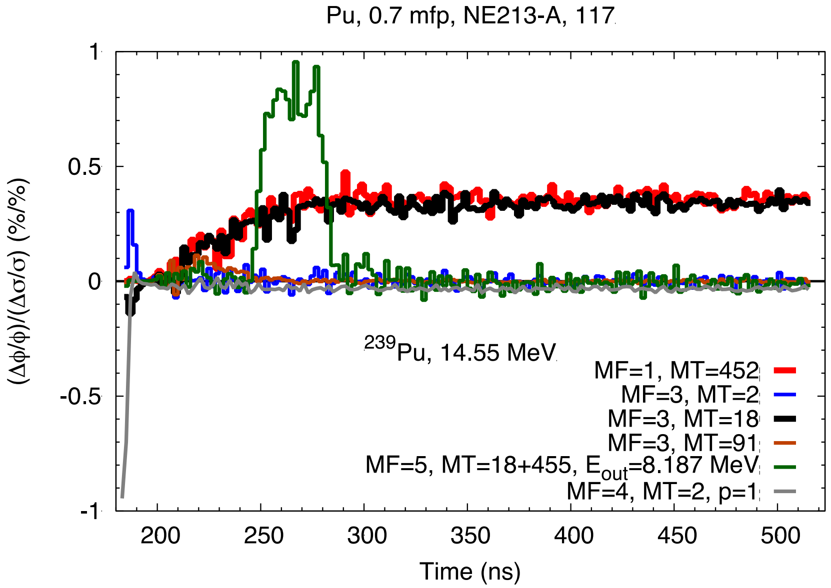
Pulsed Sphere TOF spectra enable studying fission-source term observables and angular distributions differently than criticality.

Criticality Benchmarks



Relative sensitivity of average fission neutron multiplicity versus, fission neutron spectrum, fission cross section similar for criticality benchmarks.

14-MeV LLNL pulsed spheres



Impact of angular distributions and fission-neutron spectrum for TOF spectra different from criticality benchmarks.

TOF spectra at overlapping pulse energy to criticality allow to disentangle angular distributions and fission source term.

Haeck et al., Trans. Am. Nucl. Soc. Winter Meeting, Nov. 15-19 (2020).