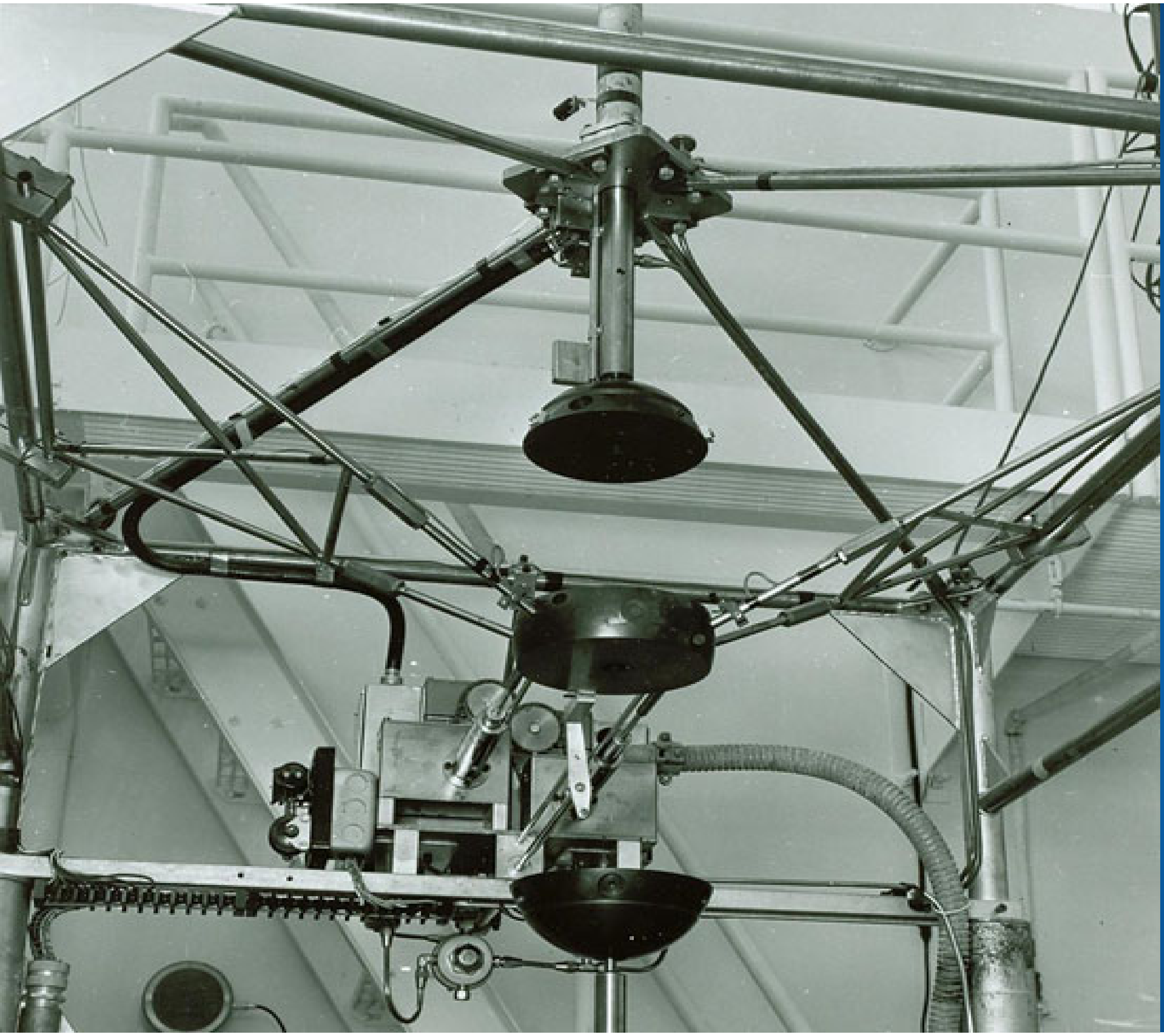

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The Zeus Assembly on Comet: Past, Present and Future Benchmarks

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November 2018
ANS Winter Meeting

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NNSA National Nuclear Security Administration

Outline

- Introduction
- Motivation
- Zeus Overview
- Present Experiments
- Future Experiments
- Current Issues and Zeus Benchmark Results
- Future Work

Introduction

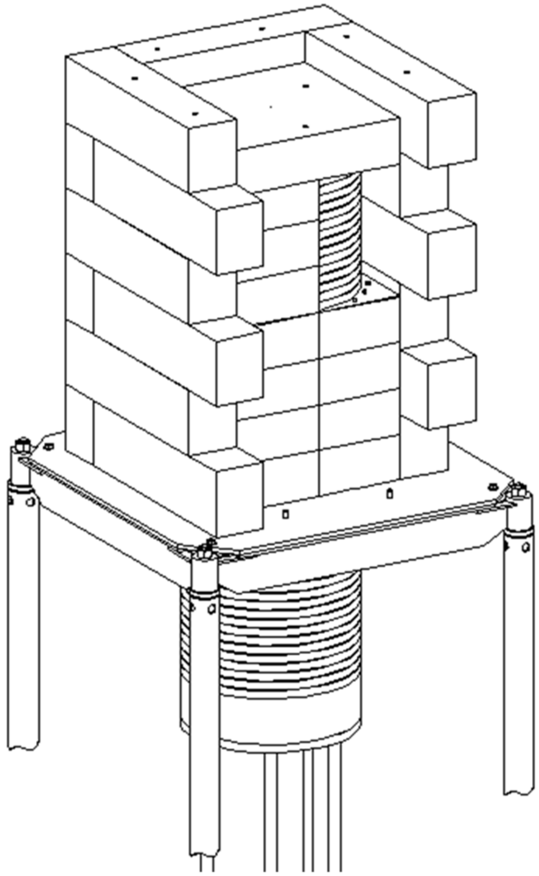
Why and when was the need for Intermediate Energy Experiments Established?

- Established in the 1990s
  - Lots of data in the fast energy region
  - Lots of data in the thermal energy region
    - Very little data in the intermediate energy region

- Why?
  - Thermal and fast systems are easy to design- both go towards the minimum critical mass points on a curve
  - Intermediate energy systems are hard

- Needs
  - Waste storage
  - Processing facility upset conditions

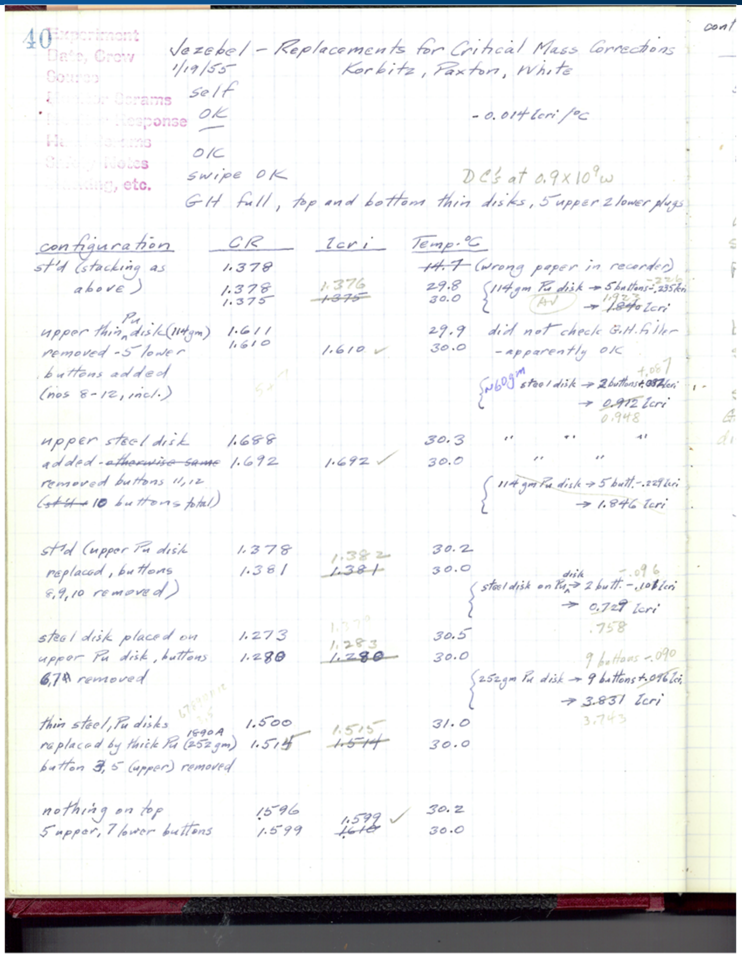
- Emerging capabilities
  - Codes continued to improve and could handle more complex structure, such as occurs in the intermediate energy region



Who?

- **Requested by the criticality safety community**

- **Why Los Alamos?**
  - The team at LACEF, now NCERC, is based on people who have been performing critical experiments for over 75 years
  - Maintained staffing and knowledge throughout the full time
    - Did not suffer from the “brain drain”
  - Known for keeping detailed records and logbooks, dating back to the very early days
  - Designers with knowledge skills and technical competence in many areas, not just criticality safety
    - Broad understanding of how to design the most useful and widely applicable experiment



Motivation

ZEUS + ^{235}U Unresolved Region Evaluation (2004)

L. Leal et al. “An Unresolved Resonance Evaluation for ^{235}U ” PHYSOR (2004)
https://www.ipen.br/biblioteca/cd/physor/2004/PHYSOR04/papers/93492.pdf

Increased work on the nuclear data associated with the intermediate energy region

Table 4 Comparisons of k_{eff} calculations using the unresolved ^{235}U evaluation.

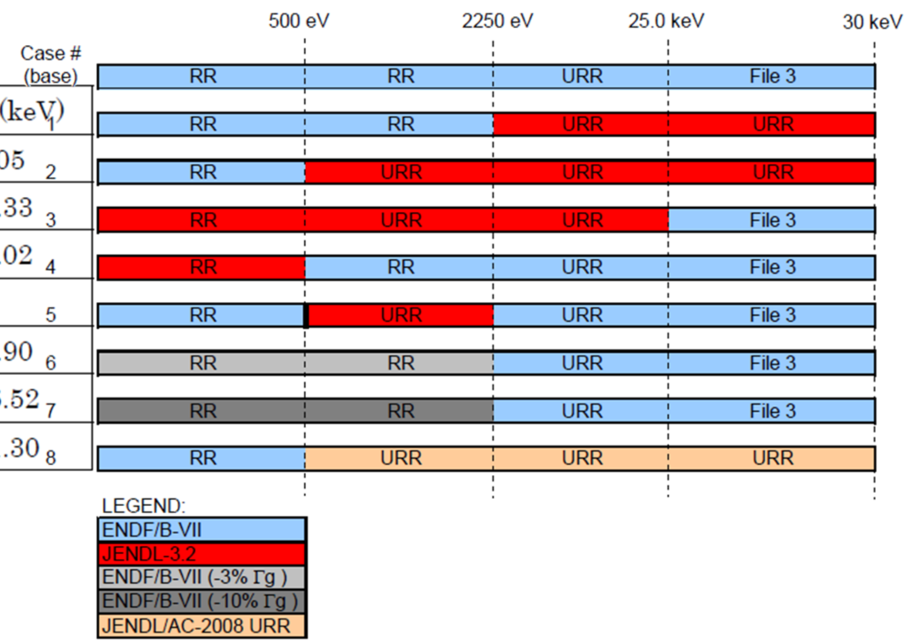
Benchmark	Experimental k_{eff}	MCNP ENDF66	MCNP ENDF66 with ^{235}U ORNL Evaluation
ORNL10	1.0015 ± 0.0010	0.9987 ± 0.0004	0.9991 ± 0.0004
HISS/HUG	1.0000 ± 0.0040	1.0099 ± 0.0005	1.0092 ± 0.0005
UH_3 (1)	1.0000 ± 0.0047	1.0040 ± 0.0050	1.0020 ± 0.0005
Zeus (1)	0.9976 ± 0.0008	0.9918 ± 0.0003	0.9899 ± 0.0003
Zeus (2)	0.9997 ± 0.0008	0.9945 ± 0.0003	0.9927 ± 0.0003
Zeus (3)	1.0010 ± 0.0009	0.9990 ± 0.0003	0.9965 ± 0.0003
Godiva	1.0000 ± 0.0010	0.9966 ± 0.0001	0.9964 ± 0.0001

ZEUS + ^{235}U Intermediate Energy Capture Evaluation (2004)

O. Iwamato et al. "^{235}U Capture Cross Section in the keV to MeV Energy Region" NEA/WPEC Subgroup 29 Final Report (2011)
https://www.oecd-nea.org/science/wpec/meeting2011/Sg29_report-20110420.pdf

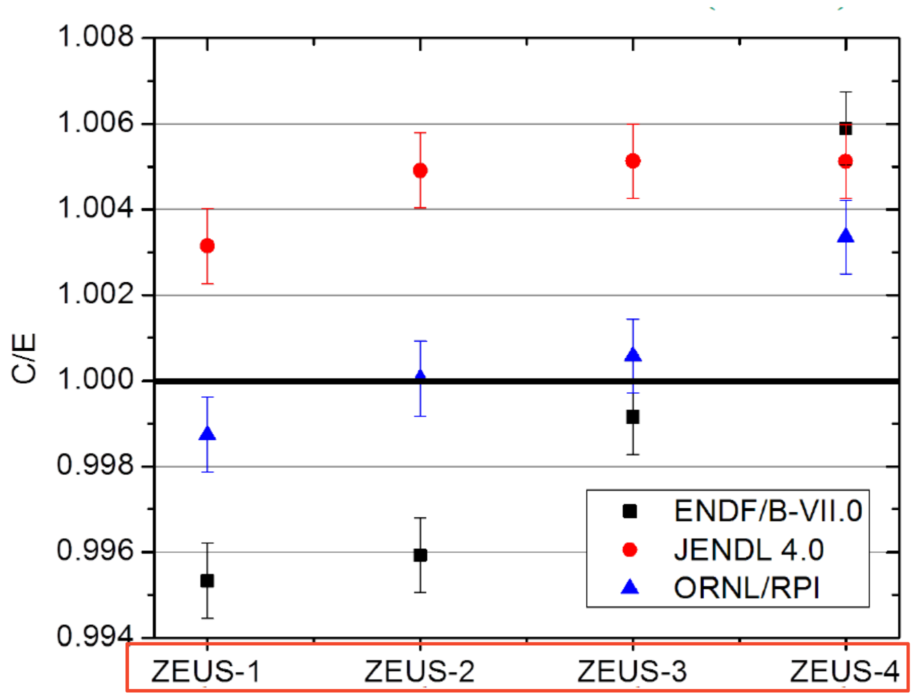
Table 2. Energy of the average lethargy causing fission (AVG)

Name	Spectrum	Handbook ID	AVG (keV)
ZEUS1	Intermediate	HEU-MET-INTER-006, case1	5.05
ZEUS2	Intermediate	HEU-MET-INTER-006, case2	10.33
ZEUS3	Intermediate	HEU-MET-INTER-006, case3	24.02
ZEUS4	Intermediate	HEU-MET-INTER-006, case4	
FCA-IX-1	Intermediate		29.90
FCA-IX-2	Intermediate		116.52
FCA-IX-3	Intermediate		211.30



ZEUS + ^{235}U Intermediate Energy Capture Evaluation (2014)

L. Leal et al. "Nuclear Data Evaluation Accomplishments" NCSP Program Review (2014)
https://ncsp.llnl.gov/TPRAgendas/2014/LEAL.pdf



Why is the Unresolved Resonance Region for ^{235}U important to re-visit?

Integral Benchmarks for Int. Energy Data and Methods Validation are Sparse

- **Only a handful of intermediate benchmarks available/used for the ^{235}U evaluation in this region.**
  - ZEUS is used in all of them.

- **Intermediate benchmark may help with other ^{235}U nuclear data validation needs**
  - Intermediate energy benchmarks found to be sensitive nubar changes (See CSWEG presentation by A. Pavlou, J Thompson).

Naval Nuclear Laboratory Analysis of the ENDF/B-VIII.0β5 Library

CSEWG 2017

November 6-9, 2017

Neutrons are Born Fast and are Easy to Thermalize…

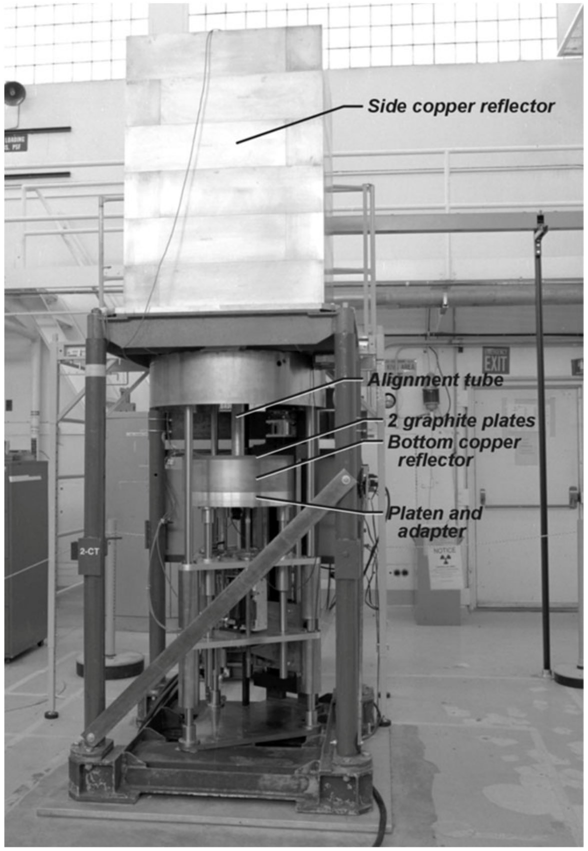
- **Which makes the design and execution of intermediate neutron energy experiments a challenge!**
  - Integral measurements require very large moderated/reflected systems.

ZEUS (LANL) and ZEBRA-8H (UKAEA)
integral measurements

Zeus Overview

Zeus

- **Initially Designed and Conducted at the Los Alamos Critical Experiments Facility in mid 1990s**
  - Designed to address need for intermediate energy integral experiments
    - Established by criticality safety community
  - Known facts about planned system
    - Requires large amount of SNM
    - Similarly, requires large overall size
    - Moderate reflector would reduce size and SNM quantity to within the LACEF inventory
    - Moderate reflector would return neutrons to core with some energy loss, but not overly thermalized
    - Large amounts of reflector meant cost had to be considered
  - Nuclear Data Gaps considered
    - Iron had known issues, so could not be used
    - Copper met cost/ nuclear data quality requirements



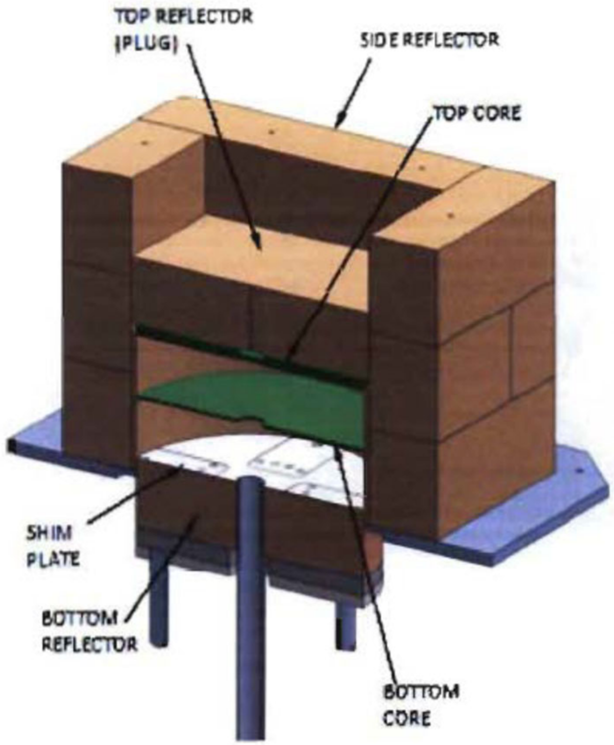
- **National Criticality Experiments Research Center located at the Nevada National Security Site**
  - Four critical assembly devices: Comet, Planet, Flat-Top, Godiva-IV
    - Zeus experiments have been reproduced here on Comet

Zeus- General Description

- **HEU plates**
  - 0.299 cm thick, 53.34 cm OD
  - ~93 wt% U-235

- **Copper Reflector**
  - 16.205 cm thick on all sides (including top and bottom)
  - Log form to reduce leakage gaps
  - All pieces are well characterized with known impurity content
  - All at least 95 wt% Cu

- **Moderators**
  - Varying amounts of plates of stock thickness
  - Well-characterized
  - Continuous Pattern

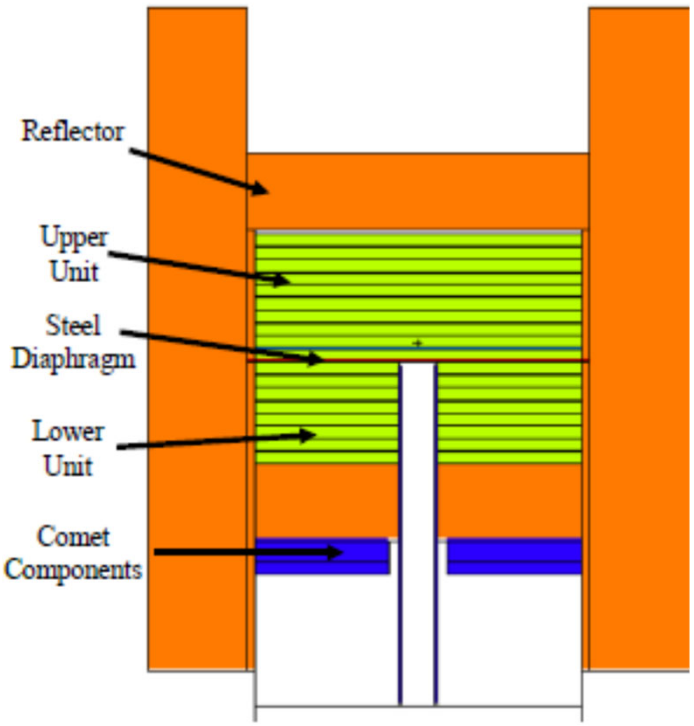


Zeus- Experiments and Benchmarks

- **Initial Experimental Series**
  - Graphite moderator/ interstitial plates of varying thicknesses
    - Graphite thicknesses: 8.05888, 6.04416, 4.02944, 2.01472 cm
    - Percent fissions in the Intermediate Energy Range: 72.8, 69.8, 63.6, 50.3
    - HEU-MET-INTER-006

- **Unmoderated Zeus Experimental Series**
  - \- no moderator/ interstitial plates
    - HEU-MET-FAST-073

- **Additional Zeus Series**
  - Iron moderator/ interstitial plates of varying thickness
    - HEU-MET-FAST-072



Present Experiments

Zeus Variations at NCERC

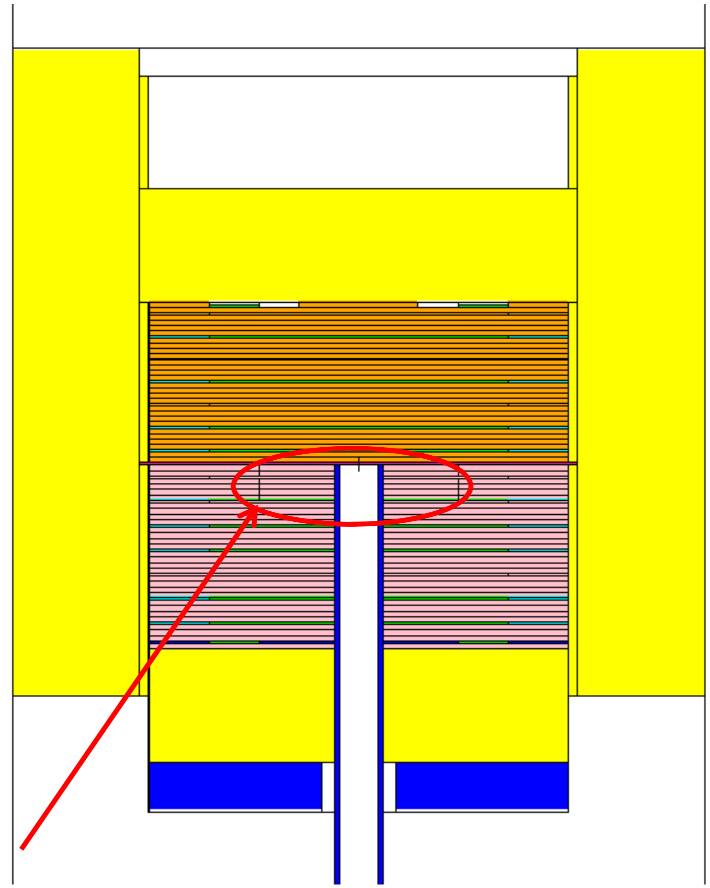
- **JAEA approached LANL in 2014 for desire for lead-void experiments**
  - Needed to support their planned ADS system with lead-bismuth eutectic coolant
  - Lead cross sections in JENDL 3.3 and 4.0 give vastly different results
  - Return of FCA fuel (HEU and Pb) to US presented challenges to their testing capability

- **Why Zeus?**
  - Zeus provided the spectrum and characteristics of interest to the JAEA
  - Knowledge based on Zeus ICSBEP benchmarks
  - LANL worked with the JAEA to help them get what they desired

- **First joint experiments in March 2015**
  - Zeus setup
  - Lead interstitial
  - Replacement measurements with void for lead

Zeus Experiments at NCERC

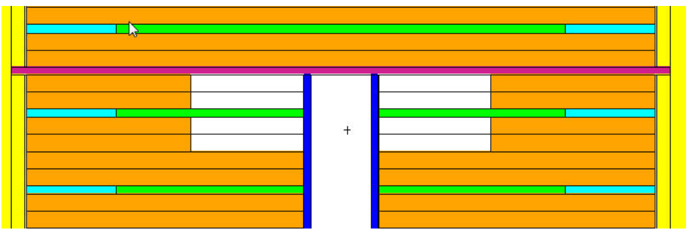
- **March 2015 Experiments: HEU-Lead Zeus**
  - Used Zeus copper
  - Zeus Jemima plates (HEU)
  - Lead and void interstitial
- **Unit**
  - Each consisted of 2 Al-Pb-Al pieces, 1 HEU pieces, and 2 Al-Pb-Al pieces
  - 6 units on top, 9 units on bottom
  - Spacers for void: Al mass matched mass of Al sandwich pieces
- **Goal**
  - Measure the void reactivity worth
  - New lead benchmark
  - Void Region is centered within the experiment



Region where voids are introduced

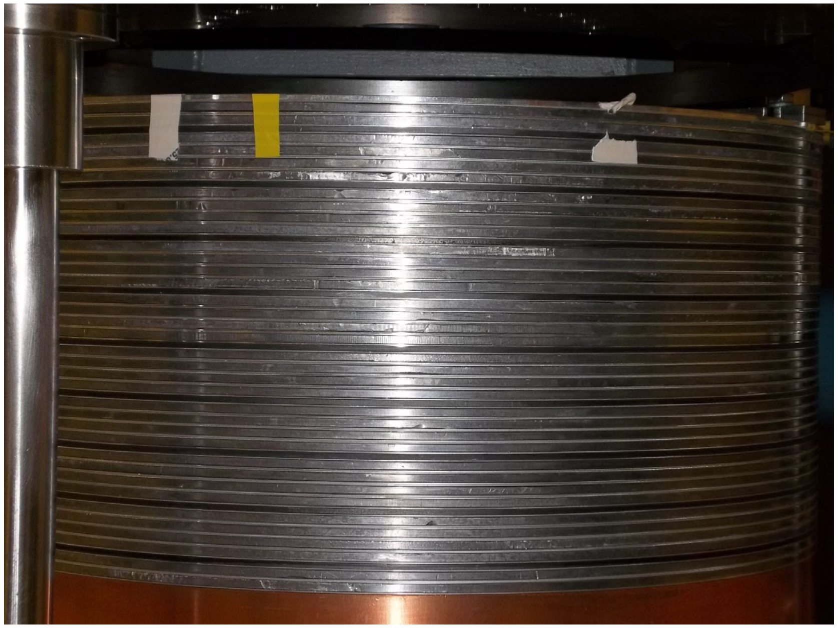
HEU Core Lead Void Experiments

HEU core (not to scale)
Void is 10” diameter



green/blue=HEU
orange=lead
yellow=copper
magenta=steel
blue=aluminum

Removed lead to measure change in reactivity
2V—One void above and one void below U plate.
4V—Void above and below two U plates.
Void with aluminum piece

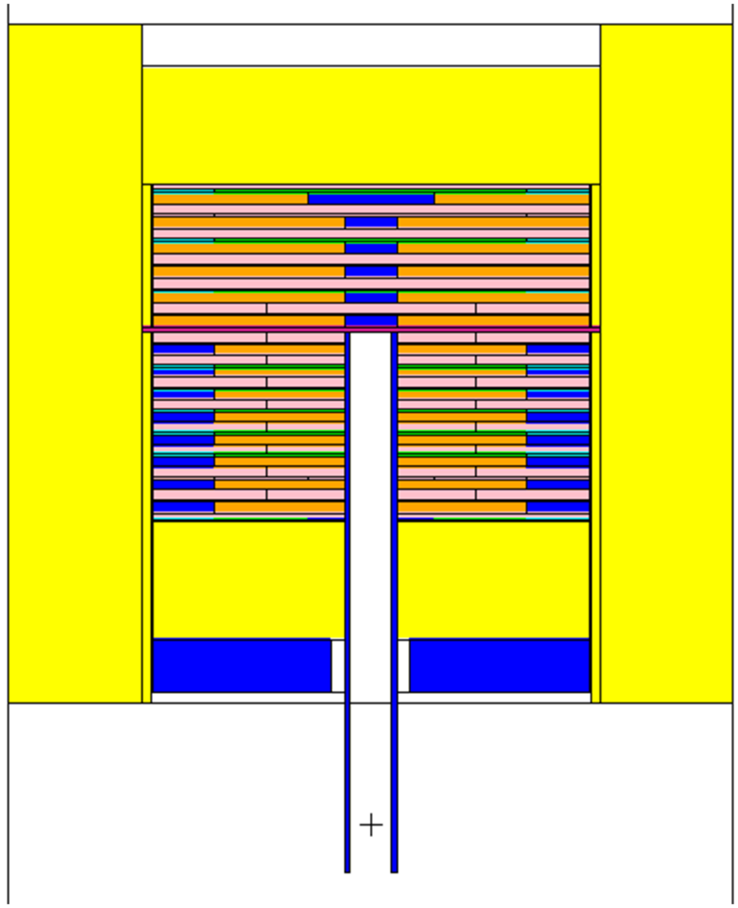


Zeus Experiments at NCERC Round 2

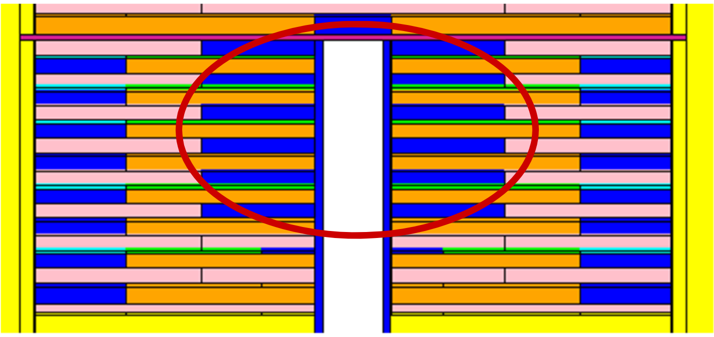
- **Continued work with JAEA**
  - Similar to HEU lead-void, but with pseudo LEU
  - Again, used Zeus setup, Jemima plates, lead

- **LEU?**
  - Mixed HEU Jemima plates with NatU Big Ten plates (same diameter)
  - Effective enrichment ~20%
  - Used Aluminum rings in place of some outer NatU to cut down on weight (Comet limitation of 2,000 lbs on movable platen)

- **Additional Goals**
  - Void worth predicted to be positive, whereas it was negative for HEU



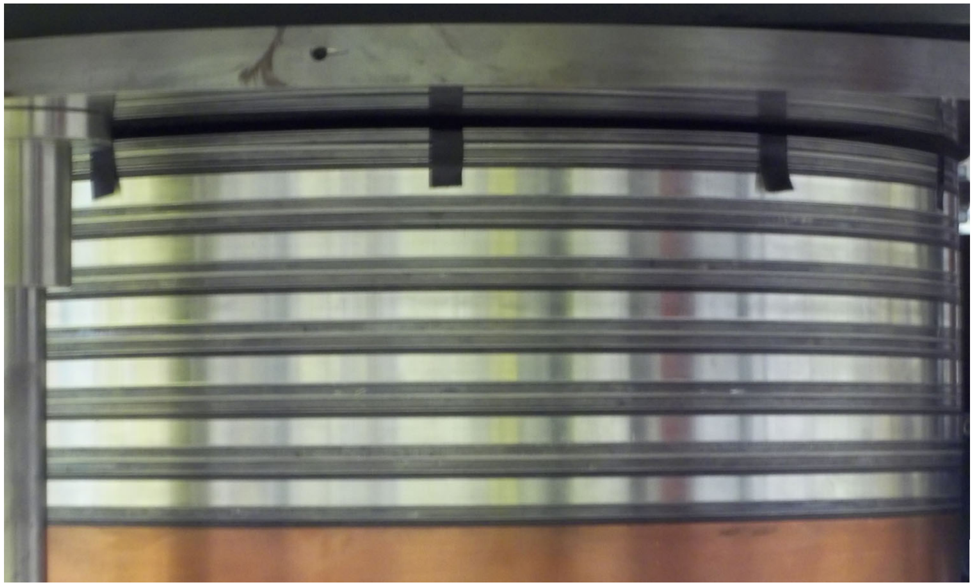
LEU Core Lead Void Experiments



Void region
6V case
shown

green/blue=HEU
orange=lead
yellow=copper
magenta=steel
blue=aluminum

Removed lead to measure
change in reactivity

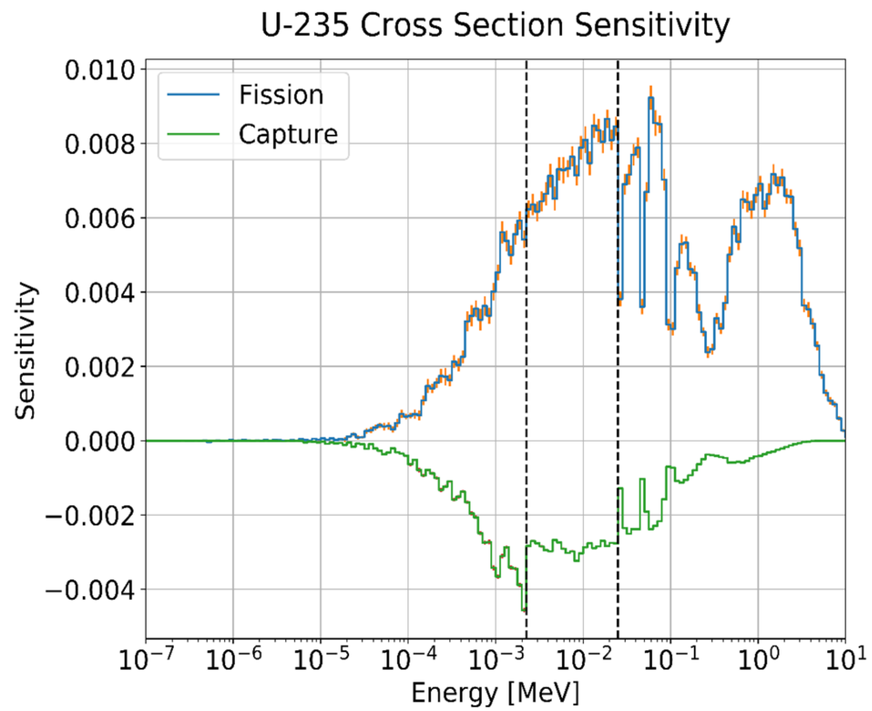


Preliminary results show good agreement between model and experiment

Future Experiments

Critical Unresolved Region Integral Experiment (CURIE)

- **Zeus setup (same HEU plates, same copper reflector)**
- **Moderators**
  - Teflon
  - Optimized thickness for fission sensitivity in the URR
- **Utilized ENDF-B/VII.1 and MCNP®6.2**
- **Additional Parameters of Interest**
  - URR Capture Sensitivity
  - Total Fission Integral Sensitivity
  - Fission to Capture Ratio Integral Sensitivity
  - URR Fission to Capture Ratio Integral Sensitivity
  - Financial Feasibility
  - Nuclear Data Quality Associated with Materials
- **Focus is validation and testing of URR inside the Intermediate Energy Region**



Current Issues and Zeus Benchmark Results

Current Issues

- **How reliable is the Zeus Series?**
  - (C-E) ~500 pcm
  - Should this setup be duplicated…

- **LANL View**
  - Data Sets that vary from expected results lead to improvements in nuclear data
    - They show the sensitivities and parts of the spectrum that are not well understood
  - Materials used in Zeus have been extensively characterized

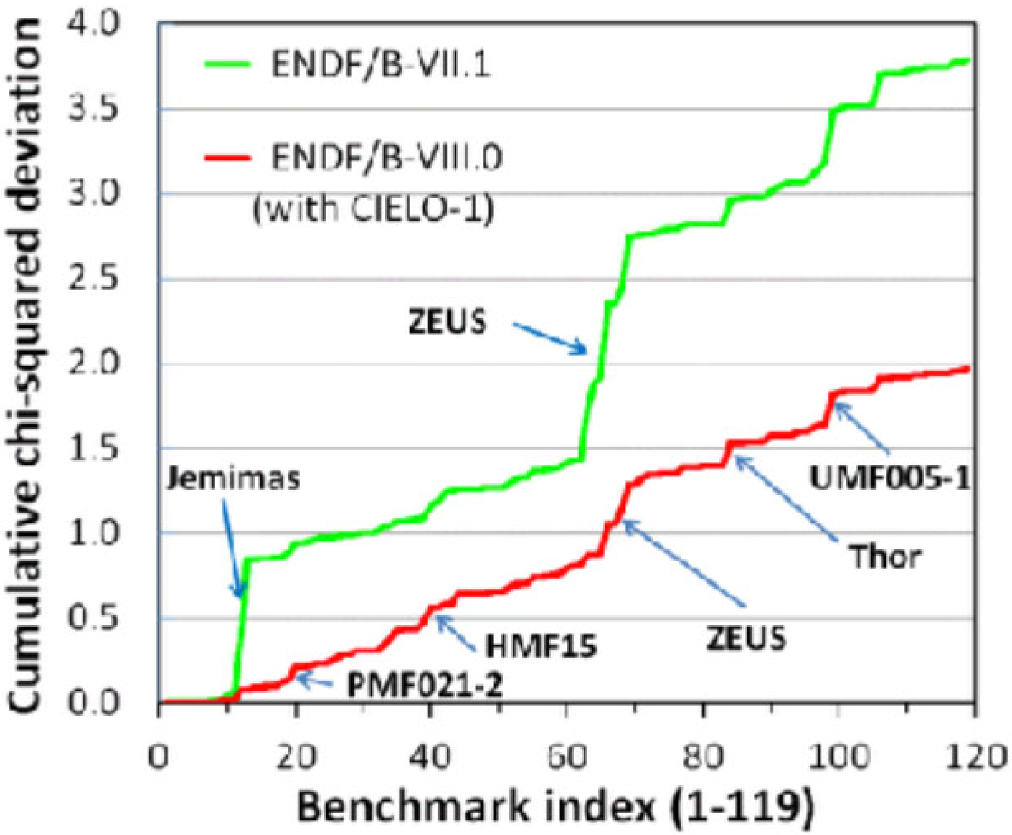
Zeus Benchmark Results

	(C-E) [pcm]				
ENDF Library	V	VI	VI.4	VII.1	VIII
HEU-MET-FAST-073-001	-420	780	-	775	-65
HEU-MET-INTER-006-001	-140	-650	-310	-471	-207
HEU-MET-INTER-006-002	-90	-450	-160	-322	16
HEU-MET-INTER-006-003	-120	-280	80	-69	201
HEU-MET-INTER-006-004	-80	320	470	548	391

Benchmark results show overall improvement as cross sections are improved to better match the integral results and nuclear data

many experiments (differential and integral) have been done to support this effort

Zeus Benchmark Results



Planned Benchmarks

- **HEU/Pb experiments**
  - Going to ICSBEP in Fall 2019
  - Joint effort by UC Berkeley and Los Alamos
- **LEU/ Pb Experiments**
  - Going to ICSBEP in Fall 2019
  - Joint effort by JAEA and LANL
- **CURIE Experiments**
  - Goal is ICSBEP in Fall 2020

Conclusions and Future Work

Conclusions and Future Work

- Zeus Series has long history and extensive use in nuclear data improvement efforts
- Since NCERC established, rise in awareness and interest Zeus intermediate energy experiments
- Zeus is a well characterized system which is highly sensitive to the intermediate energy region

Thank you!

This work was supported by the DOE Nuclear Criticality Safety Program, funded and managed by the National Nuclear Security Administration for the Department of Energy

BACKUP: Other Past Benchmarks Used for ^{235}U Intermediate Evaluation

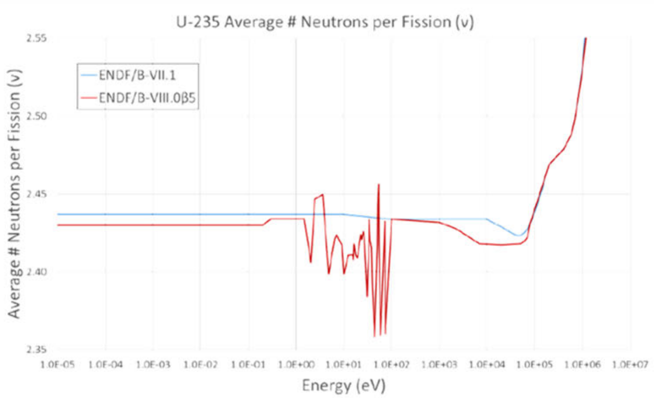
CSWEG KAPL Presentation (2017)
https://indico.bnl.gov/event/3580/contributions/10453/attachments/9386/11482/NNL_CSEWG_2017.pdf

HCI_003_04 Benchmark: Effect of ν

	E7.1	E7.1 + U-235 E8.0β5	Difference [%]
Capture ($\Sigma_\gamma\phi$)	2.094E-01	2.084E-01	-0.466
Leakage ($DB^2\phi$)	3.908E-01	3.889E-01	-0.470
Fission ($\Sigma_f\phi$)	3.998E-01	4.026E-01	+0.703
Nu (ν)	2.511	2.502	-0.351
Nu-Fission ($\nu\Sigma_f\phi$)	1.00383	1.00734	+0.349
k-eff (k)	1.00383	1.00734	+0.349

$$k = \frac{\nu\Sigma_f\phi}{\Sigma_\gamma\phi + \Sigma_f\phi + DB^2\phi} = \nu\Sigma_f\phi$$

Average neutrons per fission (nu) dropped from 2.511 to 2.502 between E7.1 and E8.0β5



- 409 pcm increase from:
  - Fe-56 ESAD/capture
  - U-235 capture/fission
  - U-235 ν

- HEU intermediate-spectrum models (HCI) are sensitive to changes in U-235 and O-16
  - nubar change has a 300-400 pcm affect

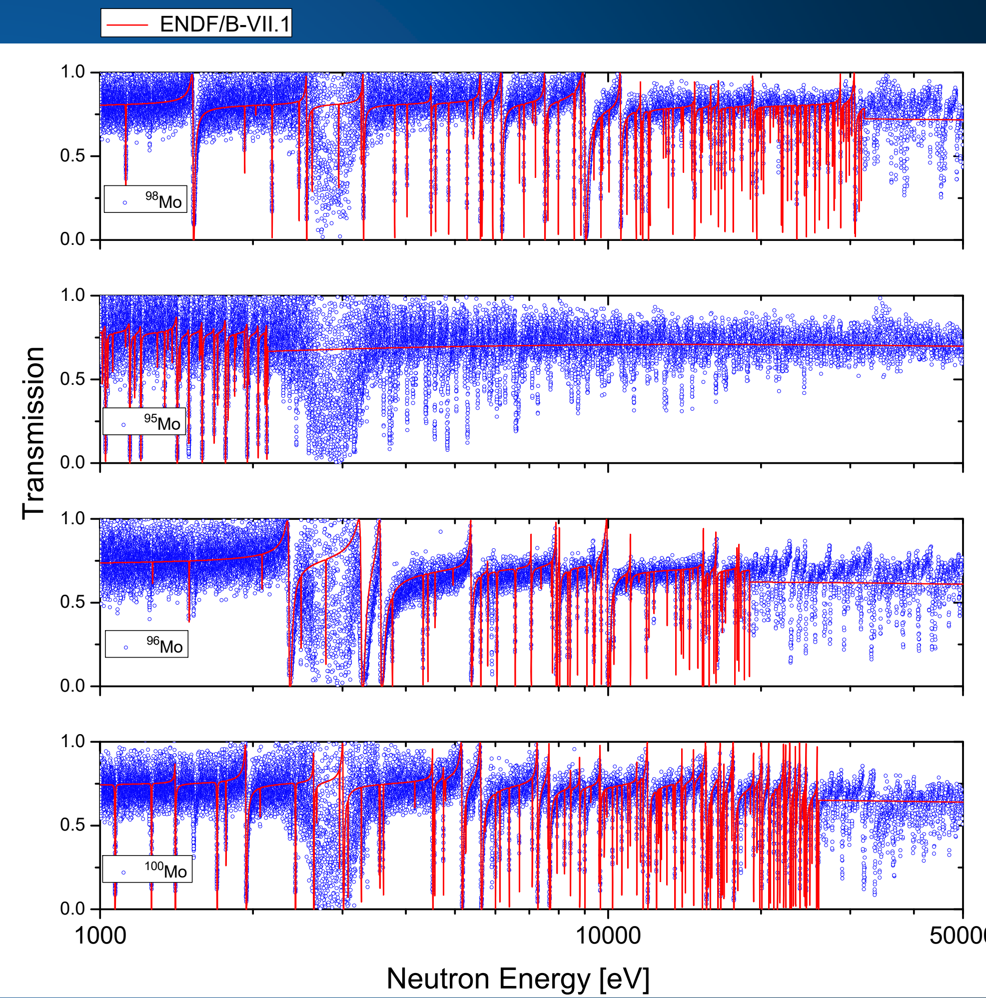
NAVAL NUCLEAR LABORATORY

Re-visiting Molybdenum Intermediate Energy Data

- **Integral Benchmarks**
  - Sparse - only one (discrepant) HEU-inter, no Pu-inter
  - Discrepancy - several thousand pcm difference.

- **Differential Data**
  - Disagreements between international evaluations including average parameters and upper URR boundaries
  - Recent RPI (Danon) high resolution isotopic Mo intermediate energy data

Figure from R. Bahran, Y. Danon et al. *Phys Rev C.* (2013)



Acknowledgments

- This material is based upon work supported by the Department of Energy Nuclear Criticality Safety Program, funded and managed by the National Nuclear Security Administration for the Department of Energy.

BACKUP: ENDF File for URR

Pointed out by Dave Brown for ^{235}U :

Infinitely dilute cross-sections calculated from the average resonance parameters in ENDF file 2 is not always in agreement with the infinitely diluted cross section in file 3 (obtained from the best combination of measurements and models as provided by evaluators).

One can enforce the LSSF=1 option and adopt resonance parameter interpolation instead of cross section interpolation in the URR for more accuracy even though interpolating the cross section is a faster calculation.

BACKUP: Why can't we just measure the resonances in the URR?

- When the level spacing between isolated resonances becomes comparable to the average natural width of these resonances, a continuum of overlapping averaged resonances will be observed.