

LA-UR-16-21659

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**Title:** **Lecture Notes on Criticality Safety  
Validation Using MCNP & Whisper**

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**Issued:** 2016-03-11

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# Lecture Notes on Criticality Safety Validation Using MCNP & Whisper

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Los Alamos National Laboratory  
2016-03-11**

## Lecture Notes on Criticality Safety Validation Using MCNP & Whisper

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2. Background for MCNP & Whisper
  - a) Best Practices for Monte Carlo Criticality Calculations
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## Whisper - Software for Sensitivity-Uncertainty-Based Nuclear Criticality Safety Validation

Whisper is computational software designed to assist the nuclear criticality safety (NCS) analyst with validation studies with the Monte Carlo radiation transport package MCNP. Standard approaches to validation rely on the selection of benchmarks based upon expert judgment. Whisper uses sensitivity/uncertainty (S/U) methods to select relevant benchmarks to a particular application or area of applicability (AOA), or set of applications being analyzed. Using these benchmarks, Whisper computes a calculational margin from an extreme value distribution. In NCS, a margin of subcriticality (MOS) that accounts for unknowns about the analysis. Typically, this MOS is some prescribed number by institutional requirements and/or derived from expert judgment, encompassing many aspects of criticality safety. Whisper will attempt to quantify the margin from two sources of potential unknowns, errors in the software and uncertainties in nuclear data. The Whisper-derived calculational margin and MOS may be used to set a baseline upper subcritical limit (USL) for a particular AOA, and additional margin may be applied by the NCS analyst as appropriate to ensure subcriticality for a specific application in the AOA.

Whisper provides a benchmark library containing over 1,100 MCNP input files spanning a large set of fissionable isotopes, forms (metal, oxide, solution), geometries, spectral characteristics, etc. Along with the benchmark library are scripts that may be used to add new benchmarks to the set; this documentation provides instructions for doing so. If the user desires, Whisper may analyze benchmarks using a generalized linear least squares (GLLS) fitting based on nuclear data covariances and identify those of lower quality. These may, at the discretion of the NCS analyst and their institution, be excluded from the validation to prevent contamination of potentially low quality data. Whisper provides a set of recommended benchmarks to be optionally excluded.

Whisper also provides two sets of 44-group covariance data. The first set is the same data that is distributed with SCALE 6.1 in a format that Whisper can parse. The second set is an adjusted nuclear data library based upon a GLLS fitting of the benchmarks following rejection. Whisper uses the latter to quantify the effect of nuclear data uncertainties within the MOS. Whisper also has the option to perform a nuclear covariance data adjustment to produce a custom adjusted covariance library for a different set of benchmarks.

**Background:** These lecture notes were prepared during 2015-2016 for educational & technical interchanges between the Monte Carlo Codes Group (XCP-3) and Criticality Safety Analysts in the Nuclear Criticality Division at LANL.

**Acknowledgements:** Thanks to the XCP & NCS Division Leaders for promoting and supporting the XCP3-NCS interchange sessions. Thanks to the DOE Nuclear Criticality Safety Program for its long-term support for developing advanced MCNP6 capabilities, including the iterated fission probability, adjoint-weighted tallies, sensitivity/uncertainty features, and Whisper statistical analysis. Thanks to the LANL PF4-Restart program for supporting some of the LANL-specific portions of this work, including direct support for assisting the NCS criticality safety analysts.

## Whisper? Who cares?

- Sensitivity/Uncertainty methods for validation have been under development for > 18 years at ORNL (Broadhead, Rearden, Perfetti, ...)
- Kiedrowski & Brown developed MCNP iterated fission probability, adjoint weighted tallies, & S/U capabilities, 2008-2013. Whisper in 2014.
- There are now 2 calculational paths for S/U based validation:
  - SCALE/Tsunami/Tsurfer ORNL
  - MCNP/Whisper LANL
- International effort for comparisons being planned
  - LANL, ORNL, IRSN
- S/U based validation methods can supplement, support, & extend traditional validation methods, provide greater assurance for setting USLs
- The next 5 years or so should be a transition period, where both traditional & S/U methods should be used
  - Traditional methods provide a check on S/U methods
  - S/U approach to automated benchmark selection is quantitative, physics-based, & repeatable. Provides a check on traditional selection
  - Traditional methods use  $MOS_{data+code}$  of 2-5%.  
Quantitative, physics-based, repeatable  $MOS_{data+code}$  from S/U usually smaller

# Validation

## Some facts:

- Computer codes have approximations & errors
- Nuclear data have approximations & errors

## How can we ever design anything?

- Verify that codes work as intended
- **Validate** codes + data + methods against nature (experiments)
- **Reactor design:**
  - Calibrate codes & methods to nominal, but do 1000s or over/under calculations
- **Criticality safety:**
  - Focus on avoiding worst-case combination of mistakes, uncertainties, errors, ...
  - Rigor & conservatism always; never wishful thinking or "close enough"

- 10 CFR 830 Subpart A, Quality Assurance
- 10 CFR 830 Subpart B, Nuclear Safety Management
  
- DOE O 414.1C, Quality Assurance
- DOE G 414.1-4, Safety Software Guide for use with 10 CFR 830 Subpart A, Quality Assurance Requirements
- DOE G 421.1-2, Implementation Guide for Use in Developing Documented Safety Analyses to Meet Subpart B of 10 CFR 830
- DOE O 420.1C, Facility Safety
  
- DOE-STD-3007-2007, Guidelines for Preparing Criticality Safety Evaluations at DOE Nonreactor Nuclear Facilities
- DOE STD 1134-99 Review Guide for Criticality Safety Evaluations
- DOE-STD-1158-2010, Self-Assessment Standard for DOE Contractor Criticality Safety Programs
- DOE-STD-3009-94, Change Notice 3, Preparation Guide for U.S. Department of Energy Nonreactor Nuclear Facility Safety Analysis
- DOE-STD-1186-2004, Specific Administrative Controls
- DOE-STD-1027-92, Change Notice 1, Hazard Categorization and Accident Analysis Techniques for Compliance with DOE Order 5480.23, Nuclear Safety Analysis Reports
  
- **ANSI/ANS-8.1-2014, Nuclear Criticality Safety in Operations with Fissionable Materials Outside Reactors**
- ANSI/ANS-8.3-2003, Criticality Accident Alarm System
- ANSI/ANS-8.5-1996(R2007), Use of Borosilicate-Glass Raschig Rings as a Neutron Absorber in Solutions of Fissile Material
- ANSI/ANS 8.7-1998(R2012), Nuclear Criticality Safety in the Storage of Fissile Materials
- ANSI/ANS-8.10-2005, Criteria for Nuclear Criticality Safety Controls in Operations with Shielding and Confinement
- ANSI/ANS 8.14-2004, Use of Soluble Neutron Absorbers in Nuclear Facilities Outside Reactors
- ANSI/ANS 8.17-2004, Criticality Safety Criteria for the Handling, Storage, and Transportation of LWR Fuel Outside Reactors
- ANSI/ANS-8.19-2014, Administrative Practices for Nuclear Criticality Safety
- ANSI/ANS 8.20-1991(R2005), Nuclear Criticality Safety Training
- ANSI/ANS-8.21-1995(R2001), Use of Fixed Neutron Absorbers in Nuclear Facilities Outside Reactors
- ANSI/ANS-8.23-2007, Nuclear Criticality Accident Emergency Planning and Response
- **ANSI/ANS 8.24-2007, Validation of Neutron Transport Methods for Nuclear Criticality Safety Calculations**
- ANSI/ANS 8.26-2007, Criticality Safety Engineer Training and Qualification Program

- From ANSI/ANS-8.24-2007, Validation of Neutron Transport Methods for Nuclear Criticality Safety Calculations:
  - **Verification:** The process of confirming that the *computer code system* correctly performs numerical calculations.
  - **Validation:** The process of quantifying (e.g., establishing the appropriate **bias** and **bias uncertainty**) the suitability of the computer code system for use in nuclear criticality safety analyses.
  - **Computer code system:** A calculational method, computer hardware, and computer software (including the operating system).
  - **Calculational Method:** The mathematical procedures, equations, approximations, assumptions, and associated numerical parameters (e.g., cross sections) that yield the calculated results.

- From ANSI/ANS-8.24-2007, Validation of Neutron Transport Methods for Nuclear Criticality Safety Calculations:
  - **Bias:** The systematic difference between calculated results and experimental data.
  - **Bias Uncertainty:** The uncertainty that accounts for the combined effects of uncertainties in the experimental benchmarks, the calculational models of the benchmarks, and the calculational method.
  - **Calculational Margin:** An allowance for bias and bias uncertainty plus considerations of uncertainties related to interpolation, extrapolation, and trending.
  - **Margin of Subcriticality:** An allowance beyond the calculational margin to ensure subcriticality.
  - **Validation Applicability:** A domain, which could be beyond the bounds of the benchmark applicability, within which the margins derived from validation of the calculational method have been applied.

- 5.1 Appropriate system or process parameters that correlate the experiments to the system or process under consideration shall be identified. ....
- 5.2 Normal and credible abnormal conditions for the system or process shall be identified when determining the appropriate parameters and their range of values.
- 5.4 Selected benchmarks should encompass the appropriate parameter values spanning the range of normal and credible abnormal conditions anticipated for the system or process to which the validation will be applied.
- 7.2 The validation applicability should not be so large that a subset of the data with a high degree of similarity to the system or process would produce an upper subcritical limit that is lower than that determined for the entire set. This criterion is recommended to ensure that a subset of data that is closely related to the system or process is not nonconservatively masked by benchmarks that do not match the system as well.
- 8.1 The validation activity shall be documented with sufficient detail to allow for independent technical review.
  - 8.1.5 The margin of subcriticality and its basis shall be documented.
- 8.2 An independent technical review of the validation shall be performed. The independent technical review should include, but is not limited to, the following:
  - (1) a review of the benchmark applicability;
  - (2) a review of the input files and output files to ensure accurate modeling and adequate convergence;
  - (3) a review of the methodology, and its use, for determining bias, bias uncertainty, and margins;
  - (4) concurrence with the validation applicability.

- **Identify the range of applications to be considered**
  - Fissile material, geometry, reflection, moderation, etc.
  - Metrics to help characterize neutronics – EALF, % fast/thermal fissions, H/U or H/Pu for solutions, etc.
- **Select a set of experimental benchmarks from ICSBEP Handbook that are neutronically similar to the applications**
  - Must select sufficient number for valid statistical analysis
  - Analyze the set of benchmarks with Monte Carlo
- **Statistical analysis**
  - Determine bias & bias uncertainty for the set of benchmarks
  - For conservatism, usually set positive biases to zero & only consider negative biases for individual benchmarks
- **Estimate additional margin of subcriticality (MOS)**
  - Extra margin to account for nuclear data uncertainty
  - Extra margin to account for unknown code errors
  - Extra margin if applications not similar enough to benchmark set

- To consider a simulated system subcritical, the computed keff must be less than the Upper Subcritical Limit (USL):

$$K_{\text{calc}} < \text{USL}$$

$$\text{USL} = 1 + (\text{Bias}) - (\text{Bias uncertainty}) - \text{MOS}$$

**Note:** Bias = calculated – experiment,

For conservatism:

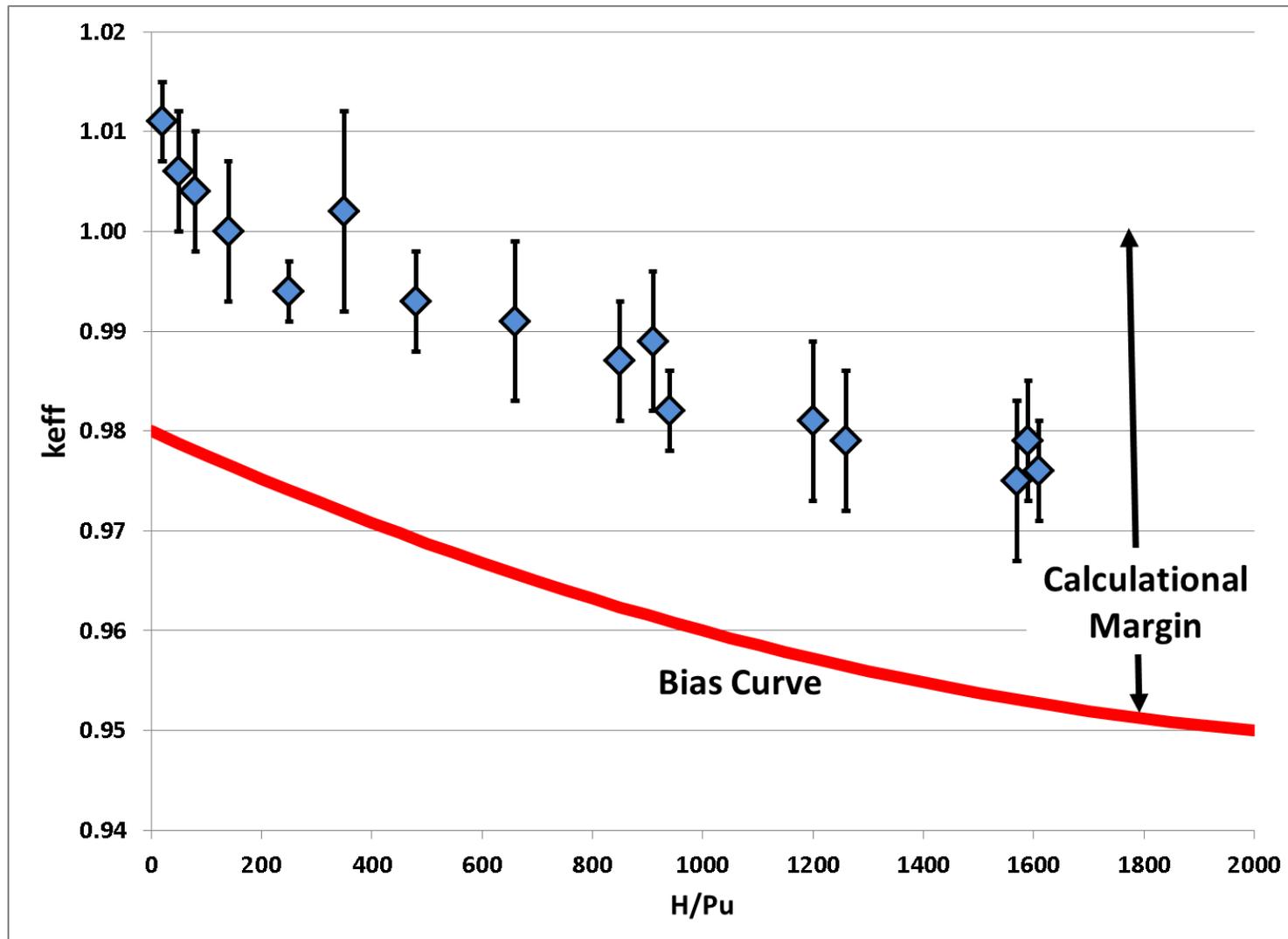
- positive biases are normally set to zero
- only negative biases are considered

- Bias & bias uncertainty are at some confidence level, typically 95% or 99%.
  - If these confidence intervals are derived from a normal distribution, the normality of the bias data must be justified.
  - Alternatively, the confidence intervals can be set using non-parametric methods.

- The calculational margin is the sum of the bias and the bias uncertainty.
  - **Bias:** represents the systematic difference between calculation and benchmark experiments.
  - **Bias uncertainty:** relates to uncertainties in the experimental benchmarks and the calculations.
  - Bias & bias uncertainty are routine calculations, for a given application & set of benchmarks
  - **Bias & bias uncertainty are only credible when the application & chosen benchmarks are neutronically similar**
  - Often quoted as 95/95 confidence, meaning that the calculation margin bounds 95% of the benchmark deviations at the 95% confidence level (assuming normality).
  - May trend calculational margin based upon physical parameters.

# Calculational Margin Example

- Hypothetical bias curve
  - Selected experiments with Pu metal and water mixtures



- **To establish a Margin of Subcriticality (MOS) need to consider the process, validation, codes, data, etc. holistically.**
  - **Confidence in the codes and data.**
    - More mature codes that are widely used have greater confidence than newer ones.
    - Deterministic methods require additional margin beyond Monte Carlo because of numerical issues (e.g., ray effects, discretization errors, self-shielding approximations, etc.).
  - **Adequacy of the validation**
    - Unlikely to find a benchmark experiment that is exactly like the model being simulated.
    - Based on trending analysis of physical parameters and/or sensitivity and uncertainty studies, can quantify “similarity”.
    - Sparsity of benchmark data, extrapolations, and wide interpolations necessitate larger margins.
- **Major contributors**
  - **Margin for uncertainties in nuclear cross-section data**
  - **Margin for unknown errors in codes**
  - **Additional margin to consider the limitations of describing process conditions based upon sensitivity studies, operating experience, administrative limits, etc.**

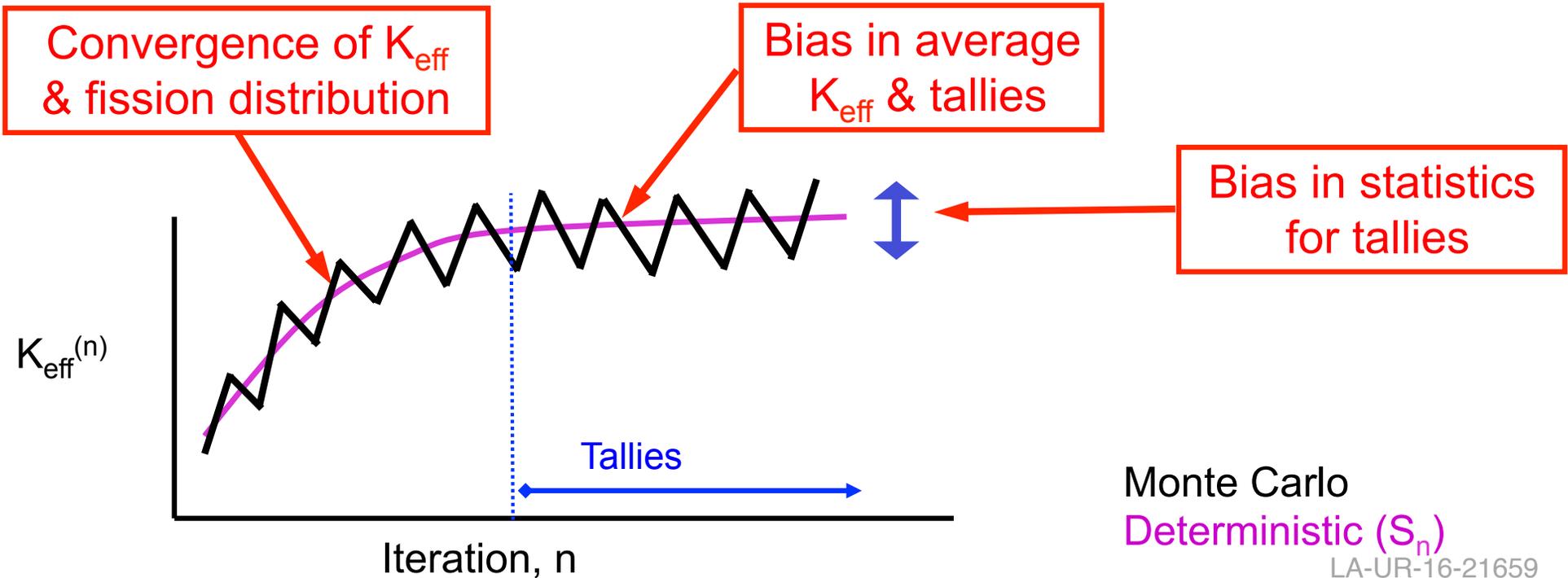
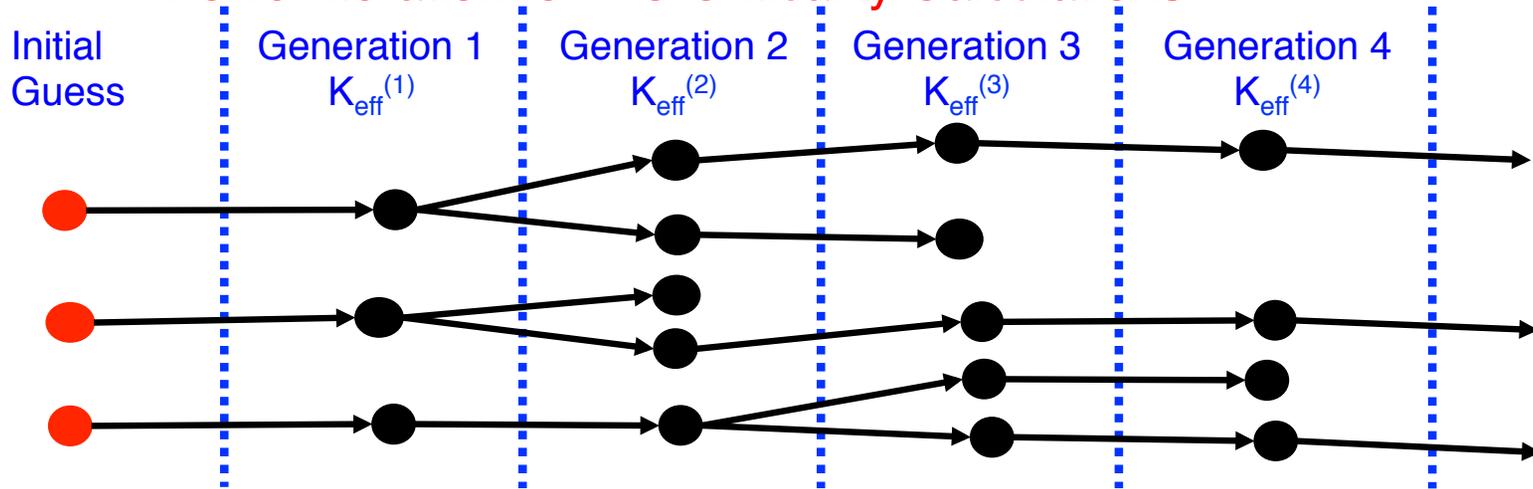
# Comparison of Validation Approaches (Simplified)

	Traditional, Simple	Traditional, Enhanced	S/U-Based Method
<b>Benchmark Collection</b>	Expert judgment, 1 set, Geometry & materials cover applications	Expert judgment, Several subsets (metal, solutions, other)	Large collection with sensitivity profile data, Reject outliers, Estimate missing uncertainties
<b>Selecting Benchmarks</b>		Expert judgment, Select subset based on geometry & materials	Automatically select benchmarks with sensitivity profiles closest to application
<b>Calculational Margin</b>	Determine bias & bias uncertainty	Determine bias & bias uncertainty, Possible trending within subset	Determine bias & bias uncertainty, Automatically use weighting based on application-specific Ck similarities
<b>Margin of Subcriticality</b>	Expert judgment, Very large	Expert judgment, Large	Automatically determine specific margin for data uncertainty by GLLS, Code-expert judgment for code, Expert judgment for additional
<b>Comment</b>	Easy to use, Highly dependent on expert judgment, Requires large conservative MOS	More work if trending, Very dependent on expert judgment, Subsets & trending may permit smaller MOS	Computer-intensive, quantitative, Less reliance on expert judgment, Calculated estimate for most of MOS

# Best Practices for Monte Carlo Criticality Calculations

- **Monte Carlo Criticality Calculations**
  - Methodology & Concerns
  - Convergence
  - Bias
  - Statistics
- **Best Practices**
  - Discussion
  - Conclusions

## Power Iteration for MC Criticality Calculations



Monte Carlo  
Deterministic ( $S_n$ )

- Monte Carlo codes use power iteration to solve for  $K_{\text{eff}}$  &  $\Psi$  for eigenvalue problems

- Power iteration convergence is well-understood:

$n$  = cycle number,  $k_0, u_0$  - fundamental,  $k_1, u_1$  - 1st higher mode

$$\Psi^{(n)}(\vec{r}) = \vec{u}_0(\vec{r}) + a_1 \cdot \rho^n \cdot \vec{u}_1(\vec{r}) + \dots$$
$$k_{\text{eff}}^{(n)} = k_0 \cdot \left[ 1 - \rho^{n-1} (1 - \rho) \cdot g_1 + \dots \right]$$

- First-harmonic source errors die out as  $\rho^n$ ,  $\rho = k_1 / k_0 < 1$
  - First-harmonic  $K_{\text{eff}}$  errors die out as  $\rho^{n-1} (1 - \rho)$
  - Source converges slower than  $K_{\text{eff}}$
- Most codes only provide tools for assessing  $K_{\text{eff}}$  convergence.
- MCNP also looks at Shannon entropy of the source distribution,  $H_{\text{src}}$ .

- **Power iteration is used for Monte Carlo  $K_{\text{eff}}$  calculations**
  - **For one cycle (iteration):**
    - $M_0$  neutrons start
    - $M_1$  neutrons produced,  $E[ M_1 ] = K_{\text{eff}} \cdot M_0$
  - **At end of each cycle, must renormalize by factor  $M_0 / M_1$**
  - **Dividing by stochastic quantity ( $M_1$ ) introduces bias in  $K_{\text{eff}}$  & tallies**

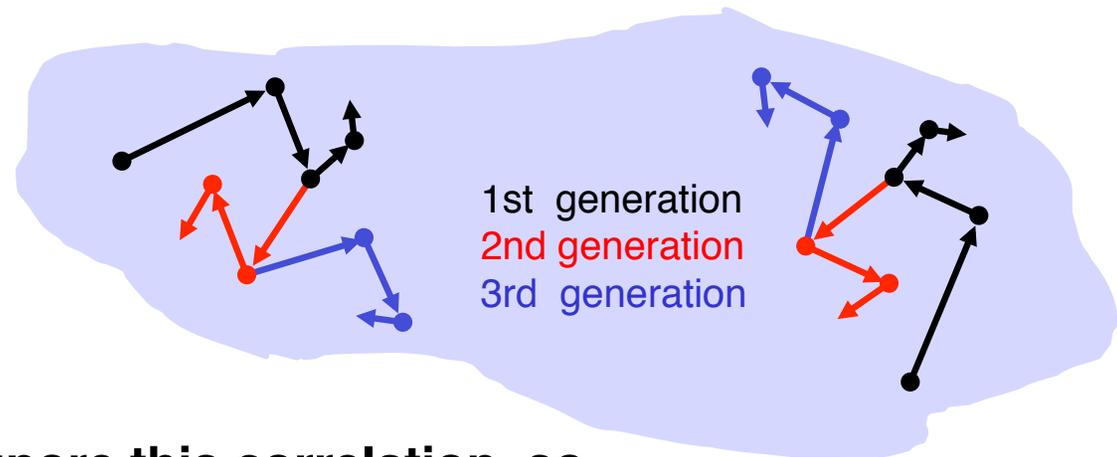
- **Bias in  $K_{\text{eff}}$ , due to renormalization**

$$\text{Bias in } K_{\text{eff}} \propto \frac{1}{M} \quad M = \text{neutrons / cycle}$$

- **Power & other tally distributions are also biased, produces “tilt”**

- MC eigenvalue calculations are solved by power iteration

- Tallies for one generation are spatially correlated with tallies in successive generations



- The correlation is positive

- MCNP & other MC codes ignore this correlation, so computed statistics are smaller than the real statistics

- Errors in statistics are small/negligible for  $K_{\text{eff}}$ , may be significant for local tallies (eg, fission distribution)

- Running more cycles or more neutrons/cycle does not reduce the underprediction bias in statistics

- (True  $\sigma^2$ ) > (computed  $\sigma^2$ )**, since correlations are positive

$$\frac{\text{True } \sigma_{\bar{X}}^2}{\text{Computed } \sigma_{\bar{X}}^2} = \frac{\sigma_{\bar{X}}^2}{\tilde{\sigma}_{\bar{X}}^2} \approx 1 + 2 \cdot \left( \begin{array}{l} \text{sum of lag-i correlation} \\ \text{coeff's between tallies} \end{array} \right)$$

- **To avoid bias in  $K_{\text{eff}}$  & tally distributions:**
  - Use 10K or more neutrons/cycle (maybe 100K+ for large system)
  - Always check convergence of both  $K_{\text{eff}}$  &  $H_{\text{src}}$
  - Discard sufficient initial cycles
- **To help with convergence & coverage:**
  - Take advantage of problem symmetry, if possible
  - Use good initial source guess, cover fissionable regions --  
points in each fissile region, or volume source for large systems
- **Run at least a few 100 active cycles  
to allow codes to compute reliable statistics**
- **Statistics on tallies from codes are underestimated, often by 2-5x;  
possibly make multiple independent runs**  
[note: statistics on  $k_{\text{eff}}$  are OK, not underestimated]

**For serious work, my work-flow includes the actions below:**

- In MCNP input files, include a summary of { date, names, changes }
- Confirm that calculations used correct versions of code, data, scripts
- Always look at geometry with MCNP plotter
- Always check convergence plots for Keff & Hsrc
- Always check output file (not screen) for lost particles
- Check details if any unusual warnings appear
- Record for each run:
  - Name, date, computer, input/output file names
  - keff  $\pm$   $\sigma$  (combined col/trk/abs only)
  - EALF, ANECF, % fast/intermed/thermal fissions
  - For solutions, H/Pu<sup>239</sup> or H/U<sup>235</sup>
  - Any issues?

**If I'm in a hurry & skip some of the above, I usually end up paying big-time later on – having to repeat work to resolve errors or confusion**

## Previous discussion of details concerning bias, convergence, & statistics and "Best Practices" presented at

- 2008 - PHYSOR Monte Carlo workshop
- 2009 - M&C Monte Carlo workshop
- 2009 - Paper at NCSD topical meeting (best paper award)
- 2010 - PHYSOR Monte Carlo Workshop
- 2008 – present – MCNP Criticality Classes

Presentations available at [mcnp.lanl.gov](http://mcnp.lanl.gov)

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# Neutron Spectra

- Neutron slowing down theory
- Lethargy
- Neutron spectra
- Resonance absorption
- Spectral indicators
- Examples

- **Consider the transport equation for:**

- Infinite medium of hydrogen
- Steady source at energy  $E_s$
- Isotropic elastic scatter
- Scattering nuclides are stationary, no upscattering occurs
- No absorption

$$\cancel{\Omega \cdot \nabla} \phi(E) + \Sigma_T(E)\phi(E) = \int_E^{E_s} dE' \Sigma_S(E' \rightarrow E)\phi(E') + S \cdot \delta(E - E_s)$$

- **For hydrogen at rest ( $E \gg kT$ )**  $\Sigma_S(E' \rightarrow E) = \frac{\Sigma_S(E')}{E'}$

- **Slowing down in hydrogen at rest:**

$$\Sigma_S(E)\phi(E) = \int_E^{E_s} dE' \frac{\Sigma_S(E')}{E'} \phi(E') + S \cdot \delta(E - E_s)$$

- **Solution**

$$\phi(E) = \frac{S}{\Sigma_S(E) \cdot E} + \frac{S}{\Sigma_S(E)} \delta(E - E_s)$$

- For theory, visualization, understanding, it is useful to change variables from energy ( $E$ ) to lethargy ( $u$ )

$$u = \ln \frac{E_0}{E}, \quad \text{where } E_0 \text{ is large, eg 20 MeV}$$

$$du = -\frac{dE}{E}, \quad E = E_0 e^{-u}$$

$$\phi(u) = \left| \frac{dE}{du} \right| \phi(E) = E \cdot \phi(E)$$

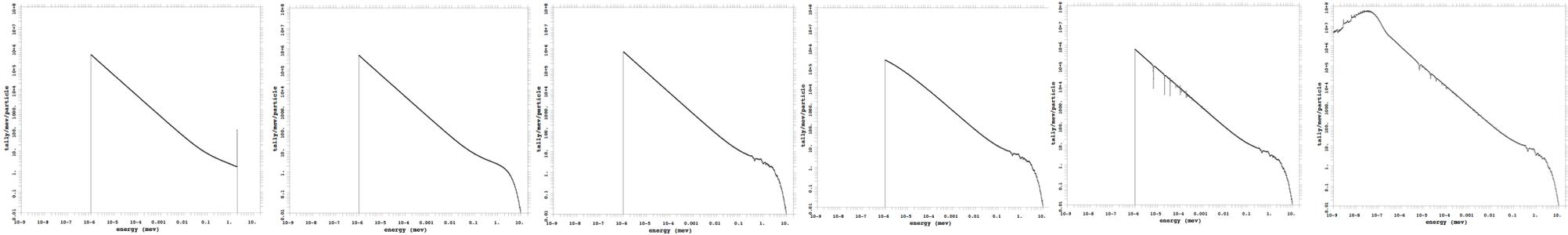
– As energy decreases, lethargy increases

- Consider slowing down flux in hydrogen,  $E < E_s$

$$\phi(E) = \frac{S}{\Sigma_s(E) \cdot E} \sim \frac{1}{E}$$

$$\phi(u) = \frac{S}{\Sigma_s(u)} \sim \text{constant}$$

## loglog plots of $\phi(E)$ vs $E$



**2 MeV neutrons  
hydrogen**

**fission neutrons  
hydrogen**

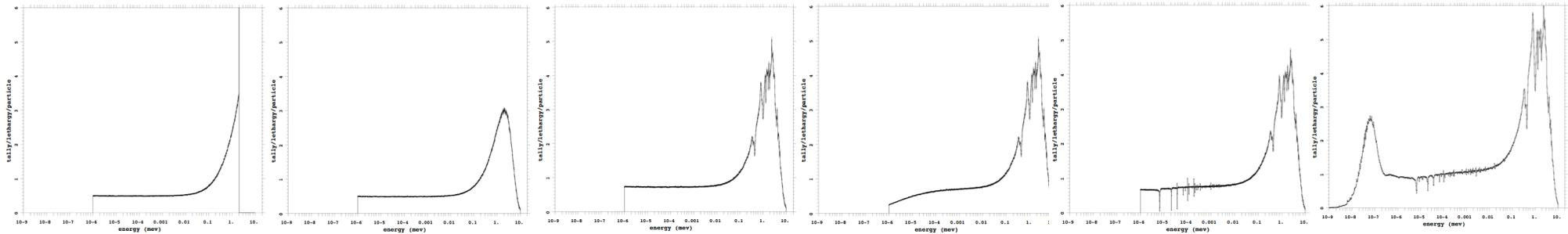
**fission neutrons  
water**

**fission neutrons  
water + B<sup>10</sup>**

**fission neutrons  
water + U<sup>238</sup>**

**Fuel Pin  
Unit Cell**

## loglin plots of $\phi(u)$ vs $u$



**2 MeV neutrons  
hydrogen**

**fission neutrons  
hydrogen**

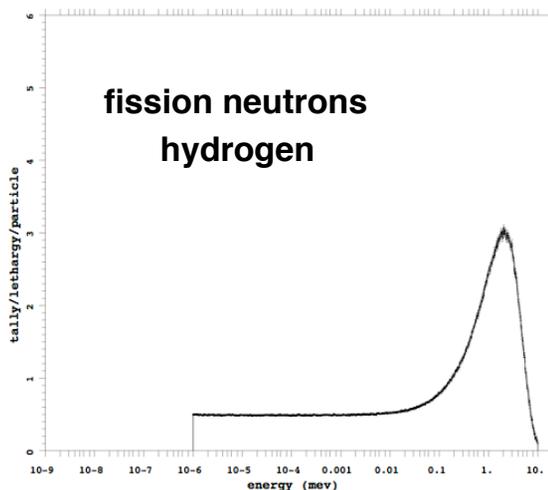
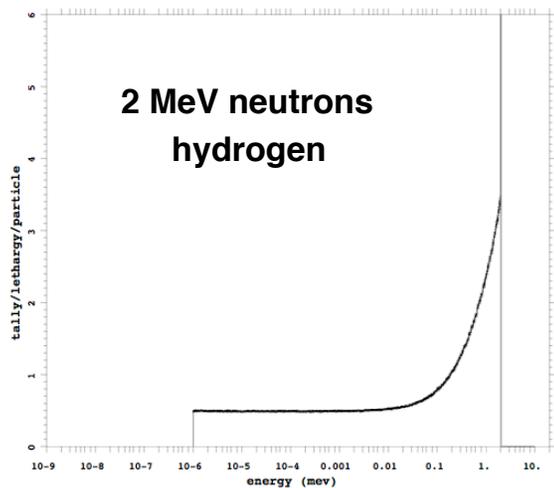
**fission neutrons  
water**

**fission neutrons  
water + B<sup>10</sup>**

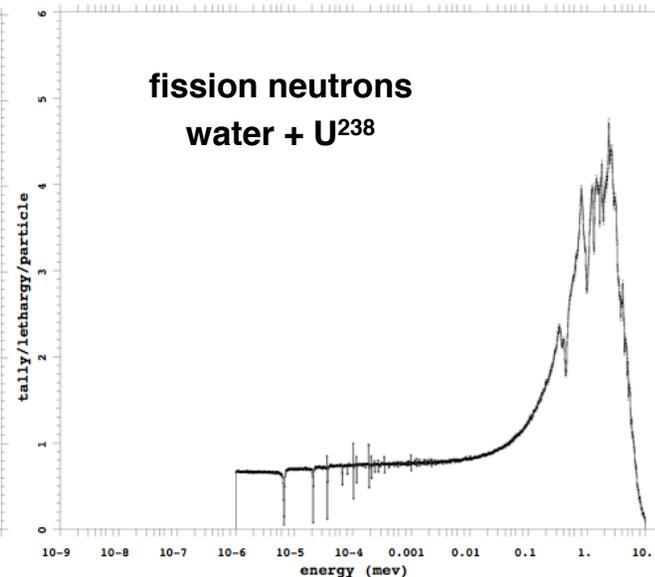
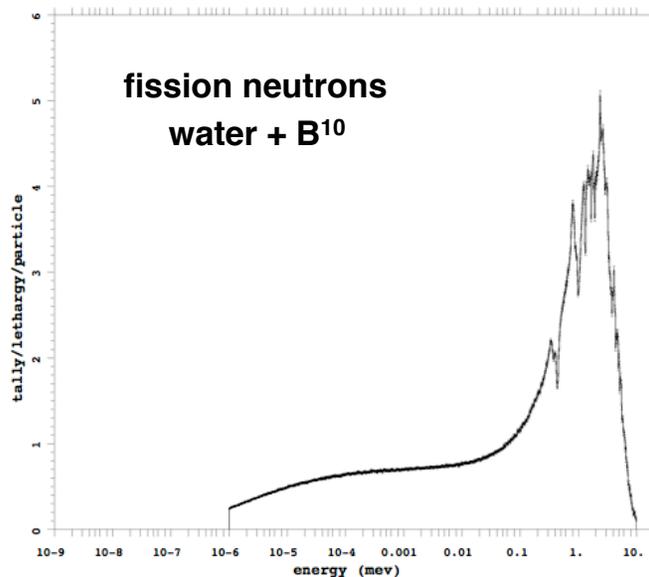
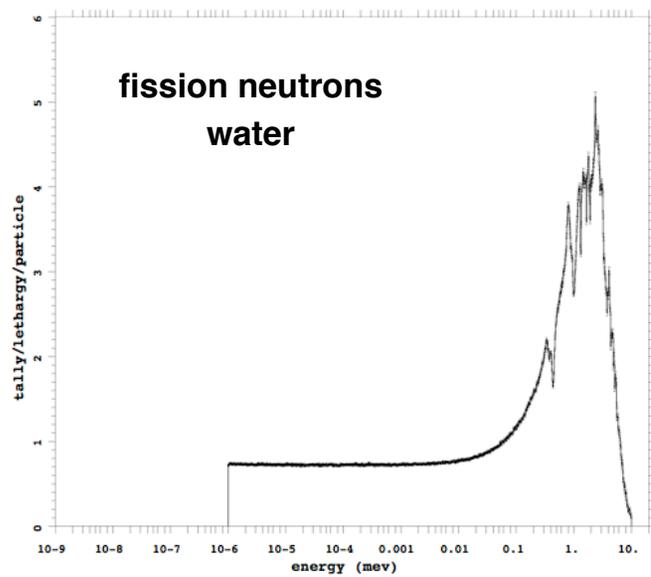
**fission neutrons  
water + U<sup>238</sup>**

**Fuel Pin  
Unit Cell**

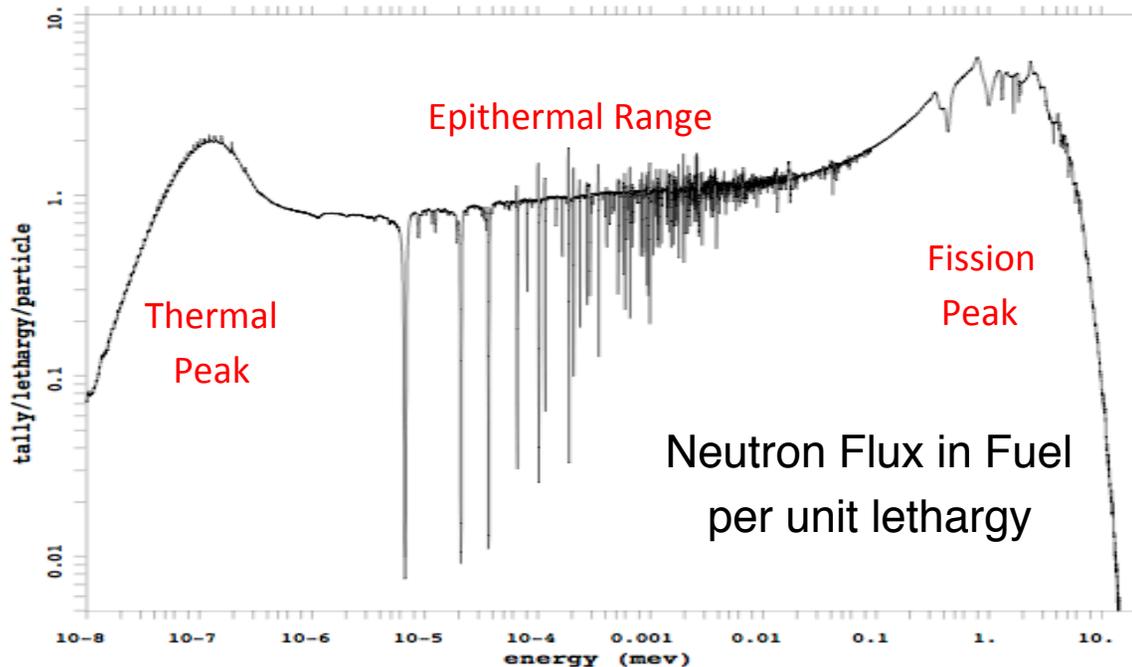
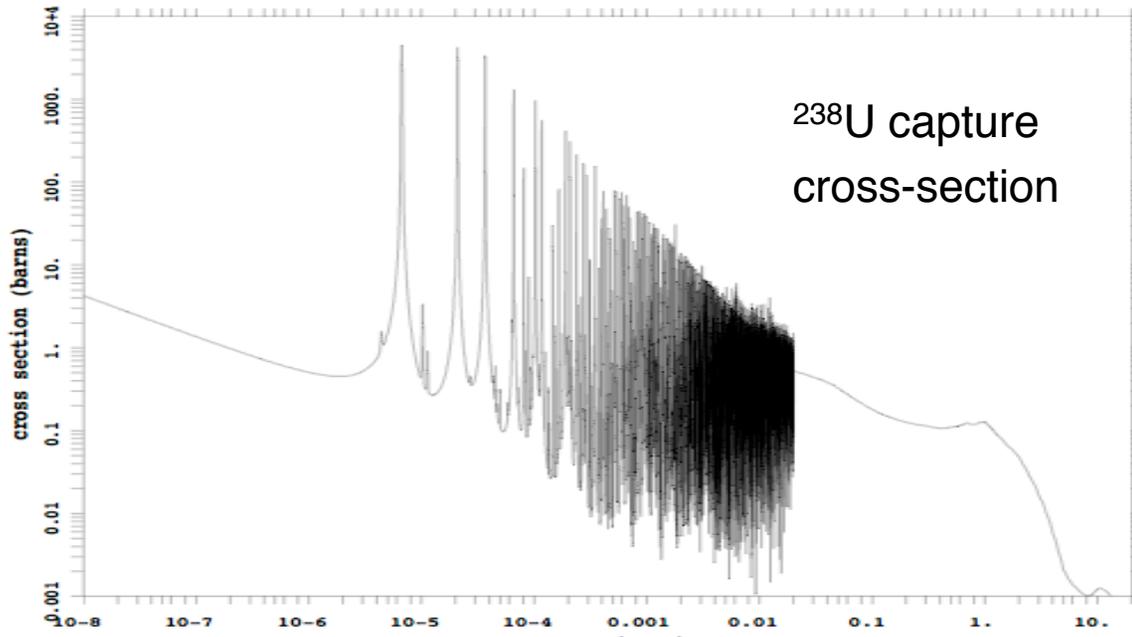
# Flux Spectra for Neutron Slowing Down



loglin plots of  $\phi(u)$  vs  $u$



# UO<sub>2</sub> Fuel Pin



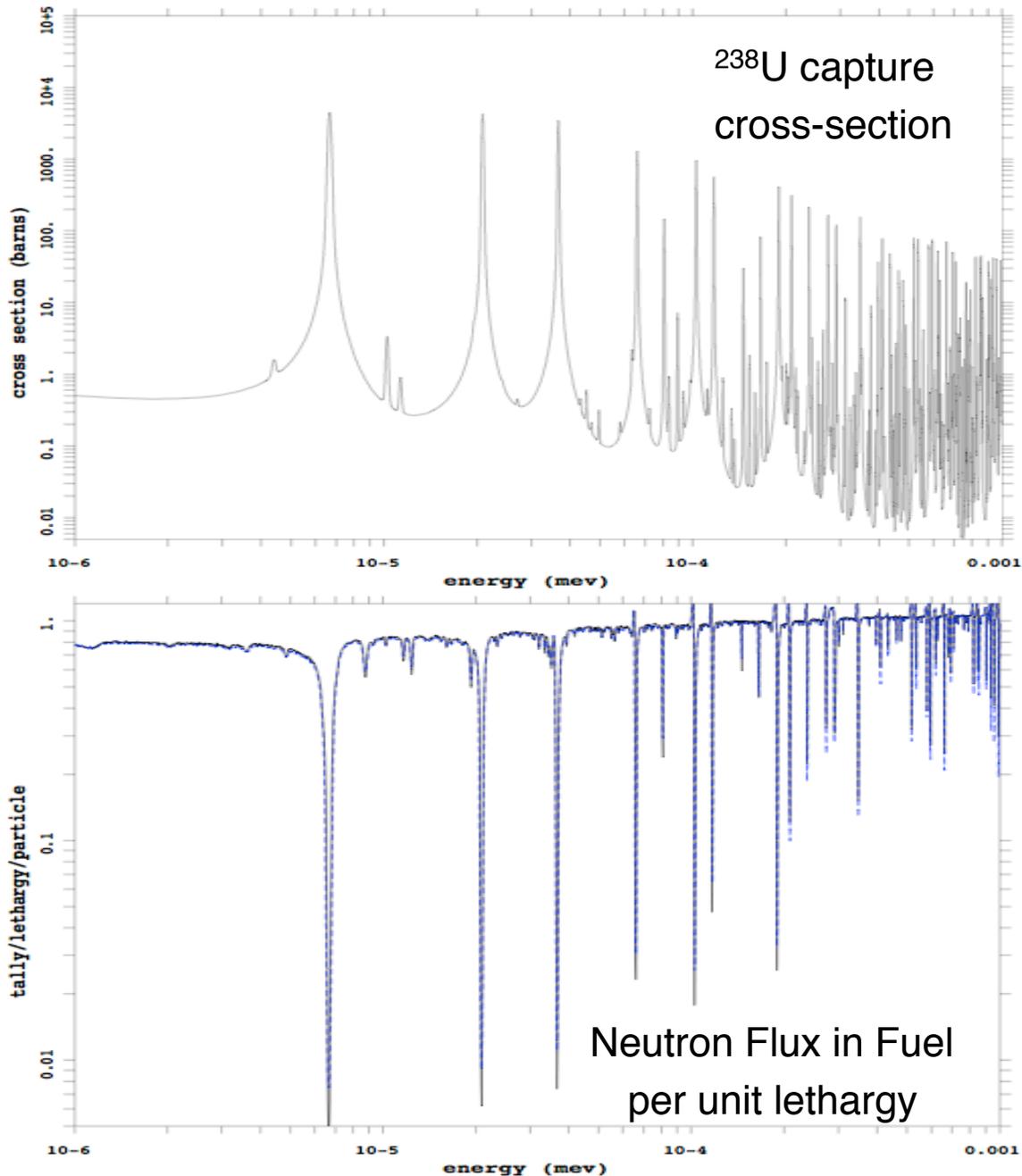
## UO<sub>2</sub> Fuel Pin

3.1% Enriched  
293.6 °K

.01 eV – 20 MeV

- Neutrons born in MeV range from fission
- Most fissions caused by thermal neutrons
- **1/3 of neutron losses are due to <sup>238</sup>U capture in epithermal energy range during slowing down**

# UO<sub>2</sub> Fuel Pin



## UO<sub>2</sub> Fuel Pin

3.1% Enriched  
293.6 °K

Detail for  
1 eV – 1 KeV

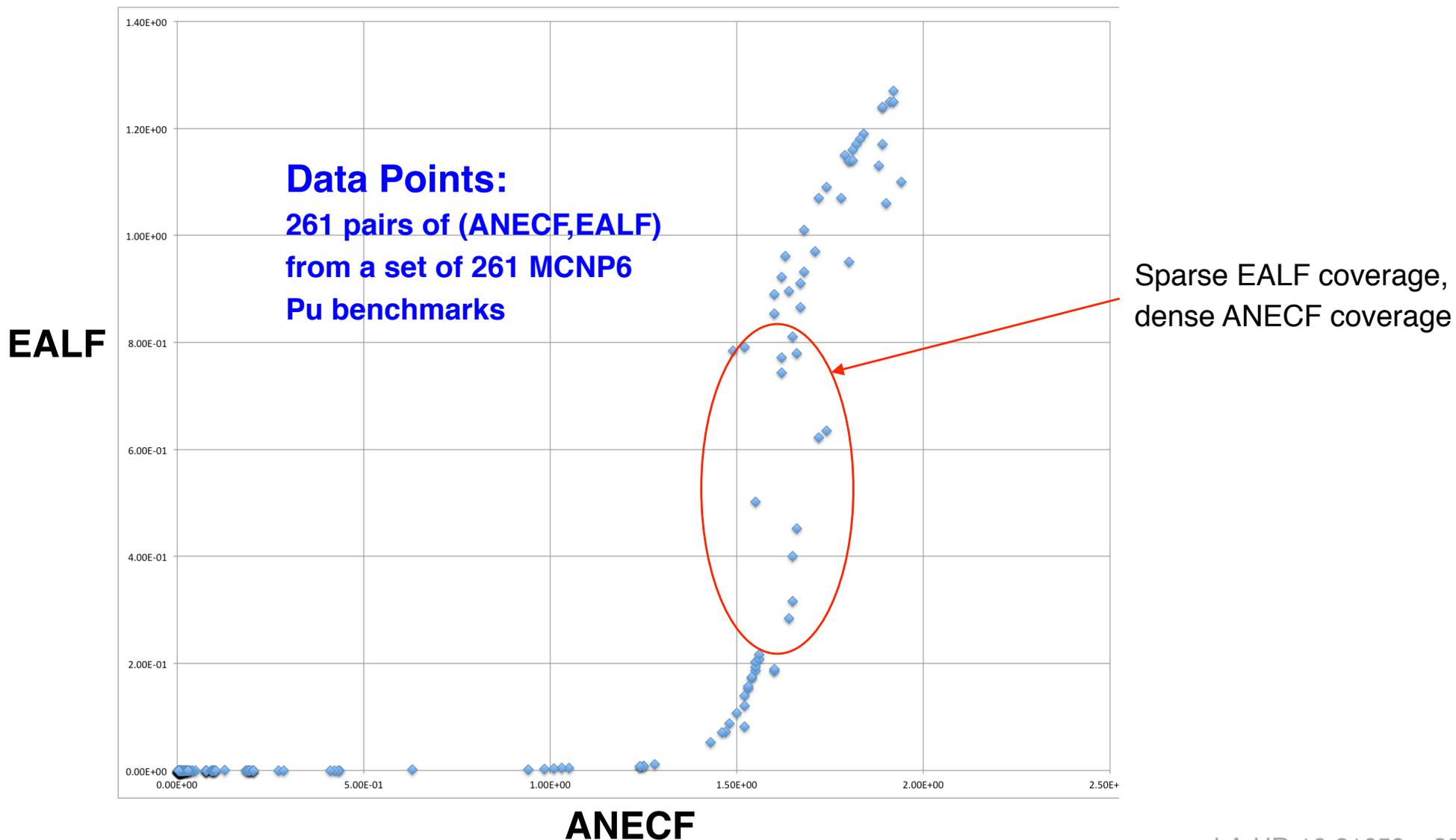
1/3 of neutron losses  
are due to <sup>238</sup>U capture  
at epithermal energies  
during slowing down

- The neutron spectrum –  $\phi(E)$  or  $\phi(u)$  – is a complex function of geometry, materials, isotopes, reflectors, temperature, cross-sections, ...
- Many different **spectral index** parameters can be used to characterize the spectrum
  - EALF – energy corresponding to the average lethargy of neutrons causing fission
  - ANECF – average energy of neutrons causing fission
  - Above thermal leakage fraction
  - H/Pu <sup>239</sup> or H/U<sup>235</sup> ratios, for solutions
  - Fraction of fissions caused by fast ( $E > 100$  keV), intermediate ( $1$  eV  $< E < 100$  keV), and thermal ( $E < 1$  eV) neutrons
  - <sup>238</sup>U(n,f)/<sup>235</sup>U(n,f), <sup>237</sup>Np(n,f)/<sup>235</sup>U(n,f), other ratios
  - etc.
- These parameters are useful for comparing different reactors or benchmark experiments, in looking for trends in code or cross-section accuracy
- **Spectrum hardness** is often characterized by one of these parameters
- No single parameter tells the whole story

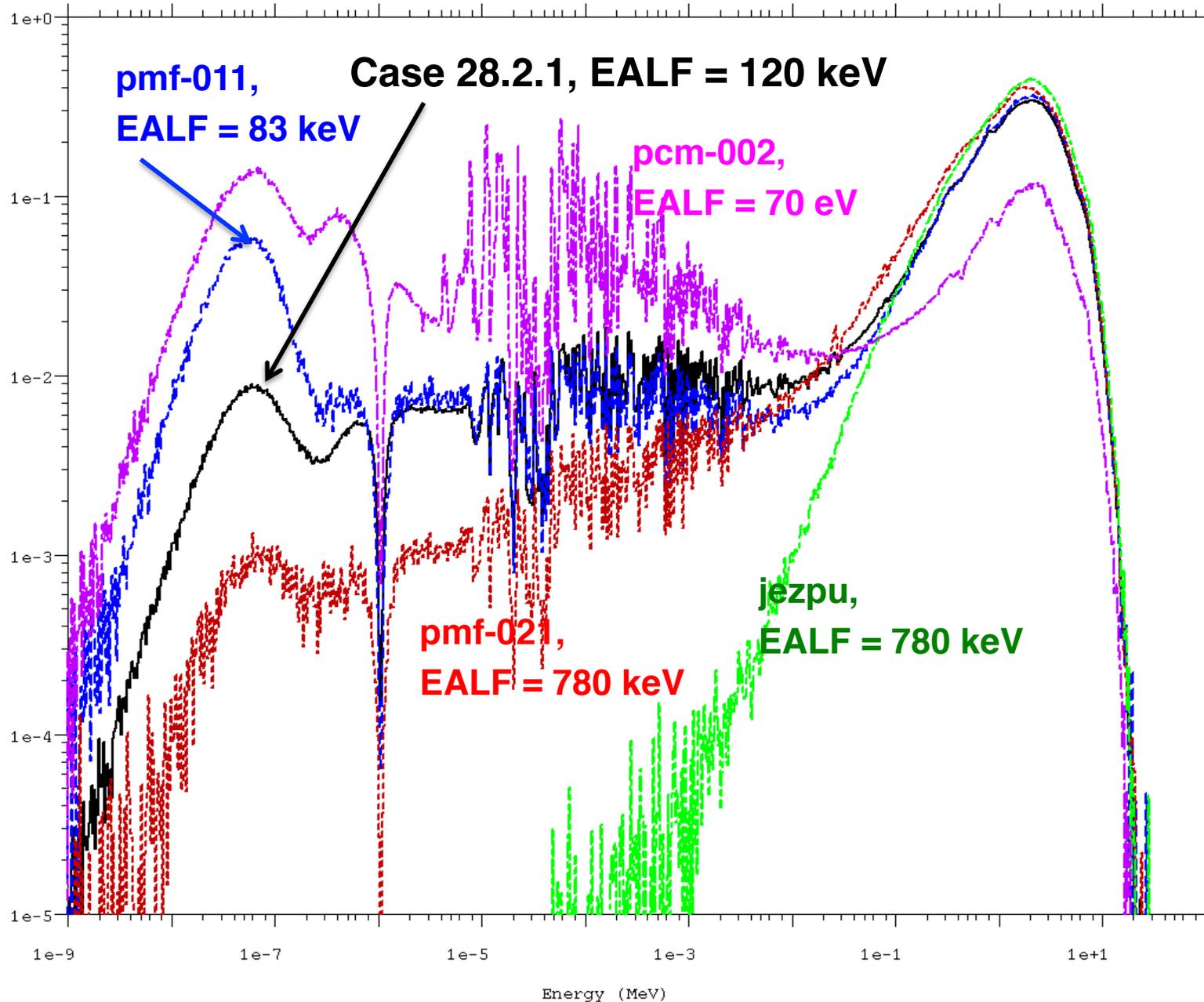
# EALF vs ANECF

**ANECF = average neutron energy causing fission**

**EALF = energy of the average neutron lethargy causing fission**



# Pu Systems – $\nu\Sigma_F\Phi$ production & spectrum hardness



```

mcnp
probid: 04/09/15 11
tally 14
n
nps 2349281
f(u)=ef(e) bin norm
runtpe = case28-2-1:
dump 2
f Cell
d Flag/Dir
u User
s Segment
m Mult
c Angle
e Energy
t Time
----- case28-2-1r
----- pmf-011r
----- pmf-021r
----- jezpur
----- pcm-002r
    
```

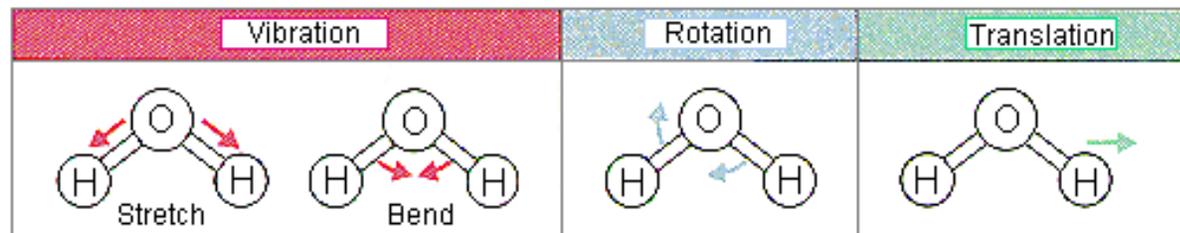
# **S( $\alpha,\beta$ ) Thermal Neutron Scattering Data**

- At low energies ( $E < 9$  eV), neutron scattering interactions are influenced by chemical binding, temperature, molecular effects, ...
  - Important for light nuclei (moderators)
  - MCNP libraries include thermal scattering laws,  $S(\alpha,\beta)$  libraries, for water, heavy water, polyethylene, methane, benzene, graphite, beryllium, zirconium, etc.
  - Include thermal scattering law(s) for every moderator nuclide in any problem where neutrons reach energies of 9 eV or less, using an **MTn** card
- **SAB2002**
  - ENDF/B-VI-based  $S(\alpha,\beta)$  data, released in 2002
  - Data for 15 combinations of nuclides and materials
  - Typical temperature ranges are from 294 K to 1200 K, in increments of 200
  - Data typically tabulated at 16 angles and 64 energies for each temperature
  - Data are provided at  $\sim 20$  K for a limited number of nuclides
- **ENDF70SAB (discrete), ENDF71SaB (continuous)**
  - ENDF/B-VII - based  $S(\alpha,\beta)$  data, ca. 2008
  - Many more nuclide - material combinations:
    - al27, be, be-o, benz, dortho, dpara, fe56, grph, h-zr, hortho, hpara, hwtr, lmeth, lwtr, o-be, o2-u, poly, smeth, u-o2, zr-h
  - Many more temperatures, data every 50 K or 100 K
  - See **Listing of Available ACE Data Tables, LA-UR-13-21822**

# Neutron S(a,b) Thermal Scattering Libraries

ENDF/B-V	ENDF/B-VI	ENDF/B-VII.0	ENDF/B-VII.1
tmccs	sab2002	endf70sab	ENDF71SaB
discrete	discrete	discrete	<u>continuous</u>
be	be	a127	a127
benz	benz	be	be be-o be/o
beo	beo	be/o	benz
grph	dortho	benz	dortho
h/zr	dpara	dortho	dpara
hwtr	grph	dpara	fe56
lwtr	h/zr	fe56	grph
poly	hortho	grph	h-zr h/zr
zr/h	hpara	h/zr	hortho
	hwtr	hortho	hpara
	lmeth	hpara	hwtr
	lwtr	hwtr	lmeth
	poly	lmeth	lwtr
	smeth	lwtr	o-be o/be
	zr/h	o/be	o2-u o2/u
		o2/u	poly
		poly	sio2
		smeth	smeth
		u/o2	u-o2 u/o2
		zr/h	zr-h zr/h

- **Moderator materials contain light isotopes (H, D, He, Be, Li, C)**
  - Water, heavy water, poly, concrete, etc.
  - Fast neutrons colliding with moderator lose lots of energy
  - **Systems with moderator material:**
    - Large thermal neutron flux
    - Fission cross-sections are very large at thermal energies
    - Significant fraction of fissions caused by thermal neutrons (maybe all!)
- **Thermal neutron physics**  $1 \times 10^{-5} \text{ eV} < E < 9 \text{ eV}$ 
  - Neutron energy comparable to chemical binding effects, gives rise to **incoherent inelastic scatter**



- **Neutron wavelength comparable to atomic spacing**
  - In solids, may need **coherent elastic scatter** (Bragg) from crystals
  - In liquids & gases, may need **incoherent elastic scatter**

- $S(\alpha, \beta)$  data is used to model the physics for
  - Inelastic scatter (chemical binding, temperature, etc.)
  - Elastic scatter for some solids & liquids
- $S(\alpha, \beta)$  data is contained in special ACE files for MCNP

$\alpha$  and  $\beta$  are dimensionless quantities representing:

$\alpha$ : momentum transfer

$$\alpha = \frac{E + E' - 2\mu\sqrt{EE'}}{A_0 kT}$$

$\beta$ : energy transfer

$$\beta = \frac{E' - E}{kT}$$

$$\sigma(E \rightarrow E', \mu, T) = \frac{\sigma_b}{2kT} \sqrt{\frac{E'}{E}} e^{-\beta/2} S(\alpha, \beta, T)$$

where:

$E, E'$ : pre- and post-collision energy

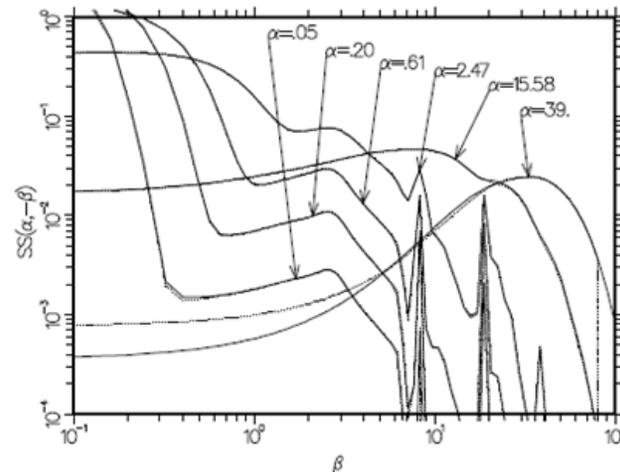
$\mu$ : cosine of the scattering angle

$\sigma_b$ : bound atom scattering cross section

$k$ : Boltzmann constant

$T$ : temperature

$S(\alpha, \beta, T)$ : symmetric form of the scattering law



- **When to NOT use  $S(\alpha,\beta)$  data:**
  - **Fast & intermediate systems, % thermal fissions small ( < 10% ? )**
  - **Whenever no significant amount of moderator material**
    - Very thin coatings, very thin reflectors, paint, varnish, trace impurities
  - **Heavy isotopes - U, Zr, Fe, Al (anything heavier than O<sup>16</sup>)**
- **When to use  $S(\alpha,\beta)$  data:**
  - **Thermal systems, significant % fissions from thermal neutrons**
  - **Solutions, sizable reflectors, concrete, hands, ....**
  - **Suggested:**
    - light water: **lwtr**
    - heavy water: **hwtr**
    - polyethylene: **poly**
    - concrete: **lwtr** (for H in concrete)
    - zirc-hydride: **h-zr**
    - oil: **benz**
    - Be metal: **be** (for thermal systems)
    - Be oxide: **be-o** (for thermal systems)
    - Graphite: **grph**

## Things to consider:

- **Always used for thermal systems:** lwtr, hwtr, grph, poly, h-zr
- **Some S( $\alpha,\beta$ ) datasets are only rarely used:** be-o, be, sio2, benz
- **Some S( $\alpha,\beta$ ) datasets are almost never used:** u-o2, o2-u, zr-h, o-be
- **Some S( $\alpha,\beta$ ) datasets were developed for specific research & experimental use (eg, ultra-cold neutron scatter experiments):** hortho, dortho, hpara, dpara, lmeth, smeth, al27, fe56
- **Cement:**  $2 \text{Ca}_3 \text{SiO}_5 + 7 \text{H}_2\text{O} \rightarrow 3(\text{CaO}) \cdot 2(\text{SiO}_2) \cdot 4(\text{H}_2\text{O})(\text{gel}) + 3\text{Ca}(\text{OH})_2$   
**Usually just use lwtr (for H)**

## S( $\alpha,\beta$ ) - Examples

- **Reactor fuel pin, 3.1% enriched UO<sub>2</sub>, with clad & water**
  - using lwtr (for H in water)  $k = 1.44853 \pm 0.00005$
  - using lwtr + o2-u (for O in UO<sub>2</sub>)  $k = 1.44853 \pm 0.00005$

Can ignore S(a,b) for O, must include for H

- **pu-met-fast-018-001**
  - using S(a,b) for be:  $k = 0.99944 \pm 0.00005$
  - no S(a,b)  $k = 0.99942 \pm 0.00005$

For fast spectrum systems, S(a,b) makes no difference

- **pu-comp-mixed-001-001**
  - using S(a,b) for lwtr, sio2, fe56:  $k = 1.02464 \pm 0.00008$
  - using S(a,b) for lwtr, sio2 only:  $k = 1.02463 \pm 0.00008$
  - using S(a,b) for lwtr only:  $k = 1.02458 \pm 0.00008$

- **pu-met-fast-041-001**
  - not using S(a,b)  $k = 1.00573 \pm 0.00007$
  - using S(a,b) for lwtr  $k = 1.00582 \pm 0.00005$

0 % thermal fissions .....

# Nuclear Data Sensitivities

- **MCNP can produce sensitivity profiles to determine which data most impacts criticality.**
- **Learning Objectives:**
  - **Understand the meaning of a sensitivity coefficient**
  - **Comprehend the techniques used by MCNP to estimate those tallies**
  - **Use the KSEN card to generate both energy-integrated and energy-resolved sensitivity profiles for specific reactions**
  - **Understand sensitivity output file information**

- Nuclear cross sections are a major driver for criticality, and their uncertainties usually the largest source of bias in calculations.
- Knowing which data most impacts criticality is useful for:
  - Critical experiment design
  - Uncertainty quantification and bias assessment
  - Code validation
  - Nuclear data adjustment and qualification
- Validation requires selecting benchmarks that are appropriate for the process being analyzed.
  - One method of picking appropriate benchmarks is to find the ones where the system multiplication is impacted by the same nuclear data.
  - For example, if the process  $k_{\text{eff}}$  is very sensitive to thermal plutonium capture, you should find benchmarks where the same is true.
- Critical experiment design
  - Often experiments are performed to address some defined nuclear data need.
  - Nuclear data sensitivities can determine if the as-designed experiment meets that need.

- For criticality problems, often want to know:
  - How sensitive is  $K_{eff}$  to uncertainty in some parameter ?
- The **sensitivity coefficient** is defined as the ratio of relative change in a response to a relative change in a system parameter:

$$S_{R,x} = \frac{\Delta R / R}{\Delta x / x}$$

- Here, the response is the system multiplication  $k$  and the parameter  $x$  is some nuclear data (cross section).
- For a very small change in system parameter  $x$ :

$$S_{k,x} = \frac{x}{k} \frac{dk}{dx}$$

- This may be expressed using perturbation theory:

$$S_{k,x} = \frac{x}{k} \frac{dk}{dx} = - \frac{\langle \psi^\dagger, (\Sigma_x - \mathbf{S}_x - k^{-1} \mathbf{F}_x) \psi \rangle}{\langle \psi^\dagger, k^{-1} \mathbf{F} \psi \rangle}$$

- This includes both the forward and adjoint neutron fluxes.
- The boldface **S** and **F** are shorthand for scattering and fission integrals of the transport equation.
- The **x** subscript implies that the quantity is just for data **x**.

- The adjoint transport equation:

$$\begin{aligned} -\mathbf{\Omega} \cdot \nabla \psi^\dagger(\mathbf{r}, \mathbf{\Omega}, E) + \Sigma_t \psi^\dagger(\mathbf{r}, \mathbf{\Omega}, E) = \\ \iint dE' d\mathbf{\Omega}' \Sigma_s(\mathbf{r}, \mathbf{\Omega}' \cdot \mathbf{\Omega}, E \rightarrow E') \psi^\dagger(\mathbf{r}, \mathbf{\Omega}', E') \\ + \frac{1}{k_{\text{eff}}} \iint dE' d\mathbf{\Omega}' \chi(E \rightarrow E') \nu \Sigma_f(\mathbf{r}, E) \psi^\dagger(\mathbf{r}, \mathbf{\Omega}', E') \end{aligned}$$

- Adjoint fundamental mode has physical meaning:

The importance at a location in phase space is proportional to the expected value of a measurement, caused by a neutron introduced into a critical system at that location, after infinitely many fission generations.

- The iterated fission probability method is based on this concept, & can be used to determine adjoint or importance weighting for Monte Carlo tallies

## Example – Need for Adjoint-Weighting

- MCNP can compute lifetimes (prompt removal times) with non-importance weighted tallies:

unweighted

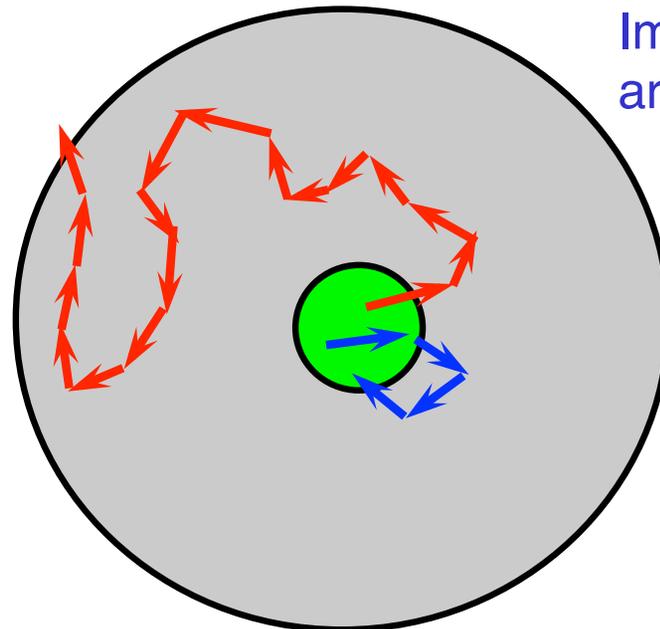
$$\Lambda_{rem} = \frac{\langle 1, 1/v \psi \rangle}{\langle 1, F\psi \rangle}$$

adjoint-weighted

$$\Lambda_{eff} = \frac{\langle \psi^\dagger, 1/v \psi \rangle}{\langle \psi^\dagger, F\psi \rangle}$$

- Example: Importance weighting is necessary in systems with thick reflectors. Unweighted lifetimes are often very much larger than effective lifetimes (adjoint-weighted)**

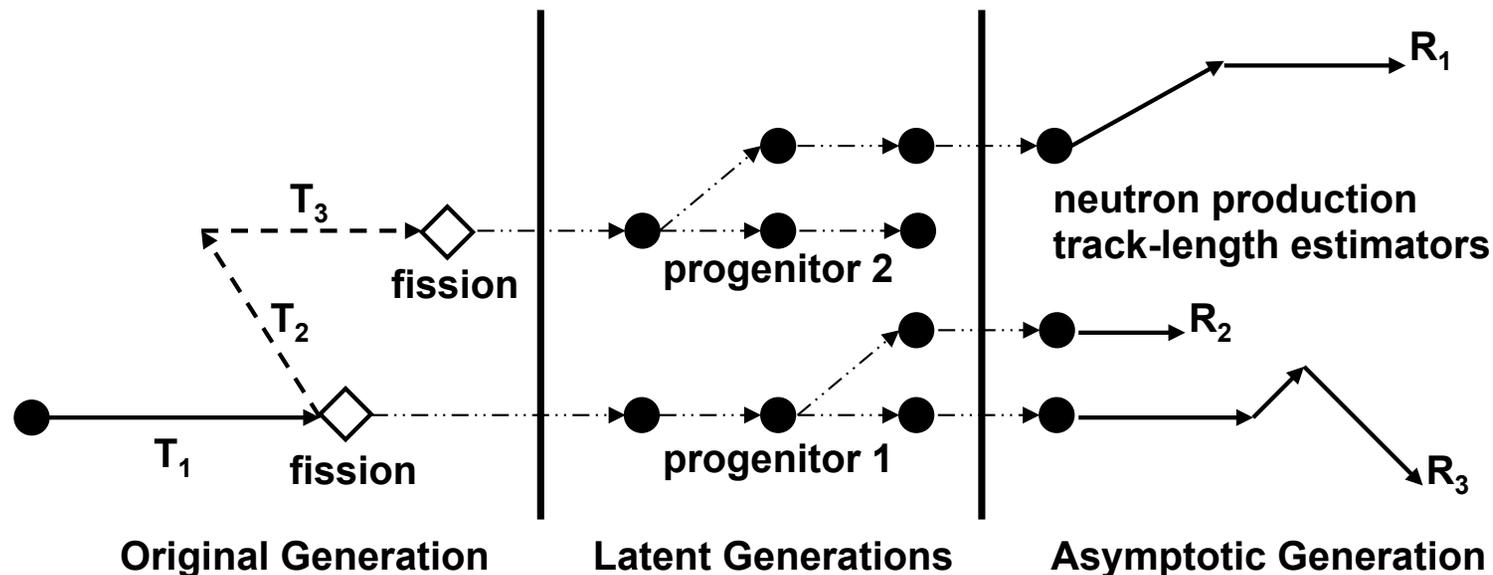
Neutrons spending significant time deep in the reflector are unlikely to cause fission and are therefore unimportant



Important neutrons are often short-lived

**Net Effect:** Not weighting by importance overvalues long-lived neutrons leading to lifetimes much too long.

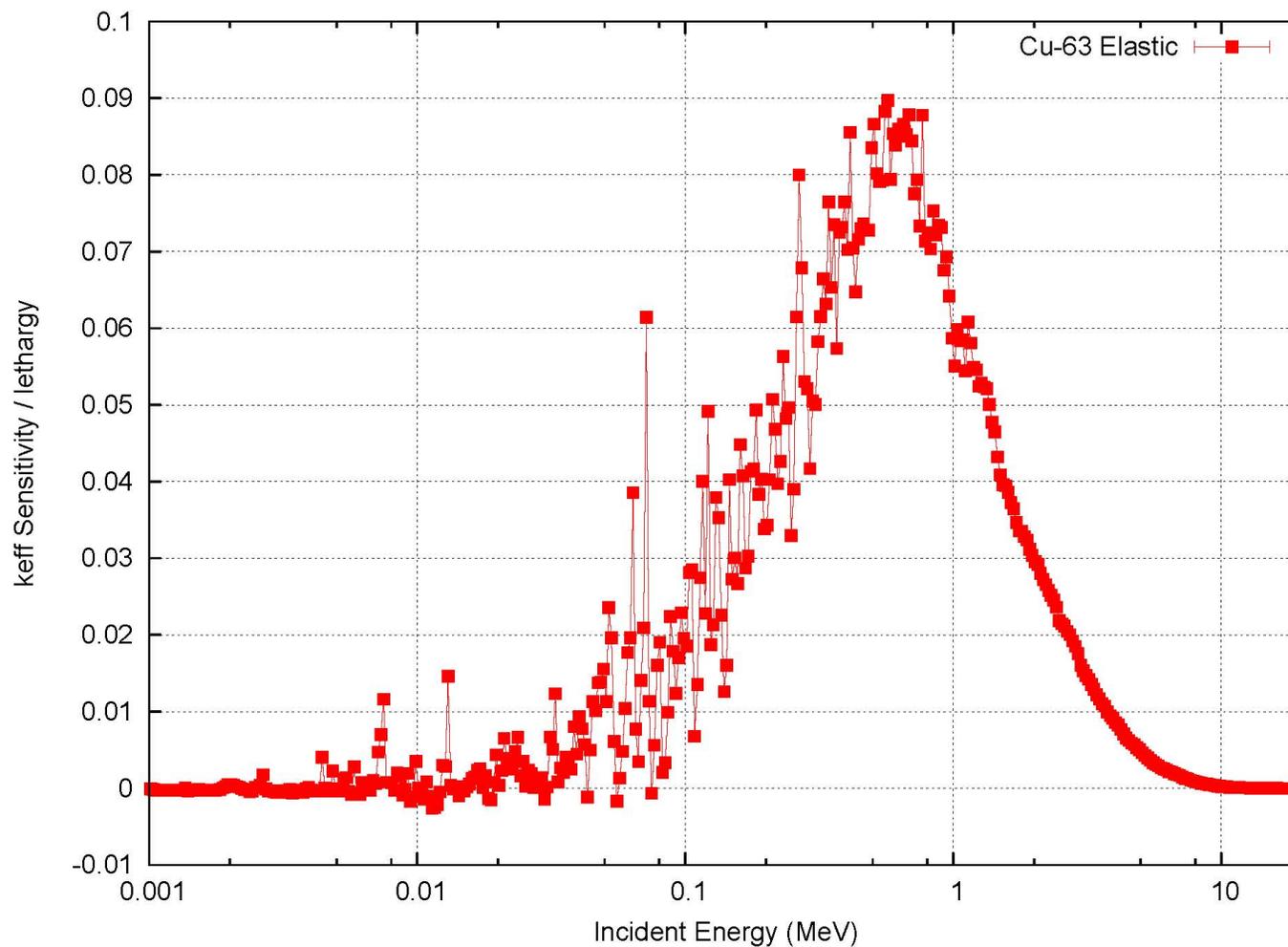
- MCNP performs adjoint-weighting of tallies using a technique called the **iterated fission probability**
- MCNP breaks active cycles into consecutive **blocks**:
  - Tally contributions collected in first generation, progenitor neutrons tagged and linked with tally contributions.
  - All subsequent progeny within the block remember their progenitor.
  - After  $N$  cycles, the population of progeny from each progenitor is measured. This is multiplied by the previously recorded tally contributions to form a tally score.



# Example Sensitivity Coefficient Profile

## Cu-63: Elastic Scattering Sensitivity

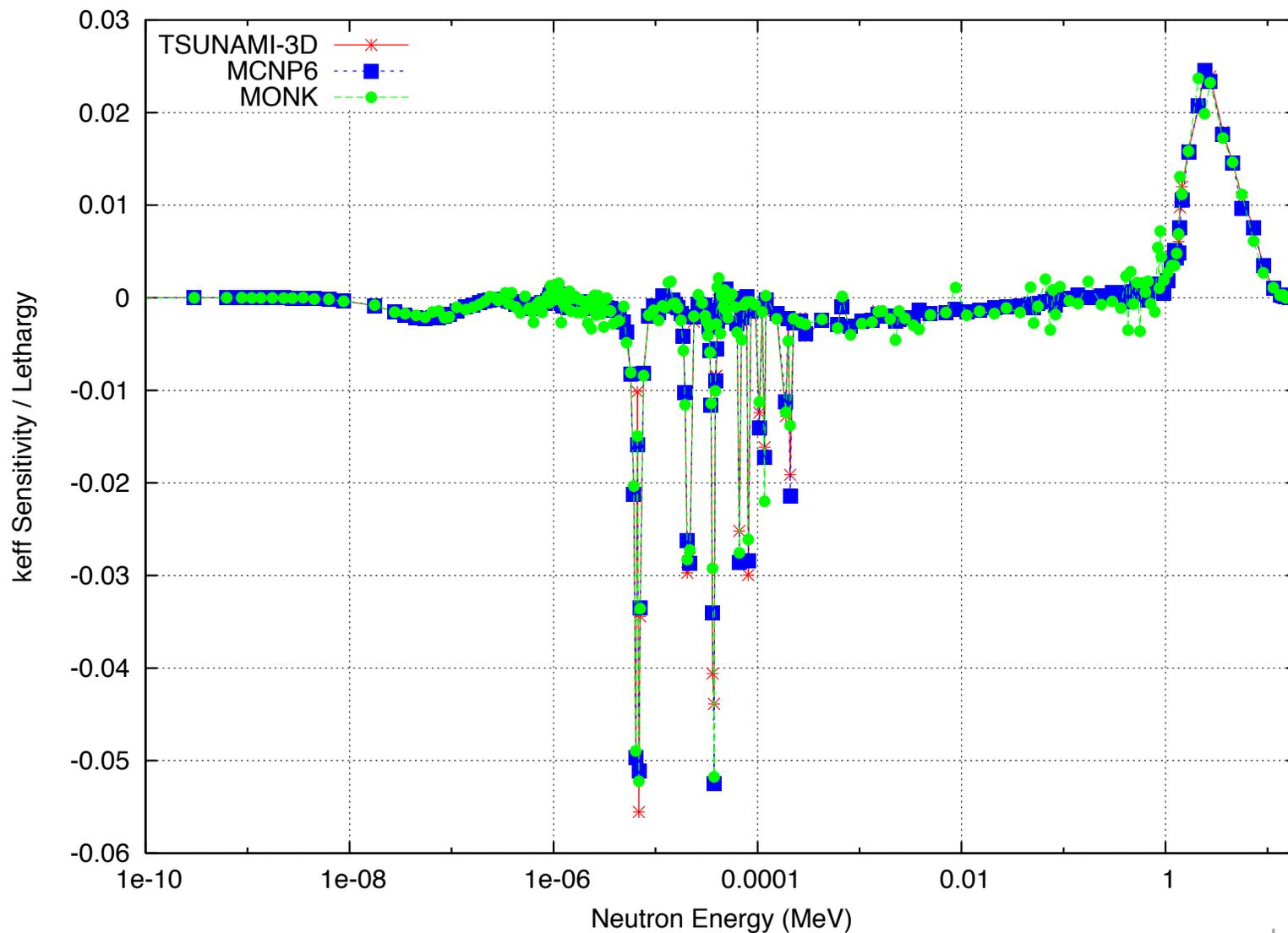
Copper-Reflected Zeus experiment:



# Example Sensitivity Coefficient Profile

## U-238: total cross-section sensitivity

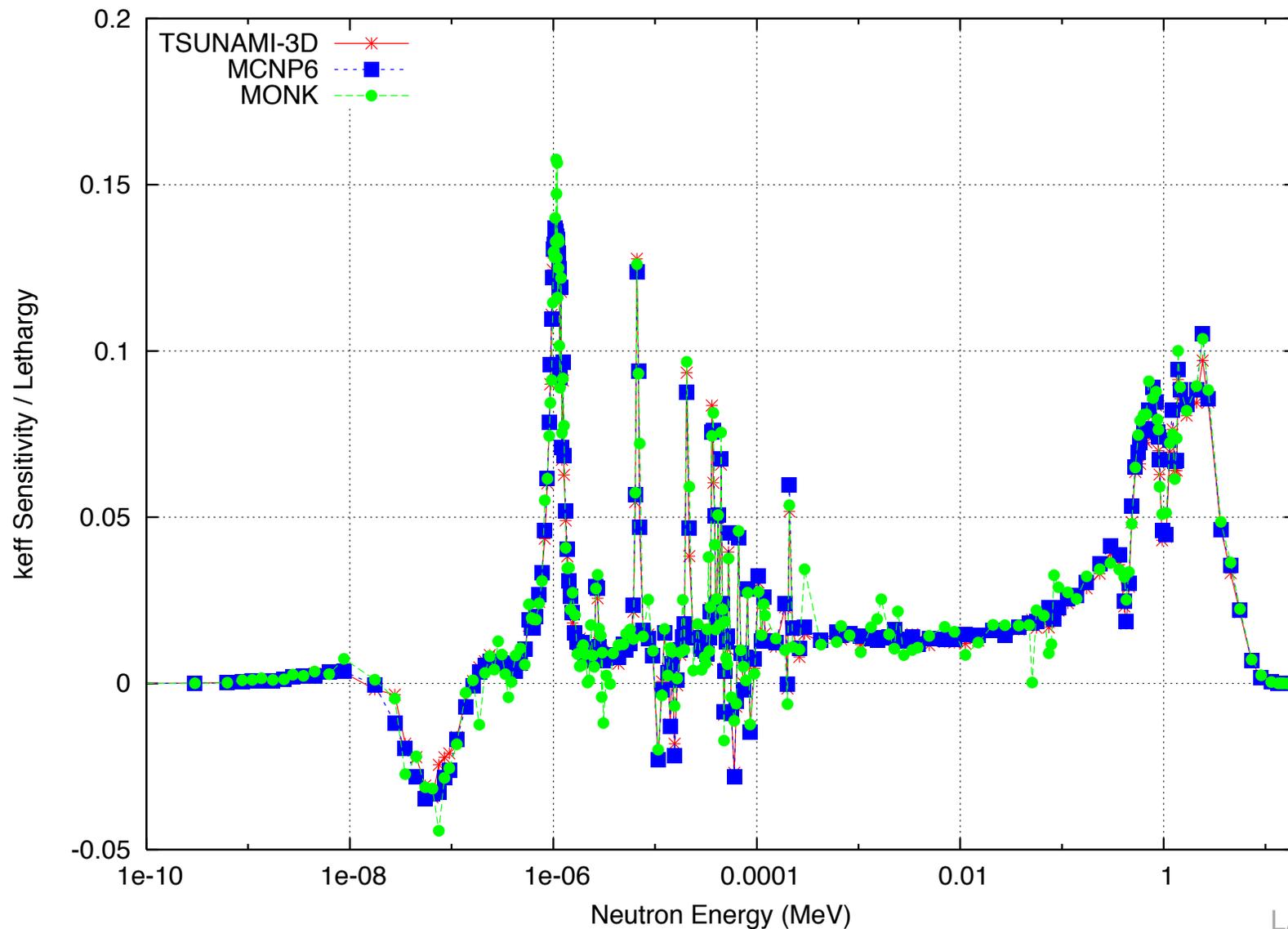
### OECD/NEA UACSA Benchmark Phase III.1



# Example Sensitivity Coefficient Profile

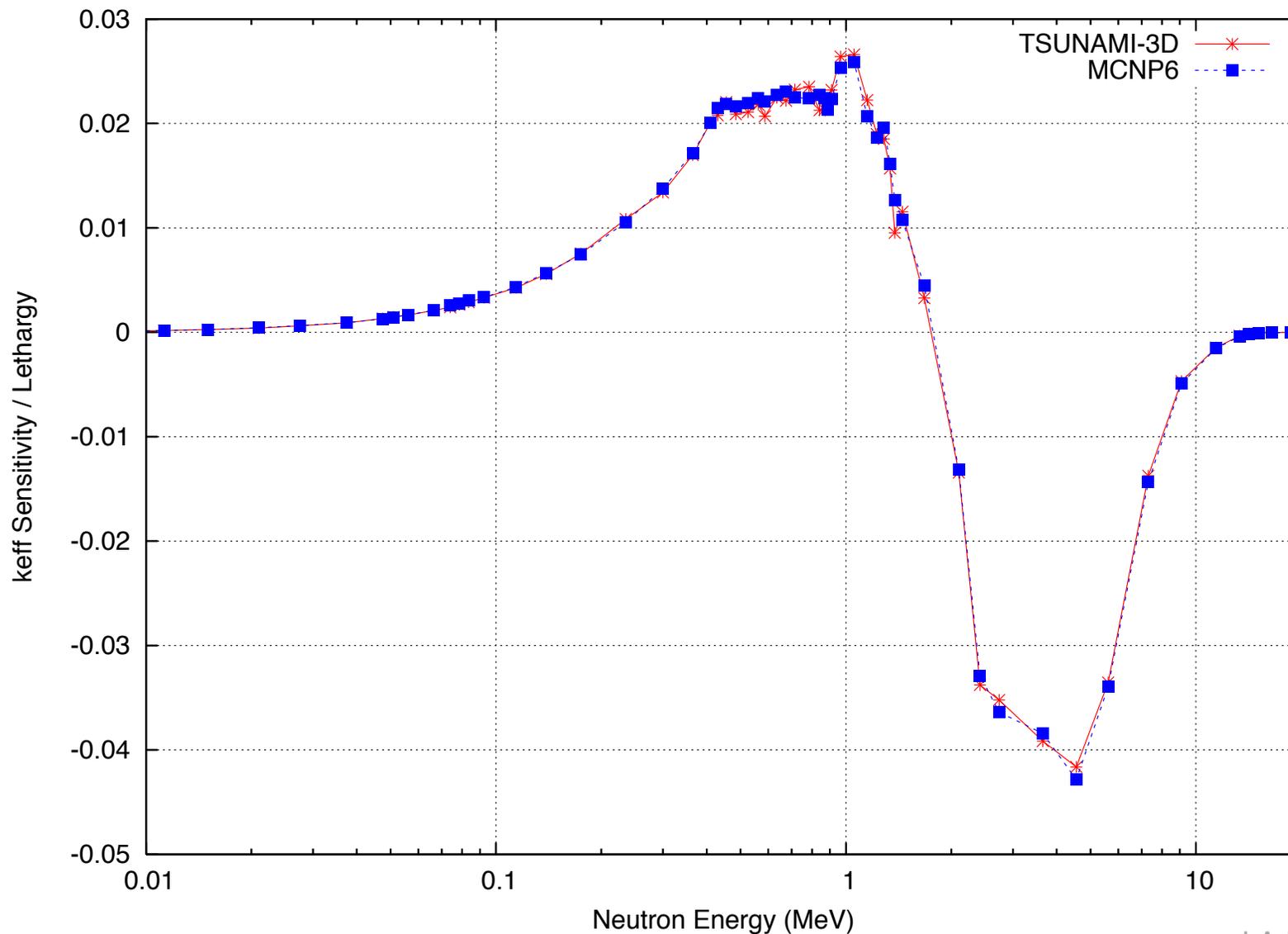
## H-1: elastic scattering cross-section sensitivity

### OECD/NEA UACSA Benchmark Phase III.1



# Example Sensitivity Coefficient Profile

- Pu-239: fission  $\chi(E)$  sensitivity**  
**OECD/NEA UACSA Benchmark Phase III.1**



- **KOPTS controls many special features for KCODE calculations**
- **For keff sensitivity calculations, KOPTS is used to control the following:**
  - **Size of the blocks (default is 10 cycles)**
  - **Sensitivity output printing (default is just to the output file).**

- **Format:**

**KOPTS    BLOCKSIZE= N    KSENTAL= FILEOPT**

- **For now, the only “FILEOPT” allowed is MCTAL, which has MCNP produce a special MCTAL results file**

- **Format for nuclear data:**

**KSENj XS ISO= ZAID1 ZAID2 ... RXN= MT1 MT2 ...  
ERG= E1 E2 ...**

- **Notes:**

- *j* is an arbitrary user index (> 0).
- XS defines the type of sensitivity (XS only allowed for now).
- ISO is followed by a list of ZAIDS or S(a,b) identifiers (e.g., 92235.70c, default is all isotopes).
- RXN is a list of MT numbers (default is total, see next slide for a shortened list).
- ERG is a user-defined energy grid in MeV (default 0 to infinity).
- More options available for secondary distributions (e.g., chi).
- Multiple instances of KSEN are allowed, so long as they have a different user index *j*.

- **Partial list of valid reaction MTs for KSEN**

– Total	1
– Capture	-2
– N,Gamma	102
– Elastic Scattering	2
– Inelastic Scattering	4
– Fission	-6
– Fission Nu	-7
– N,2N	16
– Fission Chi	-1018
– Elastic Law	-1002

- Capture cross section sensitivity for all isotopes

```
kzen1  xs  rxn= -2
```

- U-238 elastic and inelastic scattering sensitivities

```
kzen2  xs  iso= 92238.70c  rxn=  2  4
```

- H-1 and light-water S(a,b) total sensitivity with uniform lethargy grid from 1e-5 eV to 100 MeV

```
kzen3  xs  iso= 1001.70c  lwtr.10t  rxn=  1  
      erg= 1.e-11 12ilog 1e+2
```

## MCNP6 Example 1: KSEN Card

- Copy **puc6.txt** from SOLUTIONS directory to **ksen1.txt**.
- Find sensitivities to 3 x 2 array of cans containing plutonium nitrate solution.
  - Set KCODE card to use 5000 neutrons per cycle, skip 50, and run 250 cycles total.
  - Set KOPTS card to have a BLOCKSIZE of 5.
  - Add a cross section sensitivity card with no arguments, i.e., use all defaults

```
kcode    5000    1.0    50    250
...
c
c ### keff sensitivity cards
c
kopts    blocksize = 5
c
c default ksen, get total xs sensitivity to all isotopes
ksen1    xs
```

- Run the problem and analyze output.

# MCNP6 Exercise 1: Results

nuclear data keff sensitivity coefficients

sensitivity profile 1

energy range: 0.0000E+00 1.0000E+36 MeV

isotope	reaction	sensitivity	rel. unc.
1001.70c	total	4.7564E-01	0.0589
7014.70c	total	-1.0670E-02	0.5088
8016.70c	total	1.2197E-01	0.1225
24050.70c	total	-9.1837E-05	4.4999
24052.70c	total	2.5948E-03	0.3650
24053.70c	total	7.2096E-04	0.8493
24054.70c	total	1.5180E-05	7.5290
26054.70c	total	-4.5558E-04	0.8763
26056.70c	total	1.3197E-02	0.1791
26057.70c	total	7.9241E-04	0.5101
...			
94239.70c	total	8.1218E-02	0.0919
94240.70c	total	-4.5498E-02	0.0288
94241.70c	total	7.6258E-04	0.1957
94242.70c	total	-6.0798E-05	0.0480
lwtr.10t	total	1.6518E-01	0.1716

- Total cross section sensitivities can also be thought of as the sensitivity to the atomic density
- Observations:
  - Water (hydrogen and oxygen) have the most impact on k in this system.
  - Pu-239 has a significant, but smaller impact.
  - Other significant, but less important, isotopes are Pu-240 and Fe-56.
- Pu-239 total sensitivity is small for a dominant fissile isotope
  - Investigate this by decomposing this into specific reactions

- Copy **ksen1.txt** to **ksen2.txt**.
- Find sensitivities of total, capture, elastic, inelastic, and fission for H-1, light-water S(a,b), O-16, and Pu-239
  - Delete the old KSEN card and insert a new one

```
c
c ### keff sensitivity cards
c
kopts    blocksize= 5
c
c reaction sensitivities for h-1, o-16, pu-239
c capture, elastic, inelastic, fission
ksen2    xs    iso= 1001.70c lwtr.10t 8016.70c 94239.70c
          rxn=  1 -2  2  4 -6
```

- Run the problem and analyze output.

## MCNP6 Exercise 2: Results

1001.70c	total	4.7564E-01	0.0589
1001.70c	capture	-4.1980E-02	0.0110
<b>1001.70c</b>	<b>elastic</b>	<b>5.1762E-01</b>	<b>0.0541</b>
1001.70c	inelastic	0.0000E+00	0.0000
1001.70c	fission	0.0000E+00	0.0000
lwtr.10t	total	1.6518E-01	0.1716
lwtr.10t	capture	0.0000E+00	0.0000
lwtr.10t	elastic	0.0000E+00	0.0000
<b>lwtr.10t</b>	<b>inelastic</b>	<b>1.6518E-01</b>	<b>0.1716</b>
lwtr.10t	fission	0.0000E+00	0.0000
8016.70c	total	1.2197E-01	0.1225
8016.70c	capture	-1.3346E-03	0.0491
<b>8016.70c</b>	<b>elastic</b>	<b>1.2219E-01</b>	<b>0.1219</b>
8016.70c	inelastic	1.1203E-03	0.2583
8016.70c	fission	0.0000E+00	0.0000
94239.70c	total	8.1218E-02	0.0919
<b>94239.70c</b>	<b>capture</b>	<b>-3.0413E-01</b>	<b>0.0076</b>
94239.70c	elastic	-1.3872E-03	1.2795
94239.70c	inelastic	6.1685E-04	0.8563
<b>94239.70c</b>	<b>fission</b>	<b>3.8605E-01</b>	<b>0.0140</b>

- Elastic scattering with H-1 and O-16 are important, as is inelastic thermal scattering with H-1 in H2O molecule.
- Pu-239 fission and capture are of similar opposing magnitude, which is the cause of a lower than normal sensitivity to keff.
- Analyze Pu-239 capture and fission as function of energy.

- Copy **ksen2.txt** to **ksen3.txt**.
- Find sensitivities of Pu-239 capture and fission as function of energy.
  - Delete the old KSEN card and insert a new one.
  - For the energy bins, use 0 to 0.625 eV, 0.625 eV to 100 keV, and 100 keV to 100 MeV as thermal, intermediate, and fast.

```
c
c ### keff sensitivity cards
c
kopts    blocksize = 5
c
c pu-239 capture and fission sensitivity for thermal,
intermediate, and fast
ksen3    xs    iso = 94239.70c
          rxn = -2 -6
          erg = 0  0.625e-6    0.1    100
```

- Run the problem and analyze output.

# MCNP6 Exercise 3: Results

## 94239.70c capture

energy range (MeV)		sensitivity	rel. unc.
0.0000E+00	6.2500E-07	-2.7413E-01	0.0084
6.2500E-07	1.0000E-01	-2.9833E-02	0.0124
1.0000E-01	1.0000E+02	-1.7170E-04	0.0066

## 94239.70c fission

energy range (MeV)		sensitivity	rel. unc.
0.0000E+00	6.2500E-07	3.3226E-01	0.0184
6.2500E-07	1.0000E-01	4.2493E-02	0.0556
1.0000E-01	1.0000E+02	1.1298E-02	0.1122

- Most of the effect for fission and capture are in the thermal range (as expected).
- Both thermal and intermediate Pu-239 capture and fission are of similar magnitude.
- Fast Pu-239 capture is negligible relative to Pu-239 fission.

- **More complete KSEN:**

**KSENj XS ISO = ZAID1 ZAID2 ... RXN = MT1 MT2 ...**  
**ERG = E1 E2 ... COS = C1 C2 ...**  
**EIN = I1 I2 ...**  
**CONSTRAIN = YES/NO**

- **Comments:**

- For secondary distributions ERG is with respect to outgoing energies (default 0 to infinity).
- COS defines direction cosine changes from the collision (default -1 to 1)
- EIN defines the incident energy range (default 0 to infinity)
- CONSTRAIN tells MCNP whether the distribution must be renormalized to preserve probability (default is YES)
- If cross sections or fission nu listed in RXN, MCNP will calculate those as normal.

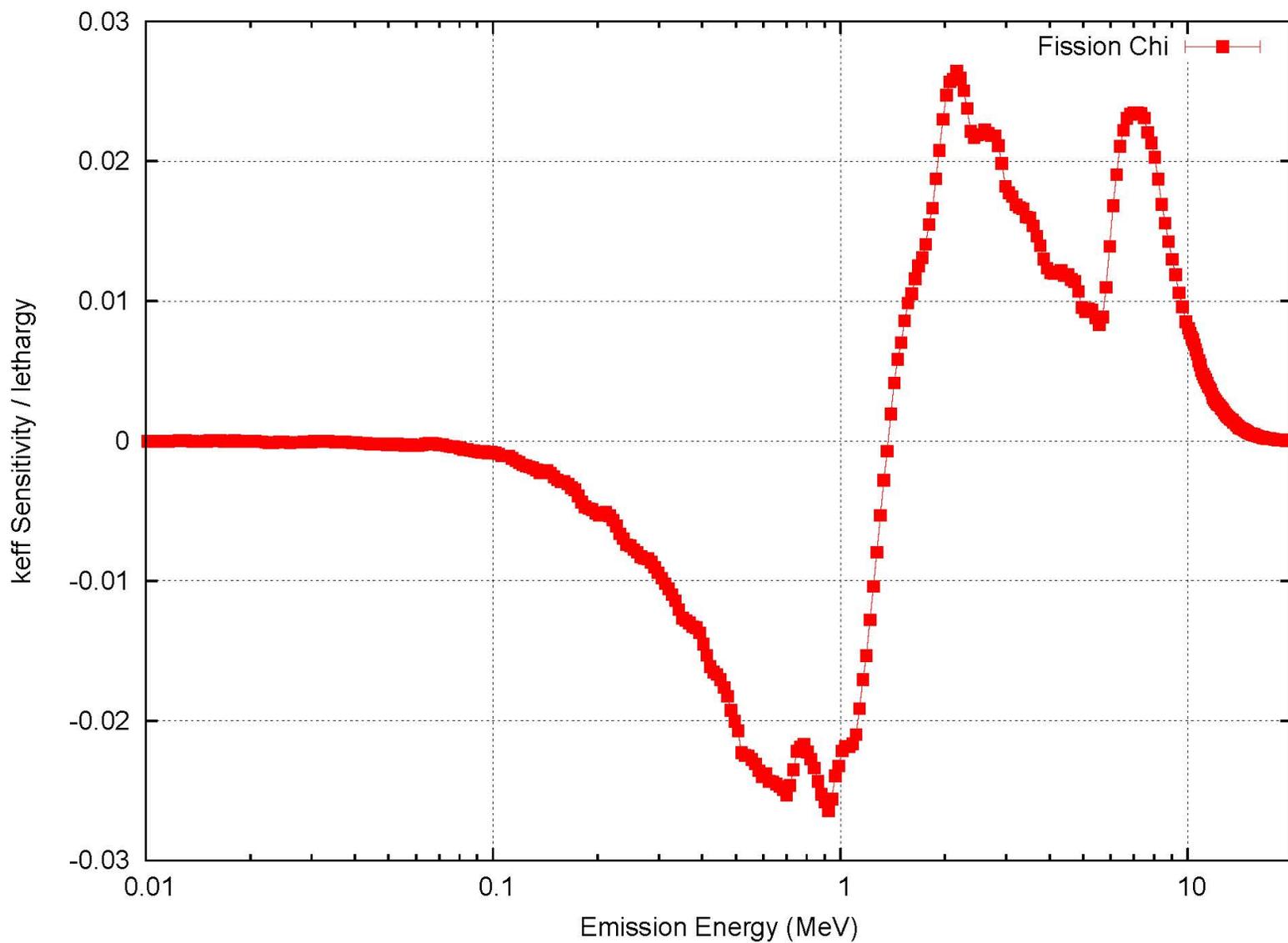
- **KSEN card of Pu-239 chi sensitivity:**

```
ksen94  xs      iso= 94239.70c
          rxn=  -1018
          erg= 1e-11 999ilog 20
          ein= 0 19i 20
          constrain= yes
```

- **Comments:**
  - Fine outgoing energy binning in lethargy
  - Incident energy bins are in 1 MeV intervals from 0 to 20 MeV
  - MCNP should give a sensitivity to a distribution that is renormalized

# Constrained Chi Sensitivity Example

- Pu-239 chi sensitivity in Jezebel (Pu Sphere):



# Covariance Data

- For a given isotope, these 12 cross-sections & sensitivities are used within Whisper:

MT	reaction
2	elastic scatter
4	inelastic
16	n,2n
18	fission
102	n, $\gamma$
103	n,p
104	n,d
105	n,t
106	n, $^3\text{He}$
107	n, $\alpha$
452	$\nu$
1018	$\chi$

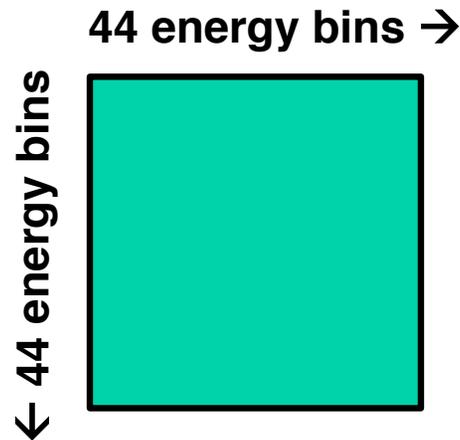
- MCNP uses continuous-energy cross-section data & collision physics, but **sensitivity profiles** are tallied in 44 energy bins
- The 44 energy bins reflect the cross-section **covariance data** files obtained for each isotope & reaction from the SCALE system

### Energy bin bounds (MeV)

1.0000e-11	3.0000e-09	7.5000e-09	1.0000e-08	2.5300e-08	3.0000e-08
4.0000e-08	5.0000e-08	7.0000e-08	1.0000e-07	1.5000e-07	2.0000e-07
2.2500e-07	2.5000e-07	2.7500e-07	3.2500e-07	3.5000e-07	3.7500e-07
4.0000e-07	6.2500e-07	1.0000e-06	1.7700e-06	3.0000e-06	4.7500e-06
6.0000e-06	8.1000e-06	1.0000e-05	3.0000e-05	1.0000e-04	5.5000e-04
3.0000e-03	1.7000e-02	2.5000e-02	1.0000e-01	4.0000e-01	9.0000e-01
1.4000e+00	1.8500e+00	2.3540e+00	2.4790e+00	3.0000e+00	4.8000e+00
6.4340e+00	8.1873e+00	2.0000e+01			

- When better cross-section covariance data become available, more energy bins will be used

- For a particular isotope & particular reaction (MT), the nuclear data uncertainties are a  $G \times G$  matrix, where  $G$  = number of energy groups = 44



- Each diagonal is the **variance** of the cross-section for a particular energy bin
- Off-diagonal elements are the **shared variance** between the data for pairs of energy bins

# Cross-section Covariance Data (4)

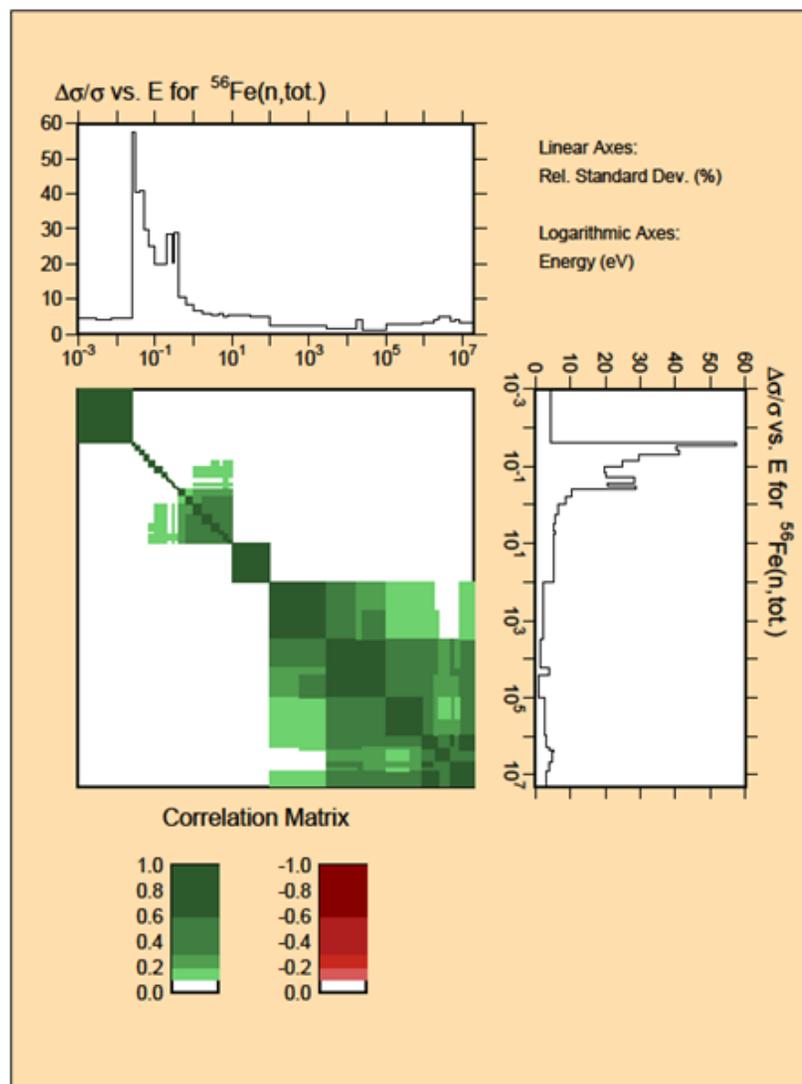


FIG. 9: A typical NJOY-generated plot of ENDF/B-VII.0 data downloaded from the National Nuclear Data Center, BNL, USA.

# Cross-section Covariance Data (5)

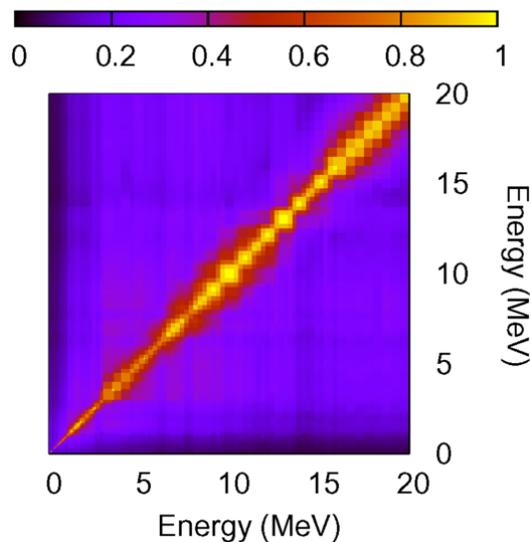


FIG. 3: Correlation matrix for the neutron-induced fission cross section on  $^{235}\text{U}$ . It was evaluated by Pronyaev *et al.* as part of the cross section standards evaluation [19].

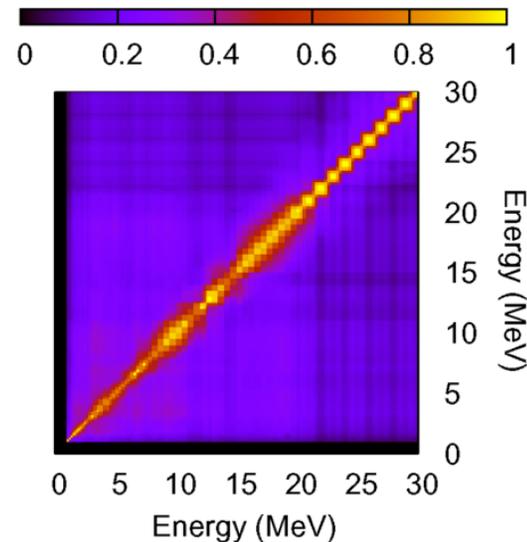


FIG. 13:  $^{238}\text{U}$  fission cross-section correlation matrix.

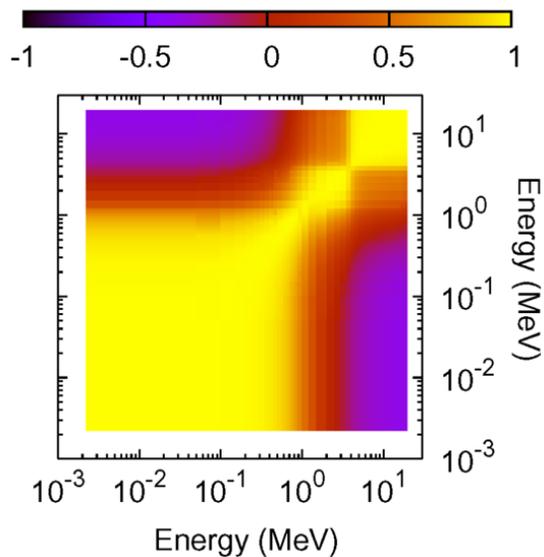


FIG. 6: Correlation matrix for the capture cross section of  $n+^{235}\text{U}$ .

Covariance plots on this & next page taken from:

P. Talou, P.G. Young, T. Kawano, M. Rising, M.B. Chadwick, "Quantification of Uncertainties for Evaluated Neutron-Induced Reactions on Actinides in the Fast Energy Range", Nuclear Data Sheets 112, 3054–3074 (2011)

# Cross-section Covariance Data (6)

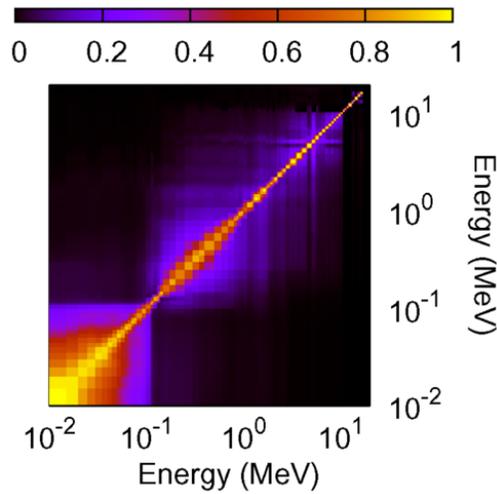


FIG. 25: Correlation matrix evaluated for the  $^{238}\text{Pu}$  (n,fission) cross section.

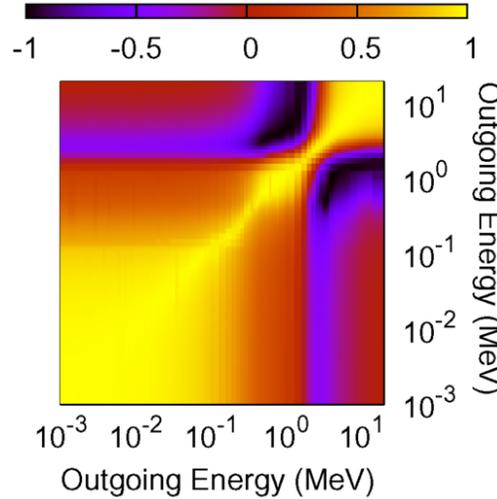


FIG. 40: Correlation matrix evaluated for the  $n(0.5\text{ MeV})+^{239}\text{Pu}$  prompt fission neutron spectrum.

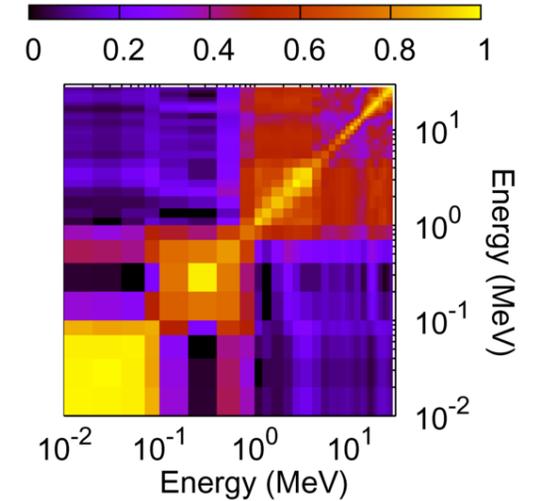


FIG. 43: Evaluated correlation matrix for the neutron-induced fission cross section of  $^{240}\text{Pu}$  in the fast energy range.

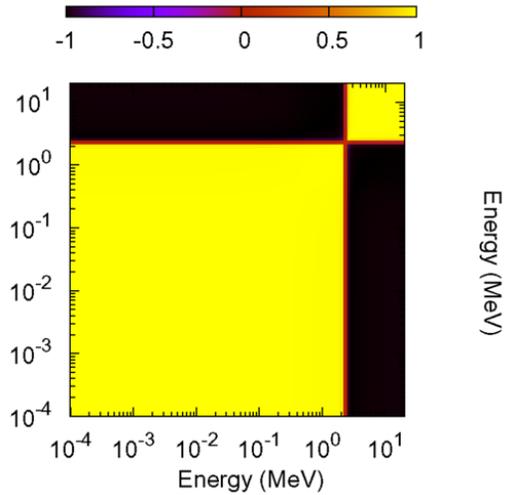


FIG. 30: Correlation matrix for the  $n(0.5\text{ MeV})+^{238}\text{Pu}$  prompt fission neutron spectrum.

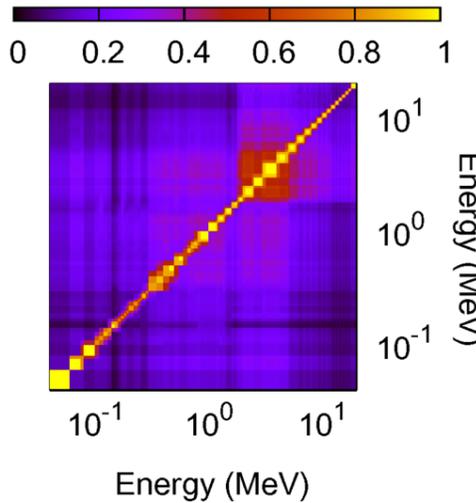


FIG. 45:  $^{240}\text{Pu}$  (n,total) cross section correlation matrix.

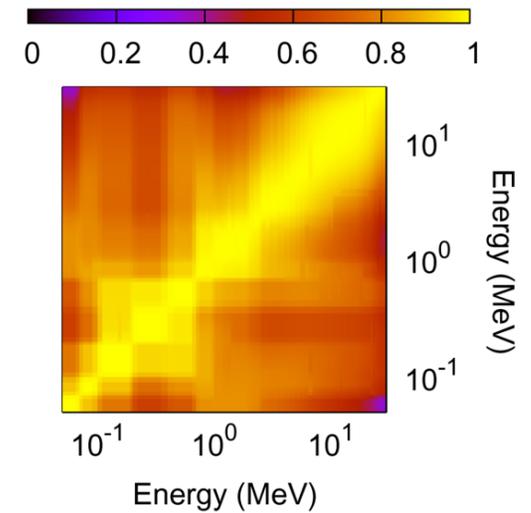


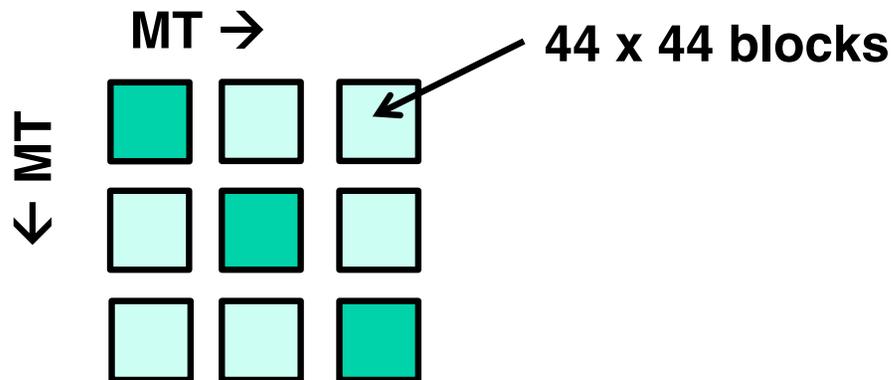
FIG. 47: Correlation matrix for the  $n+^{240}\text{Pu}$  capture cross section. Large off-diagonal elements are due mostly to model uncertainties, since no experimental data exist above 300 keV.

## Cross-section Covariance Data (7)

- For each isotope, with 44 energies & 12 reactions:

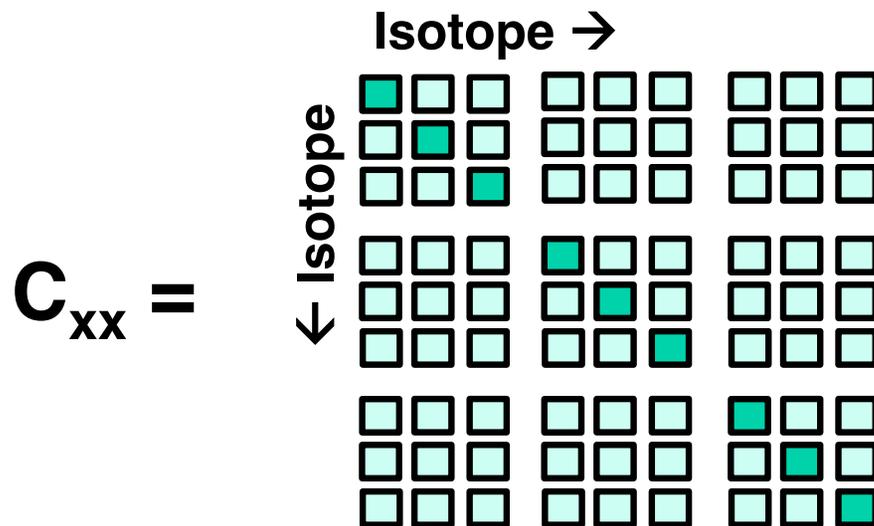
$$C_{xx}^{\text{Iso}} : \quad c(44, 44, 12, 12)$$

- Each diagonal element of  $C_{xx}$  is the **variance** of the cross-section for a particular MT & energy bin
- Off-diagonal elements of  $C_{xx}$  are the **shared variance** between pairs of MT-E & MT'-E' (Off-diagonal MT-MT' blocks would generally be 0)



- Each  $C_{xx}^{\text{Iso}}$  entry is produced by SCALE or NJOY based on covariance data from the ENDF/B libraries (with some adjustments if needed)
- The  $C_{xx}$  data is universal, independent of benchmark or application problem

- The covariance matrices for all isotopes can be combined, including off-diagonal blocks that relate uncertainties in one iso-MT-E with a different iso-MT-E



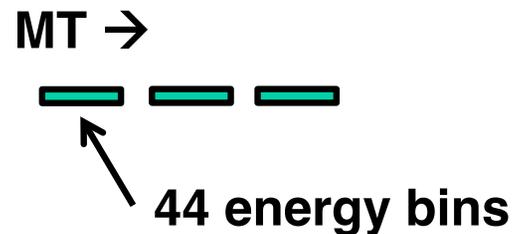
- Each diagonal element of  $C_{xx}$  is the **variance** of the cross-section for a particular isotope, MT, & energy bin
- Off-diagonal elements of  $C_{xx}$  are the **shared variance** between pairs of Iso-MT-E & Iso'-MT'-E'
- Very sparse (lots of zeros), block-structured matrix  
(Off-diagonal I-I' blocks would generally be zero)

# Sensitivity Profiles (Vectors)

- For each isotope, the sensitivity coefficients for a specific problem are stored consistent with the layout of the covariance data
  - Recall that the sensitivity of  $K_{eff}$  to a particular reaction type & energy bin is:

$$S_{k,x} = \frac{\Delta k/k}{\Delta x/x} = \frac{x}{k} \frac{dk}{dx}$$

where  $x$  is the cross-section for a particular isotope, reaction, & energy bin



- For a particular application problem,  $A$ , the sensitivity profiles for all isotopes are combined into one sensitivity vector  $S_A$



# Correlation Coefficients

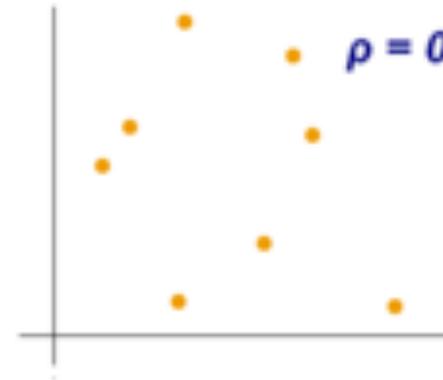
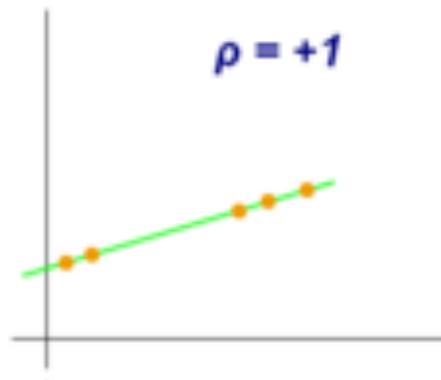
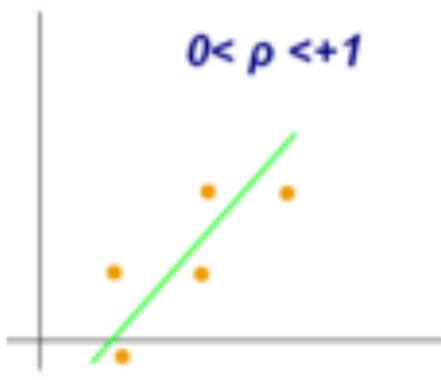
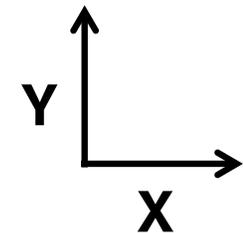
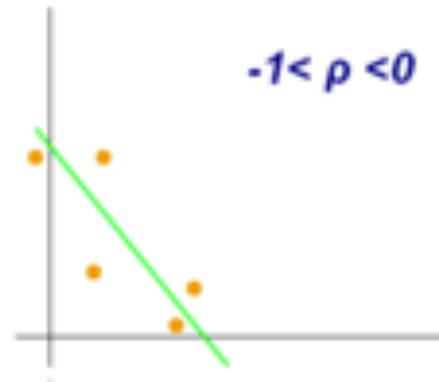
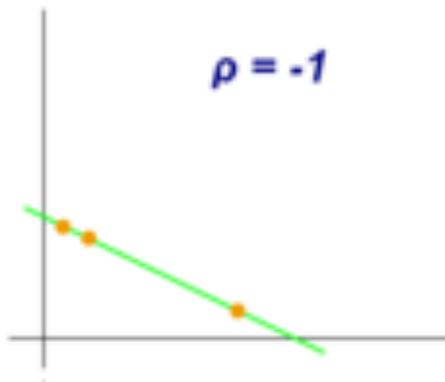
- **Correlation coefficient**

- Pearson product-moment correlation coefficient,  $r$  or  $\rho$
- A measure of the linear correlation between variables  $X$  &  $Y$

$\rho = +1$  total positive correlation

$\rho = -1$  total negative correlation

$\rho = 0$  no correlation



- **Population correlation coefficient,  $\rho$**

- Distribution of  $X$ , with mean  $\mu_x$ , standard deviation  $\sigma_x$
- Distribution of  $Y$ , with mean  $\mu_y$ , standard deviation  $\sigma_y$

$$\rho_{X,Y} = \frac{\text{cov}(X,Y)}{\sigma_X \cdot \sigma_Y} = \frac{E[(X - \mu_X)(Y - \mu_Y)]}{\sigma_X \cdot \sigma_Y} = \frac{E(XY) - E(X) \cdot E(Y)}{\sigma_X \cdot \sigma_Y}$$

$$\begin{aligned} \mu_X &= E(X) & \sigma_X^2 &= E[(X - E(X))^2] = E(X^2) - E(X)^2 \\ \mu_Y &= E(Y) & \sigma_Y^2 &= E[(Y - E(Y))^2] = E(Y^2) - E(Y)^2 \end{aligned}$$

- **Sample correlation coefficient,  $r$**

- Dataset for  $X$ :  $\{ x_1, x_2, \dots, x_n \}$ , mean  $\bar{x}$ , std dev  $s_x$
- Dataset for  $Y$ :  $\{ y_1, y_2, \dots, y_n \}$ , mean  $\bar{y}$ , std dev  $s_y$

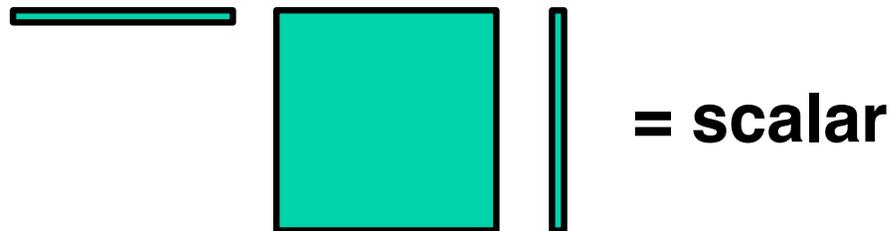
$$r = r_{xy} = \frac{\frac{1}{n} \sum x_i y_i - \bar{x} \cdot \bar{y}}{s_x \cdot s_y}$$

- Given: Problem A, Sensitivity  $S_A$  computed by MCNP  
Problem B, Sensitivity  $S_B$  computed by MCNP

- Variance in Keff due to nuclear data uncertainties:

$$Var_k(A) = \vec{S}_A \bar{C}_{xx} \vec{S}_A^T$$

$$Var_k(B) = \vec{S}_B \bar{C}_{xx} \vec{S}_B^T$$



- Covariance between A & B due to nuclear data uncertainties:

$$Cov_k(A,B) = \vec{S}_A \bar{C}_{xx} \vec{S}_B^T$$

- Correlation between Problems A & B due to nuclear data:

$$c_k(A,B) = \frac{Cov_k(A,B)}{\sqrt{Var_k(A)} \cdot \sqrt{Var_k(B)}} = \frac{\vec{S}_A \bar{C}_{xx} \vec{S}_B^T}{\sqrt{\vec{S}_A \bar{C}_{xx} \vec{S}_A^T} \cdot \sqrt{\vec{S}_B \bar{C}_{xx} \vec{S}_B^T}}$$

- Matrix-vector operations

$$Var_k(A) = \vec{S}_A \bar{C}_{xx} \vec{S}_A^T$$

$$Cov_k(A,B) = \vec{S}_A \bar{C}_{xx} \vec{S}_B^T$$

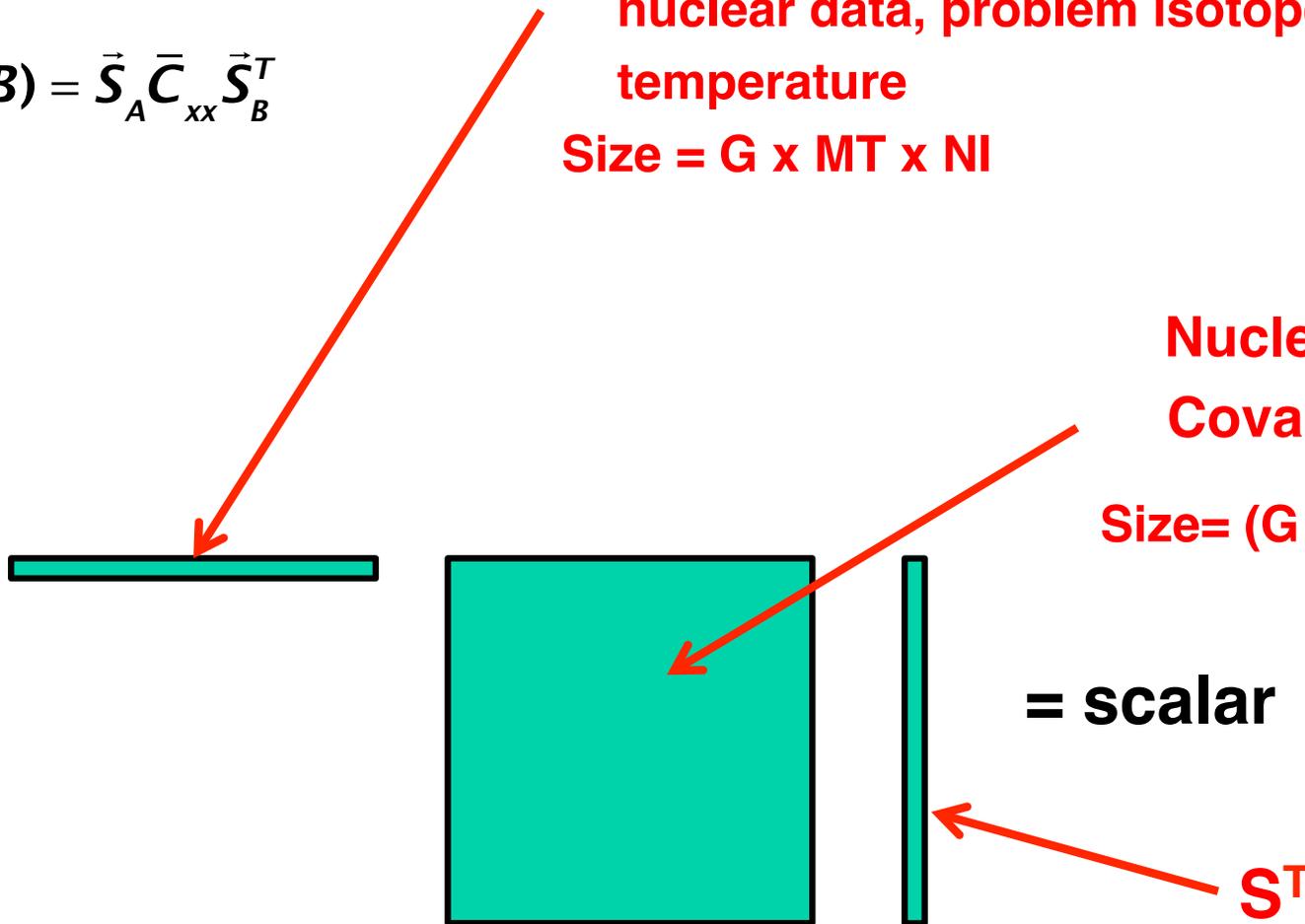
**Problem-dependent sensitivity vector, S.**

Based on flux spectrum, adjoint spectrum, nuclear data, problem isotopes, geometry, temperature

Size = G x MT x NI

**Nuclear Data Covariances**

Size = (G x MT x NI)<sup>2</sup>



- Define a linear relationship

$$\mathbf{y} = \mathbf{A}\mathbf{x} + \mathbf{b}$$

- Determine expected (mean) value of  $\mathbf{y}$

$$\mu_{\mathbf{y}} = E[\mathbf{y}] = E[\mathbf{A}\mathbf{x} + \mathbf{b}] = \mathbf{A}E[\mathbf{x}] + \mathbf{b} = \mathbf{A}\mu_{\mathbf{x}} + \mathbf{b}$$

- Determine covariance matrix of  $\mathbf{y}$

$$\begin{aligned} \mathbf{C}_{\mathbf{y}} &= \text{cov}(\mathbf{y}, \mathbf{y}) = E[(\mathbf{y} - \mu_{\mathbf{y}})(\mathbf{y} - \mu_{\mathbf{y}})^T] \\ &= E[(\mathbf{A}\mathbf{x} + \mathbf{b} - \mathbf{A}\mu_{\mathbf{x}} - \mathbf{b})(\mathbf{A}\mathbf{x} + \mathbf{b} - \mathbf{A}\mu_{\mathbf{x}} - \mathbf{b})^T] \\ &= E[(\mathbf{A}(\mathbf{x} - \mu_{\mathbf{x}}))(\mathbf{A}(\mathbf{x} - \mu_{\mathbf{x}}))^T] \\ &= E[\mathbf{A}(\mathbf{x} - \mu_{\mathbf{x}})(\mathbf{x} - \mu_{\mathbf{x}})^T \mathbf{A}^T] \\ &= \mathbf{A} E[(\mathbf{x} - \mu_{\mathbf{x}})(\mathbf{x} - \mu_{\mathbf{x}})^T] \mathbf{A}^T \\ &= \mathbf{A} \text{cov}(\mathbf{x}, \mathbf{x}) \mathbf{A}^T \end{aligned}$$

$$\mathbf{C}_{\mathbf{y}} = \mathbf{A} \mathbf{C}_{\mathbf{x}} \mathbf{A}^T \quad \leftarrow \text{“Sandwich” Rule!}$$

- **First-order Taylor series expansion of k about cross section,  $\Sigma$**

$$k(\Sigma'_1, \Sigma'_2, \dots, \Sigma'_N) \cong k(\Sigma^0_1, \Sigma^0_2, \dots, \Sigma^0_N) + \sum_{i=1}^N \left. \frac{\partial k}{\partial \Sigma_i} \right|_{\Sigma^0_i} (\Sigma'_i - \Sigma^0_i)$$

- **Define vectors for cross sections and sensitivity profiles**

$$\begin{aligned} \bar{\Sigma}' &= \begin{bmatrix} \Sigma'_1 & \Sigma'_2 & \dots & \Sigma'_N \end{bmatrix} & \bar{S} &= \begin{bmatrix} \left. \frac{\partial k}{\partial \Sigma_1} \right|_{\Sigma^0_1} & \left. \frac{\partial k}{\partial \Sigma_2} \right|_{\Sigma^0_2} & \dots & \left. \frac{\partial k}{\partial \Sigma_N} \right|_{\Sigma^0_N} \end{bmatrix} \\ \bar{\Sigma}^0 &= \begin{bmatrix} \Sigma^0_1 & \Sigma^0_2 & \dots & \Sigma^0_N \end{bmatrix} \end{aligned}$$

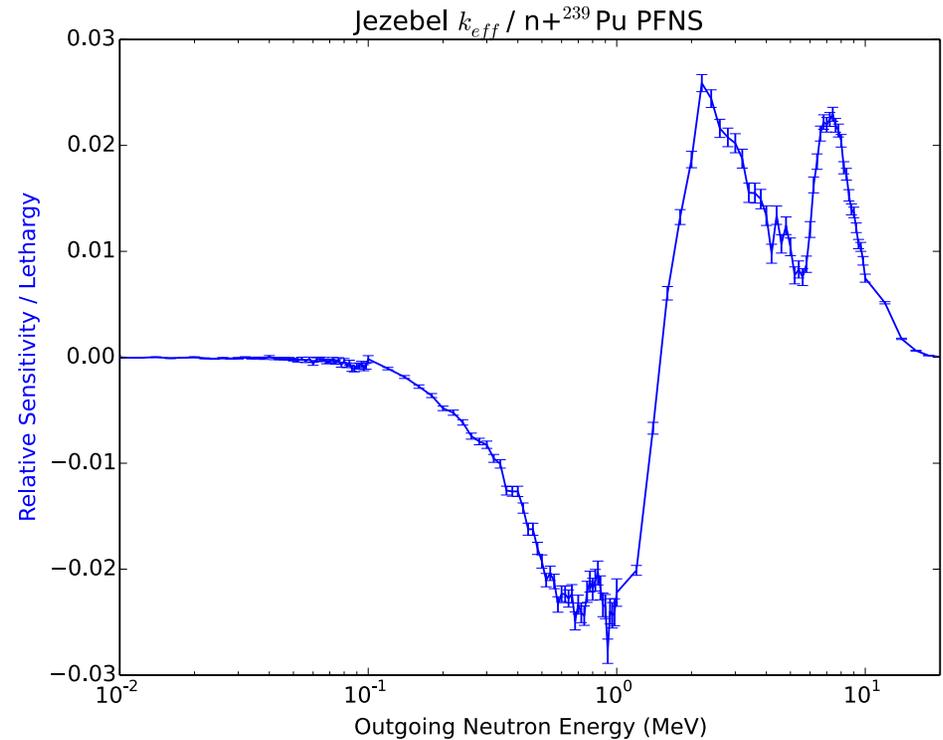
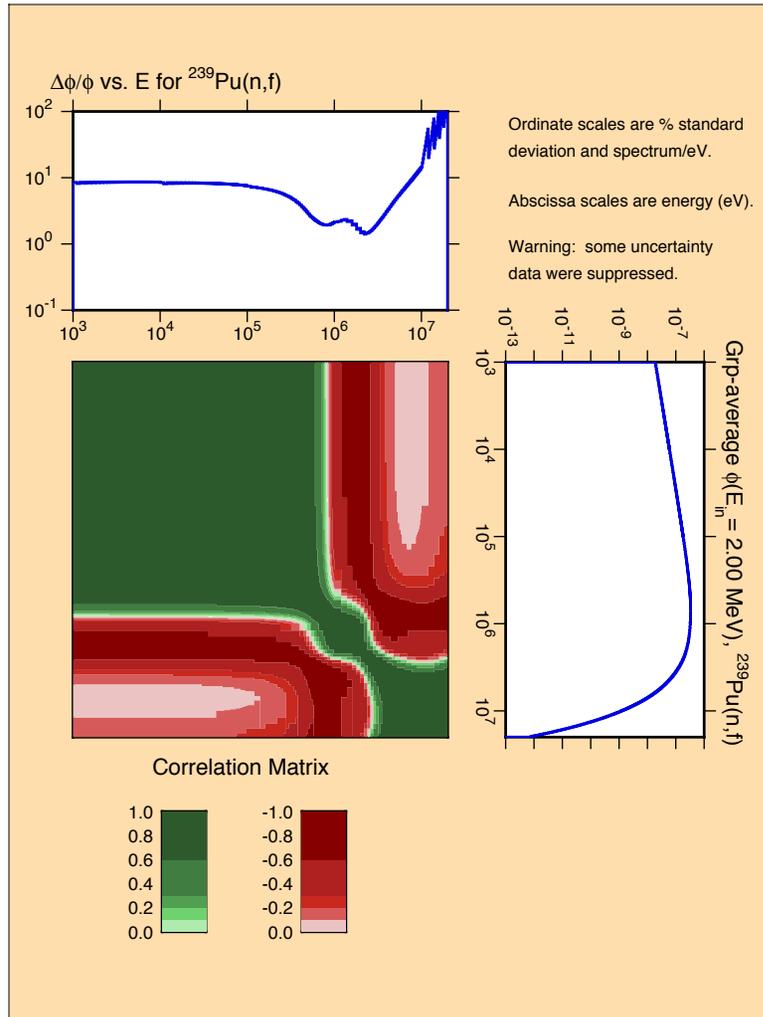
- **Determine covariance matrix (variance) of k**

$$\begin{aligned} k(\bar{\Sigma}') &\cong k(\bar{\Sigma}^0) + \bar{S} (\bar{\Sigma}' - \bar{\Sigma}^0)^T \\ &= \bar{S} \bar{\Sigma}'^T + \left[ k(\bar{\Sigma}^0) - \bar{S} \bar{\Sigma}^0{}^T \right] \\ &= \mathbf{Ax} + \mathbf{b} \end{aligned}$$

$$\mathbf{C}_k = \bar{S} \mathbf{C}_\Sigma \bar{S}^T$$

# Error Propagation (3)

- Example using sandwich rule,  $^{239}\text{Pu}$  PFNS impact on  $k$



Uncertainty in  $k$  due to  $^{239}\text{Pu}$  PFNS only!

$$\sigma_k^2 = \vec{S} \mathbf{C}_X \vec{S}^T$$

$$\frac{\sigma_k}{k} \cong 0.160\%$$

# Whisper

**Software for Sensitivity-Uncertainty-based  
Nuclear Criticality Safety Validation**

## Whisper - Software for Sensitivity-Uncertainty-Based Nuclear Criticality Safety Validation

Whisper is computational software designed to assist the nuclear criticality safety (NCS) analyst with validation studies with the Monte Carlo radiation transport package MCNP. Standard approaches to validation rely on the selection of benchmarks based upon expert judgment. Whisper uses sensitivity/uncertainty (S/U) methods to select relevant benchmarks to a particular application or area of applicability (AOA), or set of applications being analyzed. Using these benchmarks, Whisper computes a calculational margin from an extreme value distribution. In NCS, a margin of subcriticality (MOS) that accounts for unknowns about the analysis. Typically, this MOS is some prescribed number by institutional requirements and/or derived from expert judgment, encompassing many aspects of criticality safety. Whisper will attempt to quantify the margin from two sources of potential unknowns, errors in the software and uncertainties in nuclear data. The Whisper-derived calculational margin and MOS may be used to set a baseline upper subcritical limit (USL) for a particular AOA, and additional margin may be applied by the NCS analyst as appropriate to ensure subcriticality for a specific application in the AOA.

Whisper provides a benchmark library containing over 1,100 MCNP input files spanning a large set of fissionable isotopes, forms (metal, oxide, solution), geometries, spectral characteristics, etc. Along with the benchmark library are scripts that may be used to add new benchmarks to the set; this documentation provides instructions for doing so. If the user desires, Whisper may analyze benchmarks using a generalized linear least squares (GLLS) fitting based on nuclear data covariances and identify those of lower quality. These may, at the discretion of the NCS analyst and their institution, be excluded from the validation to prevent contamination of potentially low quality data. Whisper provides a set of recommended benchmarks to be optionally excluded.

Whisper also provides two sets of 44-group covariance data. The first set is the same data that is distributed with SCALE 6.1 in a format that Whisper can parse. The second set is an adjusted nuclear data library based upon a GLLS fitting of the benchmarks following rejection. Whisper uses the latter to quantify the effect of nuclear data uncertainties within the MOS. Whisper also has the option to perform a nuclear covariance data adjustment to produce a custom adjusted covariance library for a different set of benchmarks.

- **Whisper History, Background, SQA Status, Documentation**
- **Whisper Methodology**
  - **Capabilities**
  - **Correlation Coefficients**
  - **Cross-section Covariance Data**
  - **Sensitivity Profiles**
  - **Variance in Keff & Correlation Between Problems**
  - **Determining benchmark  $C_k$ 's**
  - **Determining bias & bias uncertainty**
  - **Determining portions of the MOS**
- **Using Whisper for Validation**
  - **Overview**
  - **Using whisper\_mcnp**
  - **Using whisper\_usl**
  - **Examples**

- **Whisper ICSBEP Benchmark Suite**
  - 1101 ICSBEP benchmark problems from Mosteller, Kahler, others
  - Sensitivity profiles from adjoint-weighting for all isotopes/reactions/benchmarks
- **Whisper methodology** – LA-UR-14-26558, LA-UR-14-26436, LA-UR-14-23352
  - **Validation benchmarks**
    - Estimate missing uncertainties
    - Reject inconsistent benchmarks via iterated diagonal chi-squared method (~12%)
    - Correlation data from DICE; covariance data from ORNL (10% diag for missing)
    - Automated benchmark selection for AOA problem using sensitivity data to determine  $C_k$  values;  $C_k$  values used for weighting
  - **Calculational Margin**
    - Determine bias from non-parametric method based on Extreme Value Theory, using weighting determined from  $C_k$  values
    - Determine bias uncertainty numerically from distribution of worst-case  $k_{\text{eff}}$  bias
  - **Margin of Subcriticality**
    - Margin of 0.0050 for unknown code errors (expert judgment)
    - Margin for nuclear data uncertainty from GLLS method
    - Additional margin – analyst judgment for AOA & problem, conservatism, etc.
  - **USL = 1.0 – Calculational Margin – Margin of Subcriticality**

- **Whisper is part of the MCNP software package**
  - Will be distributed to the criticality-safety community via future RSICC releases of MCNP
  - Feedback from criticality-safety analysts at DOE sites will be factored into future development
  - Potential for world-wide feedback/review/improvements
- **Maintained under MCNP version control system (GIT, TeamForge)**
  - LANL standard
  - WHISPER GIT Module for checkout into MCNP source tree
  - All revisions, additions, improvements tracked under Artifact 36407
- **MCNP SQA methodology**
  - Encompasses Whisper
  - Previous audits & reviews of MCNP SQA determined that methodology was compliant with DOE/ASC & LANL P1040 requirements
  - Review is in progress to assess current MCNP SQA P1040 compliance, and make any revisions required to continue compliance

- **THEORY**

B.C. Kiedrowski, F.B. Brown, et al., "Whisper: Sensitivity/Uncertainty-Based Computational Methods and Software for Determining Baseline Upper Subcritical Limits", Nuc. Sci. Eng. Sept. 2015, LA-UR-14-26558 (2014),

B.C. Kiedrowski, "Methodology for Sensitivity and Uncertainty-Based Criticality Safety Validation", LA-UR-14-23202 (2014)

F.B. Brown, M.E. Rising, J.L. Alwin, "Lecture Notes on Criticality Safety Validation Using MCNP & Whisper", LA-UR-16-21659 (2016)

- **USER MANUAL**

B.C. Kiedrowski, "User Manual for Whisper (v1.0.0), Software for Sensitivity- and Uncertainty-Based Nuclear Criticality Safety Validation", LA-UR-14-26436 (2014)

- **APPLICATION**

B.C. Kiedrowski, et al., "Validation of MCNP6.1 for Criticality Safety of Pu-Metal, -Solution, and -Oxide Systems", LA-UR-14-23352 (2014)

- **SOFTWARE QUALITY ASSURANCE**

R.F. Sartor, F.B. Brown, "Whisper Program Suite Validation and Verification Report", LA-UR-15-23972 (2015-05-28)

R.F. Sartor, F.B. Brown, "Whisper Source Code Inspection Report", LA-UR-15-23986 (2015-05-28)

R.F. Sartor, B.A. Greenfield, F.B. Brown, "MCNP6 Criticality Calculations Verification and Validation Report", LA-UR-15-23266 (2015-04-30)

Monte Carlo Codes Group (XCP-3), "Whisper - Software for Sensitivity-Uncertainty-based Nuclear Criticality Safety Validation", LANL TeamForge Tracker system, Artifact artf36407 (2015)

Monte Carlo Codes Group (XCP-3), WHISPER module in LANL TeamForge GIT repository (2015)

Monte Carlo Codes Group (XCP-3), MCNP6 module in LANL TeamForge GIT repository

Monte Carlo Codes Group (XCP-3), "MCNP Process Documents", LANL Teamforge wiki for MCNP

Monte Carlo Codes Group (XCP-3), "Software Quality Assurance", LANL Teamforge wiki for MCNP, P1040-rev9 requirements

# Whisper Methodology

## Whisper Methodology

- MCNP6
  - Determine Sensitivity Profiles for Benchmarks  $B_1 \dots B_N$
  - Determine Sensitivity Profiles for Application A
  
- **Whisper – Determine Benchmark  $c_k$ 's**
  - For each benchmark  $B_j$ , determine  $c_k^{(j)}$  correlation coefficient between A &  $B_j$
  
- **Whisper – Determine Benchmark Weights & Select Benchmarks**
  - Iterative procedure using  $c_k^{(j)}$  values,  $c_{k,max}$ ,  $c_{k,acc}$
  
- **Whisper – Determine Computational Margin (CM)**
  - Extreme Value Theory, with weighted data, nonparametric
  - Compute bias & bias uncertainty
  - Adjustment for non-conservative bias
  - Handling small sample sizes
  
- **Whisper – Determine portions of MOS**

## Admin

- Install code, scripts, benchmarks, covariance files, correlations
- Test the installation
- Identify inconsistent benchmarks to be rejected
- Estimate missing benchmark uncertainties
- Can add additional benchmarks
- Can reject additional benchmarks

## User

- Use **whisper\_mcnp** script to run MCNP6 for process models, to obtain  $k_{\text{eff}}$  & sensitivity profiles for all isotopes & reactions
- Use **whisper\_usl** script to run Whisper for process models
  - Whisper matches process model sensitivity profiles with benchmark library profiles, selects most similar benchmarks
  - Compute calculational margin for each process model, based on selected benchmarks (bias + bias uncertainty)
  - Estimate cross-section portion of MOS based on GLLS
  - Use 0.005 for code unknowns portion of MOS
  - Estimate baseline USL for each process model (not including additional AOA or other margin)

- **As part of Whisper installation (not day-to-day use),**
  - **For each of the 1100+ benchmarks**
    - MCNP6 is run to generate the sensitivity vector  $S_B$  for that benchmark
    - The sensitivity vector  $S_B$  for each benchmark is saved in a folder
  - **The nuclear data covariance files are saved in a folder**
  - **Benchmarks are checked for consistency, some may be rejected**
  - **Missing uncertainties for some benchmarks are estimated**
  - **Details will be covered later. All of this is the responsibility of the Admin person & needs to be done only once at installation (or repeated if the code, data, or computer change)**
- **To use Whisper for validation:**
  - Use the **whisper\_mcnp** script to make 1 run with MCNP6 for a particular application, to generate the sensitivity vector for the application,  $S_A$
  - Run Whisper, using the **whisper\_usl** script

- Given  $S_A$  for an application, the nuclear data covariance files, and the collection of 1100+  $S_B$  vectors for the benchmarks
  - For each of the benchmarks, compute the correlation between the benchmark & application problem,  $c_k(A,B)$
  - Use the  $c_k(A,B)$  values for the benchmarks to compute relative weights for each benchmark
  - Select the a set of benchmarks with the highest weights (i.e., the highest neutronics correlations between benchmarks & application)
  - Using the selected benchmarks, compute bias, bias uncertainty, & extra margin based on nuclear data uncertainty
  - There are of course details, such as acceptable  $c_k$  values, determining weights using  $c_k$  values, extra penalty if not enough similar benchmarks, benchmark correlation, .....



- Benchmarks are assigned weights  $w_J$  based on their  $c_k^{(J)}$  values,  $c_{k,max}$ , and a (to-be-determined) acceptance threshold,  $c_{k,acc}$ 
  - Benchmarks similar to the application,  $c_k^{(J)} > c_{k,acc}$ :  $0 < w_J \leq 1$
  - Benchmarks not similar to the application,  $c_k^{(J)} < c_{k,acc}$ :  $w_J = 0$
  - Scheme for determining  $w_J$  is on next slide
- The minimum required total weight,  $w_{req}$ , for the set of selected benchmarks is:

$$w_{req} = w_{min} + (1 - c_{k,max}) * w_{penalty}$$

where  $w_{min} = 25$  (default, user opt)  
 $w_{penalty} = 100$  (default, user opt)

- That is, must select enough benchmarks so that  $\text{sum}\{ w_J \} \geq w_{req}$
- Rationale
  - 25 or more are needed for reliable statistical treatment
  - If benchmarks are not close to application ( $c_{k,max}$  not close to 1.0), want to require more of them. Simple linear penalty.

- The determination of benchmark weights is iterative, based on an acceptance criteria  $c_{k,acc}$

- $c_{k,acc}$  is the minimum threshold for  $c_k^{(j)}$  values
- Benchmarks with  $c_k^{(j)} < c_{k,acc}$  are assigned  $w_j = 0$
- Benchmarks with  $c_k^{(j)} \geq c_{k,acc}$  are assigned weight

$$w_j = \frac{c_k^{(j)} - c_{k,acc}}{c_{k,max} - c_{k,acc}}$$

- Iterative procedure determines largest  $c_{k,acc}$  that satisfies requirement that  $\sum\{w_j\} \geq w_{req}$ 
  - Select a value for  $c_{k,acc}$  close to  $c_{k,max}$
  - Determine benchmark weights (by above scheme)
  - If  $\sum\{w_j\} < w_{req}$ , decrease  $c_{k,acc}$  by  $10^{-5}$  & repeat above step
  - The iteration ends when enough benchmarks with highest  $w_j$ 's are selected so that  $\sum\{w_j\} \geq w_{req}$

If not enough benchmarks to satisfy total weight requirement, adjustment scheme is used. Discussed later, at end.....

- **Whisper uses a nonparametric statistical approach to determining the calculational margin (bias + bias uncertainty)**
  - Does not rely on assumption that  $(k_{\text{calc}} - k_{\text{bench}})$  is normally distributed for the set of benchmarks
  - Can handle weighted benchmarks (Tsunami rank-order scheme can't)
  - Based on **Extreme Value Theory**
    - The addition of less-relevant benchmarks cannot reduce the calculational margin
    - Irrelevant benchmarks (i.e., low  $c_k$ ) will not non-conservatively affect results
    - Accounting for weighting avoids overly conservative calculational margin
- **Whisper uses EVT to find the value of a calculational margin that bounds the worst-case bias to some probability of a weighted population**

Note in following discussion:

- There is the fundamental assumption that for a single benchmark, the bias for that benchmark is normally distributed, according to the experimental uncertainty & Monte Carlo statistics
- There is no assumption of normality across the collection of benchmarks, however. The method is nonparametric.

- Let  $\beta_J = k_{\text{calc } J} - k_{\text{bench } J}$  and  $\sigma^2_J = \sigma^2_{\text{bench } J} + \sigma^2_{\text{calc } J}$ 
  - For convenience, the  $X_J$  below are opposite in sign to  $\beta_J$
- For a set of  $N$  benchmarks, let  $X_J$  be a random variable normally distributed about  $\beta_J$  with uncertainty  $\sigma_J$ . The cumulative distribution function (CDF) for  $X_J$  is

$$F_J(x) = \text{Prob}(X_J < x) = \frac{1}{\sqrt{2\pi} \cdot \sigma_J} \int_{-\infty}^x \exp\left[-\frac{1}{2} \left(\frac{y + \beta_J}{\sigma_J}\right)^2\right] dy = \frac{1}{2} \left[ 1 + \text{erf}\left(\frac{x + \beta_J}{\sqrt{2\sigma_J^2}}\right) \right]$$

Note:  $+\beta_J$ , due to opposite sign

- Let the random variable  $X$  be the maximum (opposite-signed) bias for the benchmark collection:

$$X = \max\{ X_1, \dots, X_N \}$$

- The cumulative distribution function (CDF) for  $X$  is

$$F(x) = \text{Prob}(X \leq x) = \prod_{J=1}^N F_J(x)$$

- When benchmarks are weighted, the following form is used for  $F_J(x)$

$$F_J(x) = (1 - w_J) + \frac{w_J}{2} \left[ 1 + \operatorname{erf} \left( \frac{x + \beta_J}{\sqrt{2\sigma_J^2}} \right) \right]$$

- For all benchmarks  $J = 1, \dots, N$ , Whisper computes

- Benchmark weight,  $w_J$
- Bias,  $\beta_J$
- Bias uncertainty,  $\sigma_J$

- Those quantities & the weighted  $F_J(x)$  determine  $F(x)$ :

$$F(x) = \prod_{J=1}^N F_J(x)$$

- Whisper determines the computational margin (bias + bias uncertainty) by numerically solving:

$$F(\text{CM}) = .99 \quad (.99 \text{ is default, user opt})$$

CM is the computational margin that bounds the worst-case benchmark bias & bias uncertainty with probability .99 (default)

- Bias & bias uncertainty**

$$\text{USL} = 1 - \text{CM} - \text{MOS}$$

$$= 1 + \text{bias} - \text{bias-uncert} - \Delta_{\text{non-conserv}} - \text{MOS}$$

- **ANSI/ANS-8.24:**

"Individual elements (e.g., bias and bias uncertainty) of the calculational margin need not be computed separately. Methods may be used that combine the elements into the calculational margin."

- Whisper computes CM by numerically solving  $F(\text{CM}) = .99$**

- Whisper computes bias & bias uncertainty numerically as:**

$$\text{bias} = - \int_{-\infty}^{\infty} x \cdot f(x) dx = - \int_{-\infty}^{\infty} x F(x) \sum_{j=1}^N w_j \frac{f_j(x)}{F_j(x)} dx$$

$$\sigma_{\text{bias}} = \text{CM} + \text{bias}$$

- If the bias is non-conservative (positive), then the CM is adjusted so that no credit is taken for non-conservative bias**

$$\text{if bias} > 0, \quad \text{CM} = \text{CM} + \text{bias}$$

What if there are not enough benchmarks to meet the requirement that  $\text{sum}\{w_J\} = w_{\text{req}}$  ?

- Define these quantities:

$W_{\text{sum}} = \text{sum}\{w_J\}$  - sum of all benchmark weights,  $W_{\text{sum}} < W_{\text{req}}$

$CM_0$  = calculational margin computed with all benchmark weights set to 1.0

- $CM_0$  is an upper bound, wide application space but not specific enough for the application being analyzed
- Typically large & very over-conservative

$CM'$  = calculation margin with weighted benchmarks, but  $w_{\text{sum}} < w_{\text{req}}$

- Note that  $CM_0 \geq CM'$

- Compute CM from: 
$$CM = CM' \cdot \frac{W_{\text{sum}}}{W_{\text{req}}} + CM_0 \cdot \left(1 - \frac{W_{\text{sum}}}{W_{\text{req}}}\right)$$

- Should probably question the benchmark suite, & include extra conservative margin of subcriticality

$$\text{MOS} = \text{MOS}_{\text{software}} + \text{MOS}_{\text{data}} + \text{MOS}_{\text{application}}$$

- **MOS = additional margin "that is sufficiently large to ensure that the calculated conditions will actually be subcritical" (ANSI/ANS-8.24)**
- **MOS<sub>software</sub> (for MCNP)**
  - **No approximations from mesh or multigroup**
  - **Exact answers to analytical benchmarks with given xsecs**
  - **Many years testing with collision physics & random sampling**
  - **Only realistic concern is unknown bugs**
    - MCNP is used a lot, for many different criticality applications
    - Bugs that produce  $\Delta k < 0.0010$  are difficult to distinguish from data uncertainties
    - Past bugs that produced  $\Delta k > 0.0020$  are very few, but reported & fixed
    - Historical detection limit for bugs is  $\Delta k \sim 0.0020$
    - Expert judgment, conservative:  $\text{MOS}_{\text{software}} = 0.0050$   
→ Any unknown bug larger than this would have certainly been found & fixed
    - Other MC codes should almost certainly use a larger margin
    - **Analysts may use a larger number, but have no basis for a smaller number**

$$\text{MOS} = \text{MOS}_{\text{software}} + \text{MOS}_{\text{data}} + \text{MOS}_{\text{application}}$$

- **MOS<sub>application</sub>**
  - **Analyst: analyses, scoping, judgment**
  - **Consider uncertainties in dimensions, densities, isotopics, etc.**
  - **Consider the number of similar benchmark cases**
  - **Consider area-of-applicability**
  
  - **Expert judgment, backed up by analysis**

$$\text{MOS} = \text{MOS}_{\text{software}} + \text{MOS}_{\text{data}} + \text{MOS}_{\text{application}}$$

- **MOS<sub>data</sub>**

- The largest portion of MOS comes from uncertainties in the nuclear cross-section data
- Data uncertainties could be as large as 0.5% - 1% in extra MOS, possibly more, possibly less
- **MOS<sub>data</sub> depends on the application**
  - For common applications, where there are lots of benchmark experiments, the relevant ENDF/B-VII data was adjusted based on those benchmarks
  - For less common applications, where there are few benchmark experiments, ENDF/B-VII adjustments for benchmarks plays little or no role in the data
- In the past, very difficult to assess MOS<sub>data</sub>, which led to large conservative margins
- Whisper (LANL) & Tsunami (ORNL) both use essentially the same methodology to address MOS<sub>data</sub> – GLLS
- Generalized Linear Least Squares (GLLS) takes into account the experiments, calculations, sensitivities, & data covariance data to predict MOS<sub>data</sub>

- **The goal of GLLS:** (start at the end.....)
  - Determine adjustments to the nuclear data,  $\Delta x$ , which produce changes in computed  $k_{\text{eff}}$  for benchmarks,  $\Delta k$ , such that this quantity is minimized for the set of benchmarks:
$$\chi^2 = \Delta \vec{k} \cdot \bar{C}_{kk} \cdot \Delta \vec{k}^T + \Delta \vec{x} \cdot \bar{C}_{xx} \cdot \Delta \vec{x}^T$$
  - $\Delta k$  is a vector of the relative changes in the ratio of calculated  $k$  to benchmark  $k$ , due to the change in cross-section data  $\Delta x$ . The length of  $\Delta k$  is the number of benchmarks
  - $\Delta x$  is a vector of the relative differences of cross-section data from their mean values. The length of  $\Delta x$  is (isotopes)\*(reactions)\*(energies)
  - $C_{kk}$  is the relative covariance matrix for the benchmark experiment  $k$ 's
    - Diagonal elements are variance of each benchmark experiment
    - Off-diagonals are correlation between benchmark measurements. (From DICE, often zero or not well-known)
  - $C_{xx}$  is the relative covariance matrix for the nuclear data
  - GLLS finds  $\Delta x$  (and the resulting  $\Delta k$ ) such that  $\chi^2$  is minimized

- **The goal of GLLS:**

- Determine adjustments to the nuclear data,  $\Delta x$ , which produce changes in computed  $k_{\text{eff}}$  for benchmarks,  $\Delta k$ , such that this quantity is minimized for the set of benchmarks:

$$\chi^2 = \Delta \vec{k} \cdot \bar{C}_{kk} \cdot \Delta \vec{k}^T + \Delta \vec{x} \cdot \bar{C}_{xx} \cdot \Delta \vec{x}^T$$

- With no data adjustment,  $\Delta x = 0$ , so  $\chi^2$  determined only by differences in calculated & benchmark k's
- If data is adjusted to decrease 1<sup>st</sup> term, then 2<sup>nd</sup> term increases
- GLLS determines optimum tradeoff (minimum  $\chi^2$ ) between  $\Delta x$  &  $\Delta k$

Measured  $k_{eff}$  values for benchmarks:

$$\vec{m} = (m_i), \quad i = 1, \dots, l \quad (l = \# \text{ benchmarks})$$

Covariance matrix for  $\vec{m}$ , relative to calculated  $k_{eff}$ 's:

$$\bar{C}_{mm} = \left( \frac{m_i}{k_i} \cdot \frac{\text{cov}(m_i, m_j)}{m_i m_j} \cdot \frac{m_j}{k_j} \right), \quad i, j = 1, \dots, l$$

Covariance between measured benchmark k's (m's) & cross-section data:

$$\bar{C}_{xm} = \left( \frac{\text{cov}(x_n, m_i)}{x_n m_i} \cdot \frac{m_i}{k_i} \right), \quad n = 1, \dots, M \quad i = 1, \dots, l$$

This represents correlations between cross-section data & the measured benchmark k's. **At present, these data do not exist. Neither Tsunami nor Whisper use  $C_{xm}$ .**

Linear changes in calculated  $k_{eff}$  due to perturbation in data,  $\vec{x}$ :

$$k_i(\vec{x}') = k_i(\vec{x} + \delta\vec{x}) = k_i(\vec{x}) + \delta k_i = k_i(\vec{x}) \cdot \left[ 1 + \sum_{n=1}^M S_n^{(i)} \cdot \frac{\delta x_n}{x_n} \right]$$

Recall that:

Sensitivity matrix for a set of benchmarks:

$$\bar{S}_k = \left( \frac{x_n}{k_i} \cdot \frac{\partial k_i}{\partial x_n} \right) \quad i = 1, \dots, I \text{ (rows)} \quad n = 1, \dots, M \text{ (cols)}$$

Covariance matrix for nuclear data,  $\vec{x}$  :

$$\bar{C}_{xx} = \left( \frac{\text{cov}(x_n, x_p)}{x_n x_p} \right) \quad n = 1, \dots, M \quad p = 1, \dots, M$$

Uncertainty matrix for the set of benchmarks, due to data:

$$\bar{C}_{kk} = \bar{S}_k \cdot \bar{C}_{xx} \cdot \bar{S}_k^T$$

Express the relative changes in k for a set of benchmarks due to data perturbations:

$$\frac{k_i(\vec{x}') - m_i}{k_i(\vec{x})} = \frac{k_i(\vec{x}) - m_i}{k_i(\vec{x})} + \left[ \sum_{n=1}^M S_n^{(i)} \cdot \frac{\delta x_n}{x_n} \right]$$

or

$$\vec{y} = \vec{d} + \bar{S}_k \cdot \vec{z}$$

For the vector  $\vec{d}$ ,  $(d_i) = \frac{k_i(\vec{x}) - m_i}{k_i(\vec{x})} \quad i = 1, \dots, l$

the uncertainty matrix for the set of benchmarks is

$$\begin{aligned} \bar{C}_{dd} &= \bar{C}_{kk} + \bar{C}_{mm} - \bar{S}_k \bar{C}_{xm} - \bar{C}_{mx} \bar{S}_k^T \\ &= \bar{S}_k \bar{C}_{xx} \bar{S}_k^T + \bar{C}_{mm} - \bar{S}_k \bar{C}_{xm} - \bar{C}_{mx} \bar{S}_k^T \end{aligned}$$

GLLS involves minimizing this quantity:

$$Q(\vec{z}, \vec{y}) = (\vec{y}, \vec{z}) \cdot \begin{pmatrix} \bar{C}_{mm} & \bar{C}_{mx} \\ \bar{C}_{xm} & \bar{C}_{xx} \end{pmatrix}^{-1} \cdot (\vec{y}, \vec{z})^T,$$

subject to the constraint  $\vec{y} = \vec{d} + \bar{S}_k \vec{z}$

This is accomplished using Lagrange multipliers & minimizing this quantity:

$$R(\vec{z}, \vec{y}) = Q(\vec{z}, \vec{y}) + 2\lambda(\bar{S}_k \vec{z} - \vec{y})$$

$\vec{z}$  and  $\vec{y}$  satisfy these relations:

$$\frac{\partial R(\vec{z}, \vec{y})}{\partial \vec{z}} = \frac{\partial R(\vec{z}, \vec{y})}{\partial \vec{y}} = 0$$

The results, giving the adjusted data & k's that minimize R are:

$$\Delta \text{data:} \quad \vec{z} = (\bar{C}_{xm} - \bar{C}_{xx} \bar{S}_k^T) \cdot \bar{C}_{dd}^{-1} \cdot \vec{d}$$

$$\Delta k: \quad \vec{y} = (\bar{C}_{mm} - \bar{C}_{mx} \bar{S}_k^T) \cdot \bar{C}_{dd}^{-1} \cdot \vec{d}$$

GLLS gives the data adjustments (& resulting  $\Delta k$ 's) that minimize the Q or R functions (also called  $\chi^2$ )

The adjustments also give reduced uncertainties:

$$\bar{C}_{m'm'} = \bar{C}_{mm} - (\bar{C}_{mm} - \bar{C}_{mx} \bar{S}_k^T) \cdot \bar{C}_{dd}^{-1} \cdot (\bar{C}_{mm} - \bar{S}_k \bar{C}_{xm})$$

$$\bar{C}_{x'x'} = \bar{C}_{xx} - (\bar{C}_{xm} - \bar{C}_{xx} \bar{S}_k^T) \cdot \bar{C}_{dd}^{-1} \cdot (\bar{C}_{mx} - \bar{S}_k \bar{C}_{xx})$$

The adjusted uncertainty matrix in k for a set of applications is:

$$\bar{C}_{k'k'} = \bar{S}_{k,A} \cdot \bar{C}_{x'x'} \cdot \bar{S}_{k,A}^T$$

where each row of  $\bar{S}_{k,A}$  is the sensitivity vector for an application.

The square roots of diagonal elements in  $\bar{C}_{k'k'}$  are the relative  $1\sigma$  uncertainties in k for the adjusted data.

For a particular application i, the portion of MOS for nuclear data uncertainty is:

$$MOS_{data} = n_\sigma \cdot \sqrt{(\bar{C}_{kk})_{i,i}}$$

where  $n_\sigma = 2$  for 95% confidence, 2.6 for 99%

- To consider a simulated system subcritical, the computed keff must be less than the Upper Subcritical Limit (USL):

$$K_{\text{calc}} < \text{USL}$$

$$\text{USL} = 1 + (\text{Bias}) - (\text{Bias uncertainty}) - \text{MOS}$$

$$\text{MOS} = \text{MOS}_{\text{data}} + \text{MOS}_{\text{code}} + \text{MOS}_{\text{application}}$$

- The bias and bias uncertainty are at some confidence level, typically 95% or 99%.
  - These confidence intervals may be derived from a normal distribution, but the normality of the bias data must be justified.
  - Alternatively, the confidence intervals can be set using non-parametric methods.

# Whisper Usage

- **As part of Whisper installation (not day-to-day use),**
  - **For each of the ~1100 benchmarks**
    - MCNP6 is run to generate the sensitivity vector  $S_B$  for that benchmark
    - The sensitivity vector  $S_B$  for each benchmark is saved in a folder
  - **The nuclear data covariance files are saved in a folder**
  - **Benchmarks are checked for consistency, some may be rejected**
  - **Missing uncertainties for some benchmarks are estimated**
  - **All of this is the responsibility of the Admin person & needs to be done only once at installation (or repeated if the code, data, or computer change)**
- **To use Whisper for validation:**
  - Use the **whisper\_mcnp** script to make 1 run with MCNP6 for a particular application, to generate the sensitivity vector for the application,  $S_A$
  - Run Whisper, using the **whisper\_usl** script

## To try it, on Moonlight HPC:

- **Set & export WHISPER\_PATH environment variable**

- **bash:**

```
export WHISPER_PATH
WHISPER_PATH="/usr/projects/mcnp/ncs/WHISPER"
export PATH
PATH="$WHISPER_PATH/bin:$PATH"
```

- **csh, tcsh:**

```
setenv WHISPER_PATH "/usr/projects/mcnp/ncs/WHISPER"
setenv PATH "$WHISPER_PATH/bin:$PATH"
```

- **Make a directory with input files**

- No blanks in pathname, directory name, input file names
  - Put mcnp6 input files in the directory

- **Run**

```
whisper_mcnp.pl -walltime 02:00:00 myjob*.i
..... wait till jobs complete
whisper_usl.pl
```

- From the front-end on an HPC system:

**whisper\_mcnp Inp1.txt**

– **Inp1.txt is an MCNP6 input file**

- Must NOT include any of these cards: **kopts, ksen, prdmp**
- May list more than 1 input file on whisper\_mcnp command line
- For now, input file names must be 40 chars or less
- May include time limit for MCNP jobs before the list of input files,  
**walltime hh:mm:ss**

– **Creates files & dirs:**

- MCNPInputList.toc
- Calcs/
- Calcs/Inp1.txt ← **modified to include kopts, ksen, prdmp, & new kcode**
- KeffSenLib/

– **Submits jobs to HPC compute nodes**

- Single-node jobs, 16 threads each
- Default time limit of 1 hr

- For each MCNP6 input file listed on the whisper\_mcnp command line:

- KCODE line is deleted & these lines are inserted:

```
kcode 100000 1.0 100 600
kopts blocksize= 5
ksen1 xs
rxn= +2 +4 -6 +16 102 103 104 105 106 107 -7 -1018
erg= 1.0000e-11 3.0000e-09 7.5000e-09 1.0000e-08 2.5300e-08 3.0000e-08
      4.0000e-08 5.0000e-08 7.0000e-08 1.0000e-07 1.5000e-07 2.0000e-07
      2.2500e-07 2.5000e-07 2.7500e-07 3.2500e-07 3.5000e-07 3.7500e-07
      4.0000e-07 6.2500e-07 1.0000e-06 1.7700e-06 3.0000e-06 4.7500e-06
      6.0000e-06 8.1000e-06 1.0000e-05 3.0000e-05 1.0000e-04 5.5000e-04
      3.0000e-03 1.7000e-02 2.5000e-02 1.0000e-01 4.0000e-01 9.0000e-01
      1.4000e+00 1.8500e+00 2.3540e+00 2.4790e+00 3.0000e+00 4.8000e+00
      6.4340e+00 8.1873e+00 2.0000e+01
prdmp j 9999999
```

- After using whisper\_mcnp, after the MCNP6 jobs complete:

- The Calcs/ directory will contain these files

- Inp1.txt modified MCNP6 input file, with kcode, ksen, kopts, prdmp
- Inp1.txto output file from MCNP6 jobs
- Inp1.txtr runtpe file
- Inp1.txts srctp file

# whisper\_mcnp.pl - Usage

## whisper\_mcnp.pl [Options] Filelist

### Options:

-help	print this information
-local	run MCNP jobs locally, on this computer
-submit	submit batch MCNP jobs, using msub [default]
-walltime x	walltime limit for submitted batch jobs (eg, 01:00:00)
-mcnp x	pathname for MCNP6 executable
-xmdir x	pathname for MCNP6 xmdir file
-data x	pathname for MCNP6 data, DATAPATH
-threads x	number of threads for MCNP6
-neutrons x	number of neutrons/cycle for MCNP6
-discard x	number of inactive cycles for MCNP6
-cycles x	total number of cycles for MCNP6

### Filelist:

Names of MCNP6 input files. The names should not contain blanks.  
The files must include a KCODE card (that will be replaced), &  
must not contain KSEnN, KOPTS, or PRDMP cards (they will be supplied)

### Defaults:

	**for local**	**for submit**
-submit		
-mcnp	hardwired in script	/usr/projects/mcnp/mcnpexe -6
-xmdir	hardwired in script	/usr/projects/mcnp/MCNP_DATA/xmdir_mcnp6.1
-data	hardwired in script	/usr/projects/mcnp/MCNP_DATA
-walltime		01:00:00
-threads	12	16
-neutrons	10000	100000
-discard	100	100
-cycles	600	600

- From the front-end on an HPC system, in the same directory where `whisper_mcnp` was executed, run Whisper using the `whisper_usl` script:

### `whisper_usl`

- Can optionally include `ExcludeFile.dat`, list of benchmark files to exclude from Whisper calculations
- Runs Whisper for application(s) `Inp1.txt` (etc)
- For each input file listed in `MCNPInputList.toc`:
  - Extract sensitivity profiles from `Calcs/Inp1.txt` to, place into directory `KeffSenLib/`
  - Create (or add to) file `KeffSenList.toc`
  - Run Whisper using the sensitivity profiles for the application (`Inp1.txt`) and the collection of Whisper benchmark sensitivity profiles
  - Output to screen & file `whisper.out`

- After running `whisper_mcnp` & `whisper_usl`:

```
whisper_mcnp    Inp1.txt    Inp2.txt
whisper_usl
```

Files created by `whisper_mcnp`, `mcnp6`, & `whisper_usl`:

```
Inp1.txt          ← original
Inp2.txt          ← original
MCNPInputlist.toc
Calcs/
    Inp1.txt Inp1.txtto Inp1.txtr Inp1.txts
    Inp2.txt Inp2.txtto Inp2.txtr Inp2.txts
KeffSenList.toc
KeffSenLib/
    Inp1.txtk
    Inp2.txtk
Whisper.out
```

- **Whisper-1.1.0, whisper\_mcnp.pl, whisper\_usl.pl**
  - **whisper\_mcnp.pl**
    - set up & run mcnp6 for application to generate application sensitivity profiles
  - **whisper\_usl.pl**
    - use whisper to select benchmarks based on comparing application sensitivity profiles to benchmark sensitivity profiles
    - compute USL using selected benchmarks (weighted)
- **Benchmarks for this demo**
  - **Don't use 1101 Whisper benchmark set – takes too long on laptop to compare application with 1101 benchmark profiles**
  - **Instead: use 246 problems from NCS Validation Suite (from 2015)**  
(not including 15 pu-met-fast-042-\* problems)
- **Application for this demo**
  - **in-28-2-1 (from Salazar, 11/06/2014)**

# whisper\_mcnp.pl

```
bash: whisper_mcnp.pl -local -neutrons 10000 -discard 25 \  
-cycles 225 -threads 4 in-28-2-1.txt
```

```
*****
```

```
* *
```

```
* whisper_mcnp * a utility script to set up input & run MCNP for Whisper
```

```
* *
```

```
*****
```

```
Input File TOC = MCNPInputList.toc
```

```
Calculation directory = Calcs
```

```
Sensitivity directory = KeffSenLib
```

```
Neutrons/cycle = 10000
```

```
Cycles to discard = 25
```

```
Total Cycles to run = 225
```

```
MCNP6 executable = /Users/fbrown/LANL/MCNP_CODE/bin/mcnp6
```

```
XSDIR file = /Users/fbrown/LANL/MCNP_DATA/xsdir_mcnp6.1
```

```
DATAPATH = /Users/fbrown/LANL/MCNP_DATA
```

```
Threads = 4
```

```
All jobs will be run locally on this computer
```

```
...process mcnp input file: in-28-2-1.txt
```

```
...modified mcnp input file: Calcs/in-28-2-1.txt
```

```
...run mcnp on this computer: in-28-2-1.txt
```

```
mcnp ver=6 , ld=06/23/14 02/07/16 14:44:03
```

```
Code Name & Version = MCNP, 6.1.1b
```

# whisper\_usl.pl (1)

```
bash: whisper_usl.pl
```

```
*****  
*  
* whisper_usl *  
*  
*****
```

```
set up & run Whisper validation calculations
```

```
=====> setup files for whisper
```

```
---> setup for problem in-28-2-1.txt
```

```
...extract sensitivity profile data from: Calcs/in-28-2-1.txto  
...copy sensitivity profile data to: KeffSenLib/in-28-2-1.txtk  
...extract calc Keff & Kstd data from: Calcs/in-28-2-1.txto  
... KeffCalc= 0.96740 +- 0.00057, ANECF= 1.4904E+00 MeV, EALF= 1.2150E-01 MeV
```

```
=====> run whisper
```

```
/Users/fbrown/CODES/WHISPER/WHISPER.git/bin/whisper -a KeffSenList.toc -ap KeffSenLib  
whisper-1.1.0 2016-02-02 (Copyright 2016 LANL)  
WHISPER_PATH = /Users/fbrown/CODES/WHISPER/WHISPER.git  
Benchmark TOC File = /Users/fbrown/CODES/WHISPER/WHISPER.git/Benchmarks/TOC/BenchmarkTOC.dat  
Benchmark Sensitivity Path = /Users/fbrown/CODES/WHISPER/WHISPER.git/Benchmarks/Sensitivities  
Benchmark Correlation File =  
Benchmark Exclusion File =  
Benchmark Rejection File =  
Covariance Data Path = /Users/fbrown/CODES/WHISPER/WHISPER.git/CovarianceData/SCALE6.1  
Covariance Adjusted Data Path =  
Application TOC File = KeffSenList.toc  
Application Sensitivity Path = KeffSenLib/  
User Options File =  
Output File = Whisper.out
```

.....

Reading benchmark data ...  
Reading application data ...  
Reading covariance data ...  
Reading adjusted covariance data ...  
Calculating application nuclear data uncertainties ...  
Calculating upper subcritical limits ...

.....case 1 Ck= 0.41263  
.....case 4 Ck= 0.36554  
.....case 3 Ck= 0.63497

.....

.....case 246 Ck= 0.18901

application	calc margin	data unc (1-sigma)	baseline USL	k(calc) > USL
in-28-2-1.txt	0.01329	0.00120	0.97860	-0.00972

# Whisper.out (1)

```
whisper-1.1.0          2016-02-02  (Copyright 2016 LANL)
WHISPER_PATH          = /Users/fbrown/CODES/WHISPER/WHISPER.git
Benchmark TOC File    = /Users/fbrown/CODES/WHISPER/WHISPER.git/Benchmarks/TOC/BenchmarkTOC.dat
Benchmark Sensitivity Path = /Users/fbrown/CODES/WHISPER/WHISPER.git/Benchmarks/Sensitivities
Benchmark Correlation File =
Benchmark Exclusion File =
Benchmark Rejection File =
Covariance Data Path  = /Users/fbrown/CODES/WHISPER/WHISPER.git/CovarianceData/SCALE6.1
Covariance Adjusted Data Path =
Application TOC File   = KeffSenList.toc
Application Sensitivity Path = KeffSenLib/
User Options File     =
Output File           = Whisper.out
```

Reading benchmark data ...

benchmark	k(bench)	unc	k(calc)	unc	bias	unc
pu-comp-inter-001-001.i	1.00000	0.01100	1.01174	0.00007	-0.01174	0.01100
pu-comp-mixed-001-001.i	0.99860	0.00410	1.02477	0.00009	-0.02617	0.0041

.....

246 benchmarks read, 0 benchmarks excluded.

Reading application data ...

application	k(calc)	unc
in-28-2-1.txt	0.96802	0.00052

Reading covariance data ...

Reading covariance data for 1001 ...

.....

Reading adjusted covariance data ...

Reading covariance data for 1001 ...

# Whisper.out (2)

Calculating application nuclear data uncertainties ...

application	adjusted	prior
in-28-2-1.txt	0.00209	0.01221

Calculating upper subcritical limits ...

<b>application</b>	<b>calc</b>	<b>data unc</b>	<b>baseline</b>	<b>k(calc)</b>
<b>in-28-2-1.txt</b>	<b>margin</b>	<b>(1-sigma)</b>	<b>USL</b>	<b>&gt; USL</b>
	0.01334	0.00209	<b>0.97623</b>	-0.00686

Benchmark population = **48**  
 Population weight = 28.56732  
 Maximum similarity = 0.96434  
  
 Bias = 0.00850  
 Bias uncertainty = 0.00484  
 Nuc Data uncert margin = 0.00209  
 Software/method margin = 0.00500  
 Non-coverage penalty = 0.00000

For this application,  
48 of the benchmarks  
were selected as neutronically similar  
& sufficient for valid statistical analysis

Benchmark rankings shown below

<b>benchmark</b>	<b>ck</b>	<b>weight</b>
pu-met-fast-011-001.i	0.9643	1.0000
pu-met-fast-044-002.i	0.9641	0.9958
pu-met-fast-021-002.i	0.9618	0.9545
pu-met-fast-003-103.i	0.9602	0.9252
pu-met-fast-026-001.i	0.9594	0.9099
pu-met-fast-025-001.i	0.9584	0.8912
pu-met-fast-032-001.i	0.9572	0.8699
pu-met-fast-016-001.i	0.9546	0.8221
pu-met-fast-027-001.i	0.9546	0.8217
.....		
pu-met-fast-012-001.i	0.9167	0.1283
pu-met-fast-040-001.i	0.9166	0.1269
pu-met-fast-045-003.i	0.9163	0.1209
pu-met-fast-045-004.i	0.9147	0.0909
pu-met-fast-002-001.i	0.9145	0.0874

- Traditional validation methods are 40+ years old; S/U methods are new
- Should not argue for exclusive use of either traditional or S/U methods
- The foundation of criticality safety includes conservatism, continuous improvement, state-of-the-art tools & data, thorough checking, .....
- The next 5 years or so should be a transition period, where both traditional & S/U methods should be used
  - Traditional methods provide a check on S/U methods
  - S/U approach to automated benchmark selection is quantitative, physics-based, & repeatable. Provides a check on traditional selection
  - Traditional methods use  $MOS_{data+code}$  of 2-5%.  
Quantitative, physics-based, repeatable  $MOS_{data+code}$  from S/U usually smaller
- Traditional & S/U methods complement each other, & provide greater assurance for setting USLs
- In today's environment of audits, reviews, & "justify everything", it is prudent to use both traditional & S/U methods for validation

## Abstract

- Whisper - abstract from LANL TeamForge Tracker system, Artifact artf36407 (2015)

## Theory

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## User Manual

- B.C. Kiedrowski, "User Manual for Whisper (v1.0.0), Software for Sensitivity- and Uncertainty-Based Nuclear Criticality Safety Validation", LA-UR-14-26436 (2014)
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## Application

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- F.B. Brown, B.C. Kiedrowski, J.S. Bull, "Verification of MCNP5-1.60 and MCNP6.1 for Criticality Safety Applications", LA-UR-13-22196 (2013).
- L.J. Cox, S.D. Matthews, "MCNP6 Release 1.0: Creating and Testing the Code Distribution", LA-UR-13-24008 (2013)

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