Sensitivity and Uncertainty Methods for Fuel Cycle Analysis

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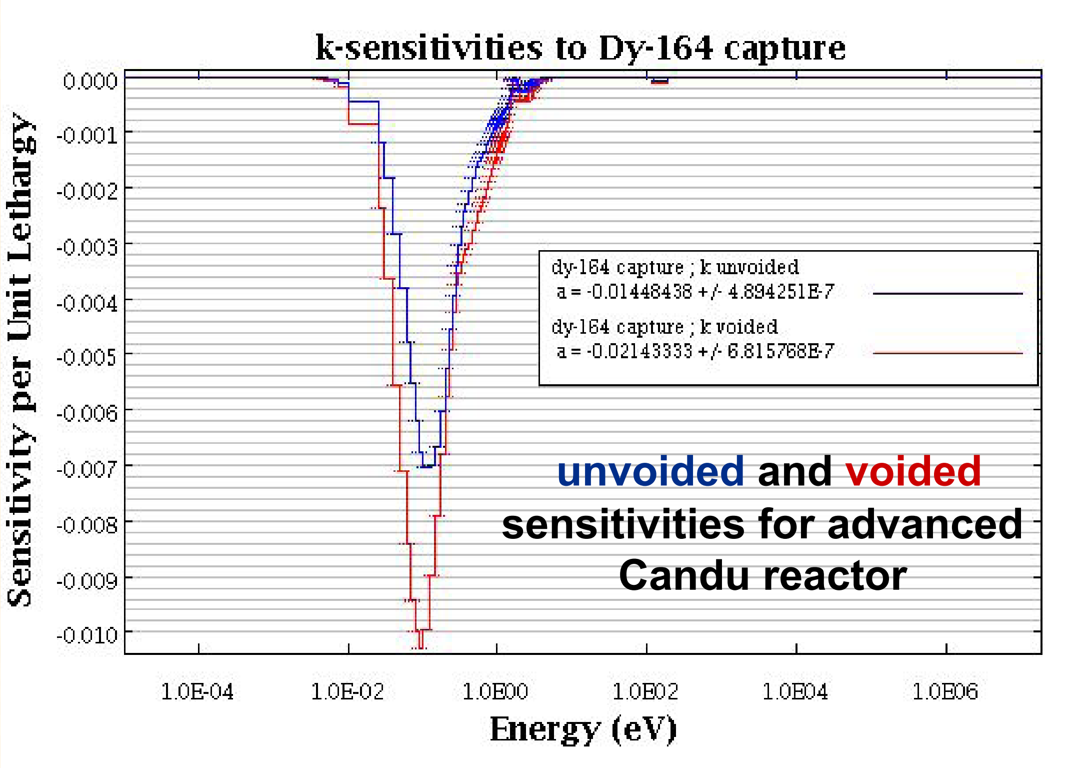
Sensitivity Coefficients Reveal the Relation Between Nuclear Data and Applications

$$\left(\frac{\delta k}{k}\right) = S_{k,\sigma}\left(\frac{\delta\sigma}{\sigma}\right)$$



S/U Methods Can Be Used to Assess Impact of Data on Design of AFC Facilities

- REACTOR CORE
  - Core performance and safety parameters
  - Fuel cycle

- CRITICALLITY SAFETY AND SHIELDING
  - Fuel fabrication
  - Reprocessing/recycling facilities
  - Transportation of spent fuel
  - Rad-waste disposition facilities

Applications of S/U Methods

- Determine sensitivity of calculated results to nuclear data used in transport calculations
- Determine uncertainty in calculations due to data uncertainties
- Identify relative contributions of nuclear data to uncertainty
- Perform similarity analysis of application vs. experiments to select or design integral benchmark experiments
- Adjust differential and integral data to obtain greater consistency
- Determine computational bias and uncertainty in response, based on benchmark experiment analysis

In 1970-80's S/U Methods Were Developed for (mainly) LMFBR Analysis

Limitations of Earlier S/U Methods

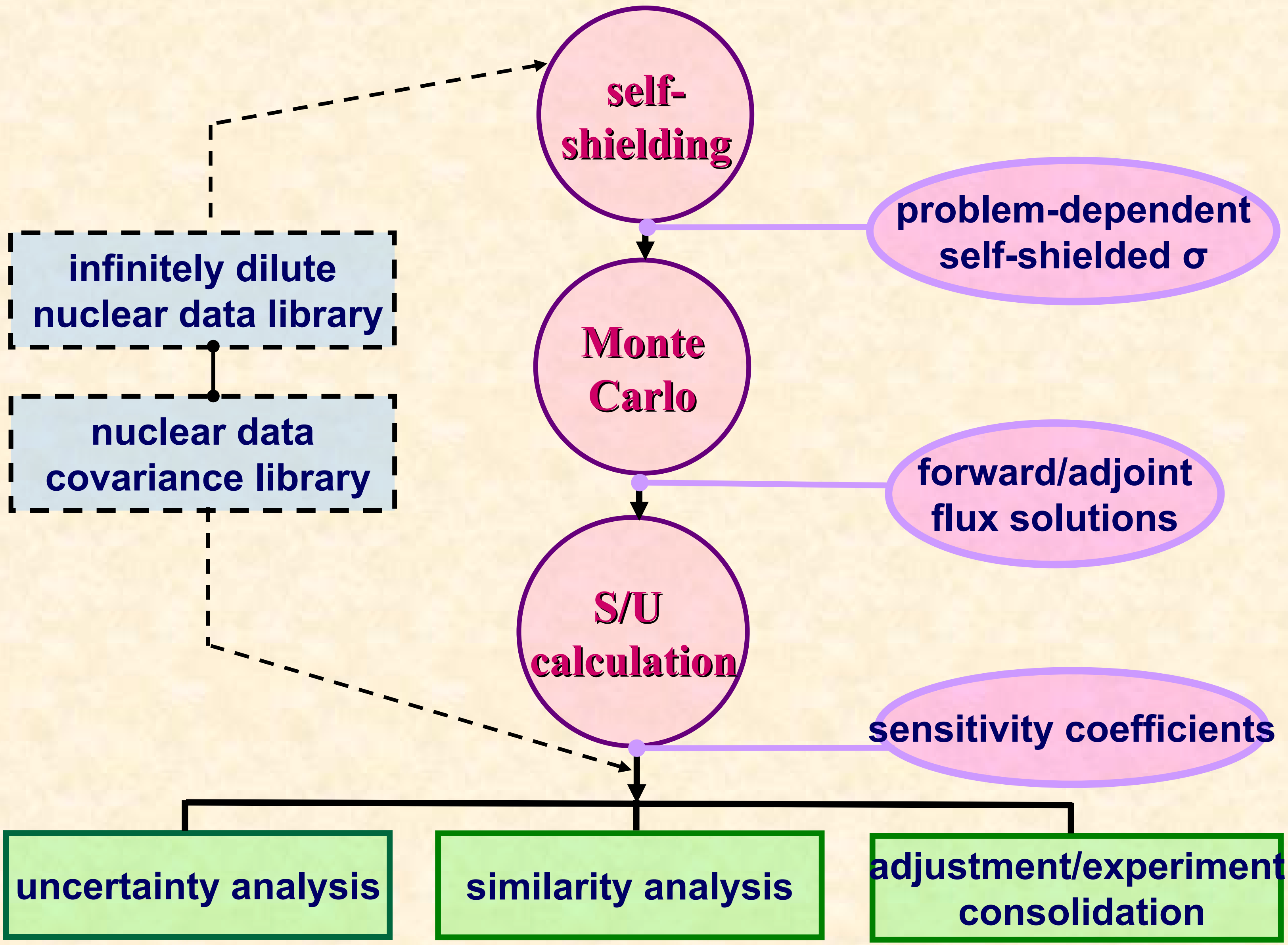
- Limited to homogenized transport models, often based on 1D/2D discrete ordinates or 3D diffusion theory
- Could not address thermal systems with significant resonance self-shielding sensitivities
- Lack of cross section covariance data
- Difficult to use– required setting up multiple calculations:
  - radiation transport
  - sensitivity coefficients
  - uncertainty analysis

TSUNAMI

The Next Generation of S/U Methods at ORNL

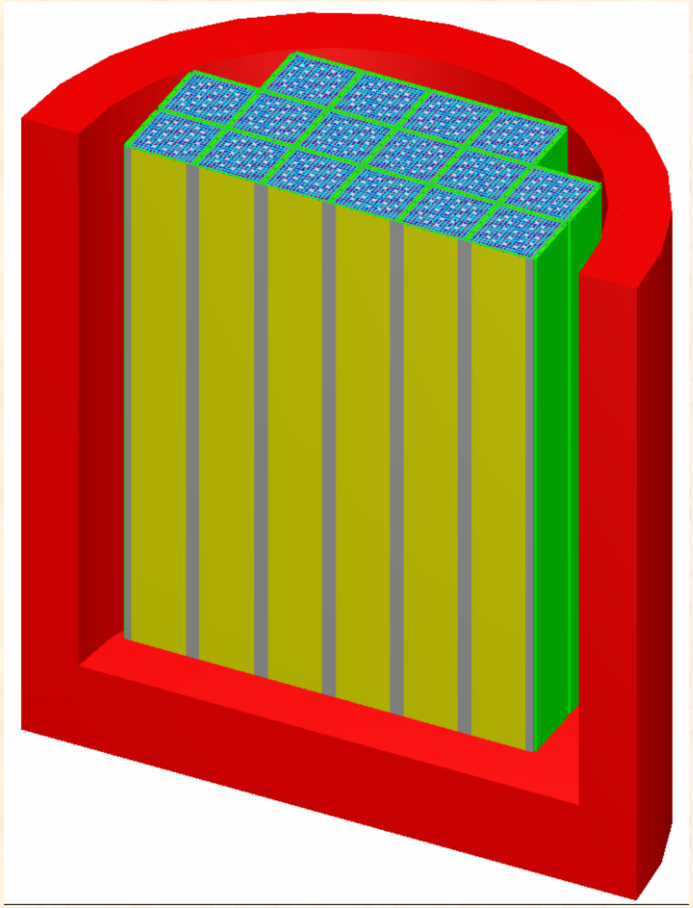
- Entire computation sequence is automated
- Sensitivity calculation based on 3D Monte Carlo or 1D SN
- Sensitivity coefficients include effects of perturbations in resonance self-shielding
- A more complete covariance library is available, based on integral approximation
- GUI's are available for displaying S/U information
- Modules available for similarity analysis and data adjustment

TSUNAMI-3D Computation Sequence

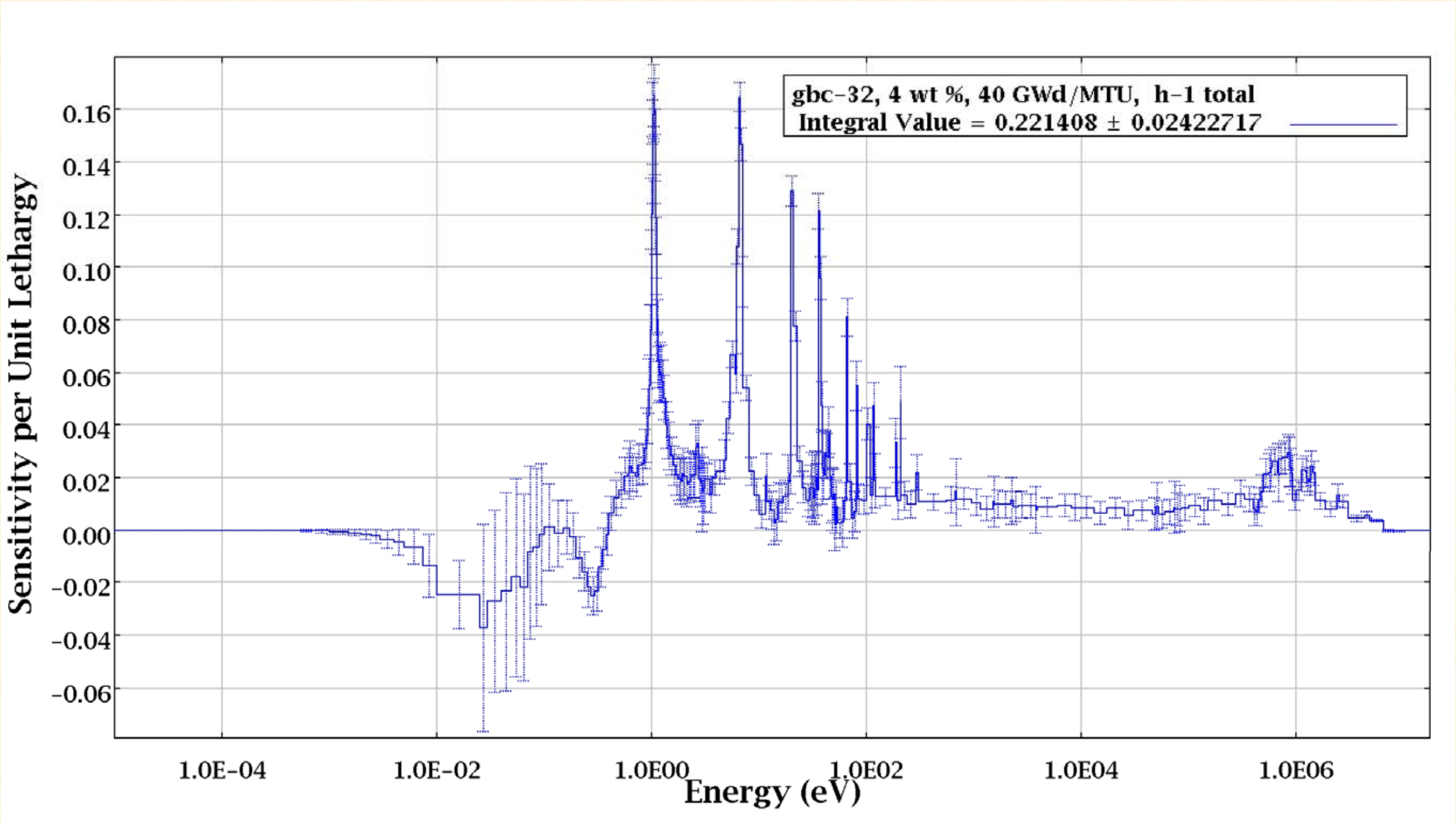


Burnup Credit Cask Model for S/U Analysis with Monte Carlo

- **32 PWR fuel assemblies**
- **4 wt% Westinghouse 17x17 assemblies**
- **18 axial burnup zones**
- **Burned to 40 GWd/MTU; Cooled for 5 years**
- **BORAL™ plates around each assembly**
- **23.76 cm (9.353”) cell pitch**
- **Cask filled with water**
- **Referred to as the GBC-32 (for details see NUREG/CR-6747)**



TSUNAMI-3D Calculation for H Total Sensitivity in Shipping Cask



Complete Sensitivity Coefficient Includes *Implicit* and *Explicit* Effects

- **"Explicit Effect"** =

  sensitivity to changes in multigroup cross sections appearing transport equation

- **"Implicit Effect"** =

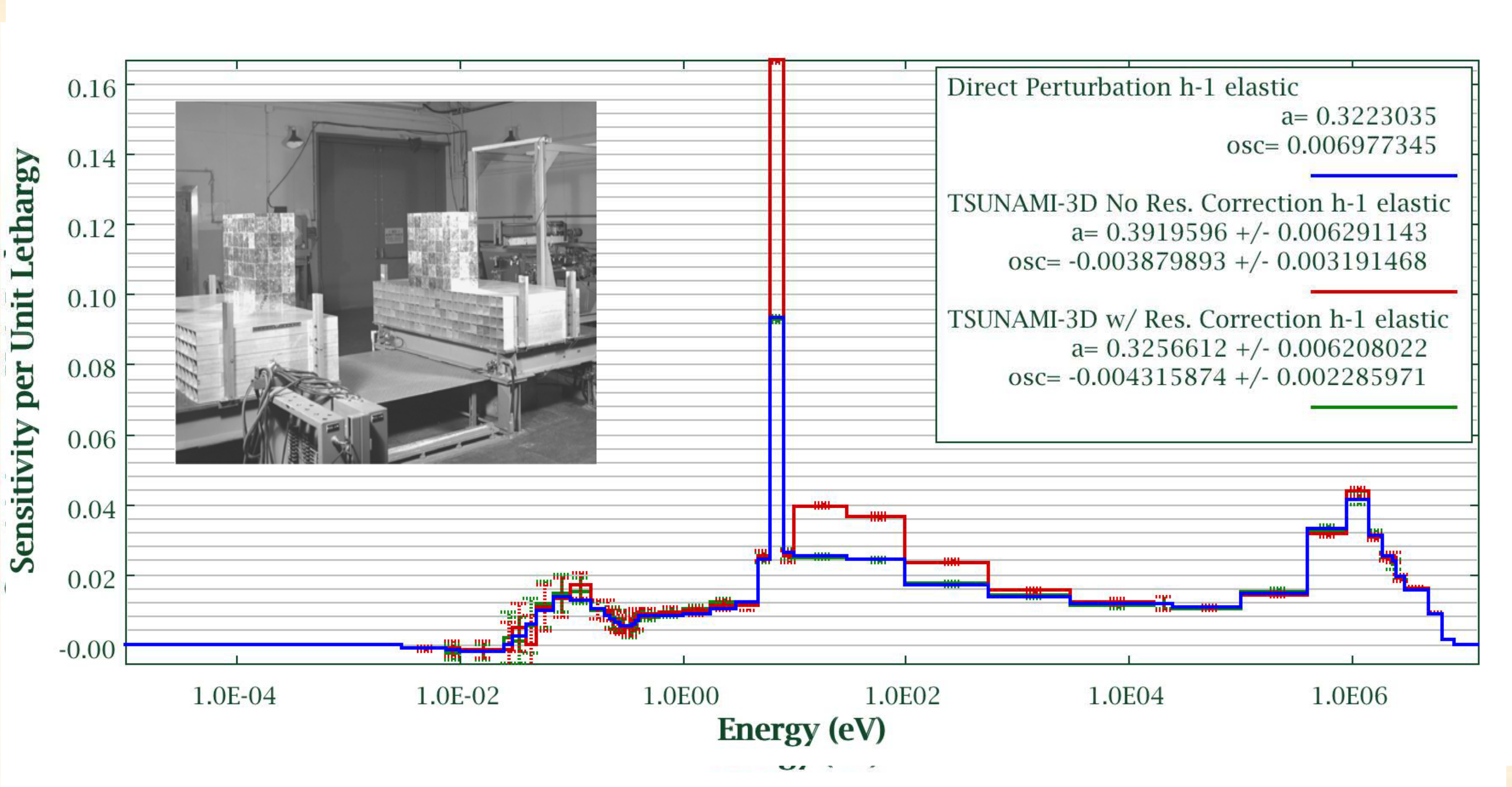
  sensitivity to cross section perturbations caused by changes in self-shielding

Example:

A perturbation in $\sigma^{(H)}$ changes self-shielded $\sigma^{(U238)}$;

→ implicit perturbation in $\sigma^{(U238)}$ changes k_{eff}

Sensitivity Coefficient for H Elastic in Thermal Critical Experiment



Approximate Covariance Library for TSUNAMI Applications

- Covariance data for >50 nuclides were taken from ENDF/B-VI, JENDL-3.3, or JEFF-3.1 if available

- Covariance data for *>250* nuclides are approximated by **integral measurement uncertainties**
  - **σ_s (moderators) ~ potential cross section uncertainty**
  - **$\sigma_c, \sigma_f, \upsilon$ [E < 0.5 eV] ~ thermal data uncertainty**
  - **σ_c, σ_f [0.5 < E < 5E3 eV] ~ resonance integral uncertainty**

NO UNCERTAINTIES INCLUDED FOR E > 5E3 eV

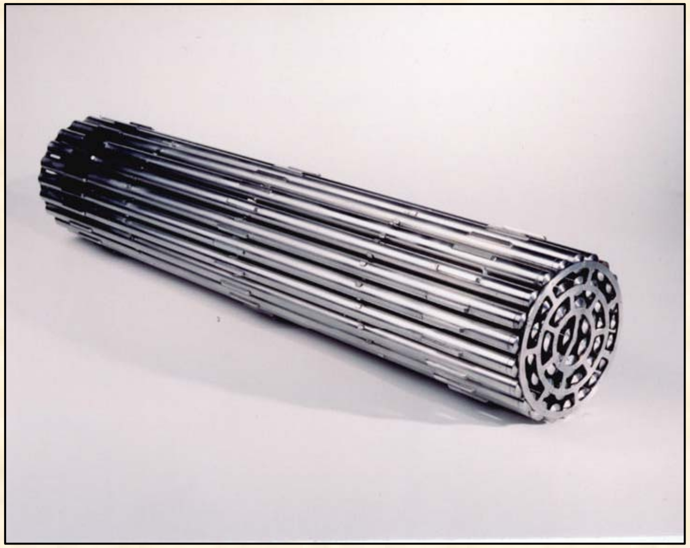
Differential versus Integral Data and Uncertainties

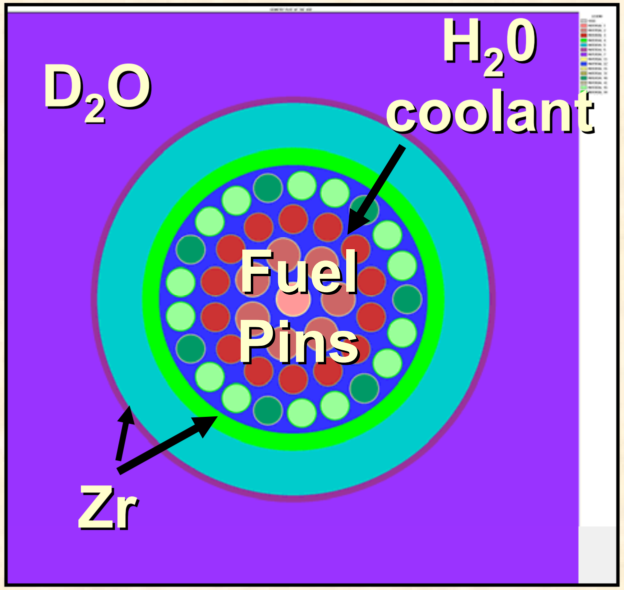
Resonance Integrals

Nuclide	ENDF/B VI	Integral experiment	difference (%)	integral uncertainty (%)
Cd-113	3.92E+2	3.90E+2	0.5	10.3
Xe-135	7.65E+6	7.60E+3	0.7	6.6
Sm-149	4.02E+4	4.01E+4	0.2	5.9
Np-237	6.60E+2	6.40E+2	3.0	7.8

Example Uncertainty Analysis:

coolant void reactivity in advanced Candu reactor





Response	Relative St. Dev. (%)
Eigenvalue, *unvoided*	0.80
Eigenvalue, *voided*	0.84
coolant void reactivity	49.8

Example Uncertainty Analysis:
Space-Reactor Shielding

Shield Design	Response ; *Uncertainty %*	Major Contributors to Uncertainty
	φ>1MeV *6.01%*	o-16 n,n'
SS316		h-1 elastic
		o-16 elastic
B4C		o-16 n,alpha
		li-6 elastic
Be + B4C		fe-56 n,n'
	Si γ-Kerma *1.34%*	fe-56 n,gamma
SS316		cr-53 n,gamma
		ni-58 n,gamma
Water+LiOH		mn-55 n,gamma
	Peak Heating *0.28%*	b-10 n,alpha
SS316		fe-56 elastic

Similarity Analysis

Similarity parameter c_k is system correlation coefficient between a design system and a critical experiment

$$c_k(A,E) = \frac{Cov[A,E]}{[std(A)]\,[std(E)]} = \frac{S_A\, Cov[\sigma,\sigma]\, S_E^{\dagger}}{[std(A)]\,[std(E)]}$$

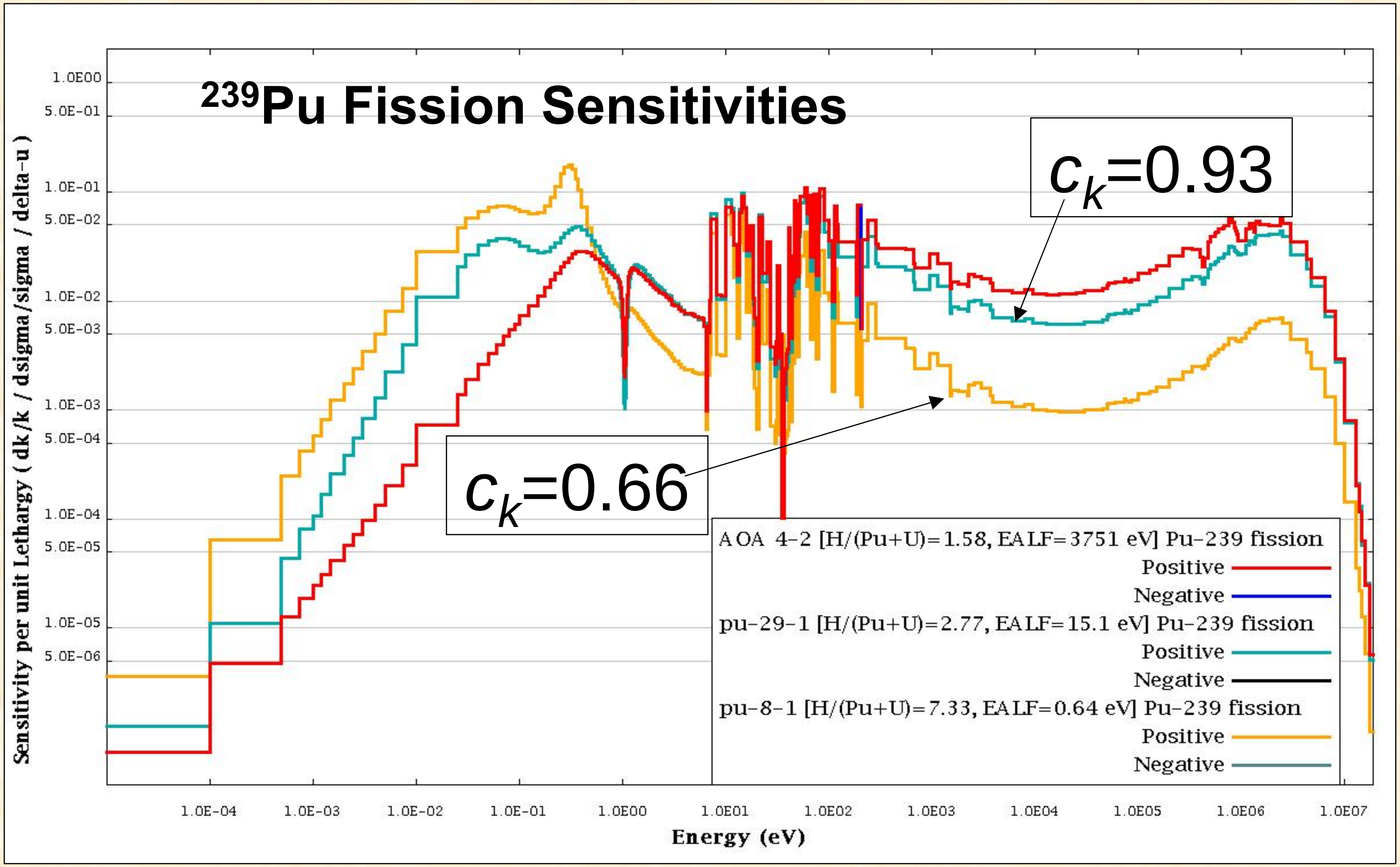
Premise: Computational bias is caused largely by uncertainties in cross section data

- Systems with similarly high sensitivities to same cross-section uncertainty data will have similar computational biases

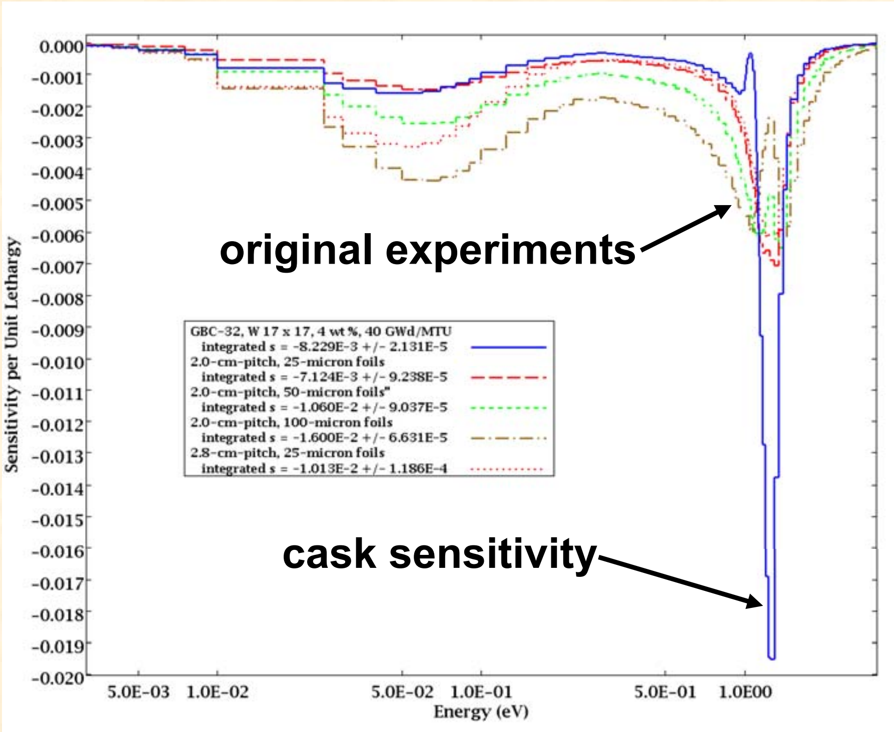
- **Normalized**: such that
  - c_k = 1.0 indicates systems are fully correlated ;
  - c_k = 0.0 indicates systems are completely uncorrelated
  - c_k = -1.0 indicates systems are fully anti-uncorrelated

EXAMPLE SIMILARITY ANALYSIS:

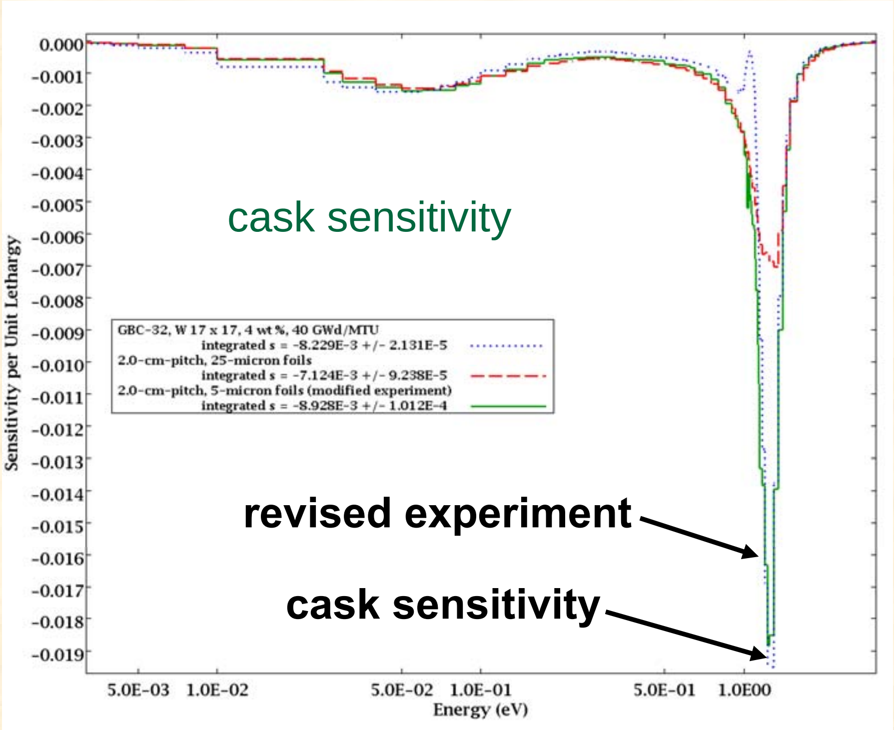
Selection of Benchmark Experiments for Criticality Safety Validation



EXAMPLE SIMILARITY ANALYSIS:
integral experiment design for shipping cask



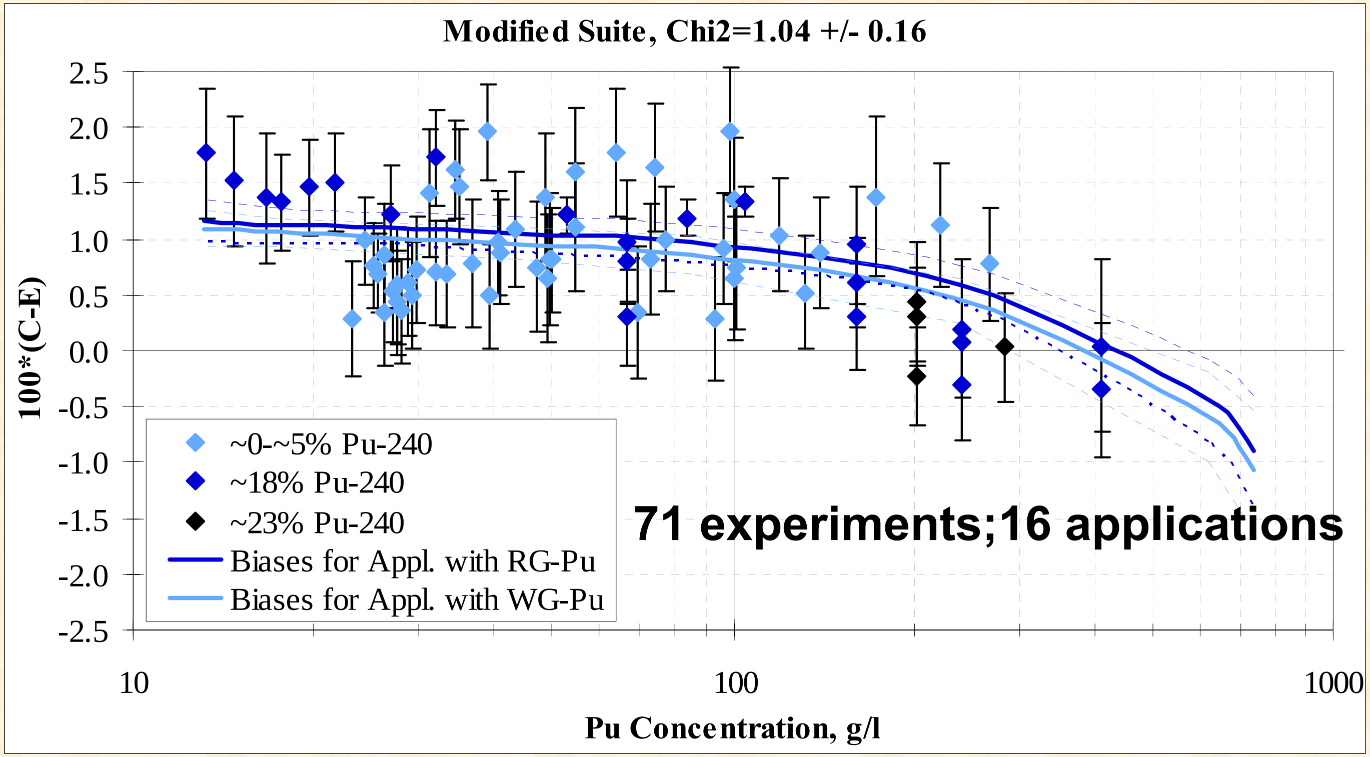
original SNL experiments



modified experiment

Generalized Least-Squares Consolidation of Differential and Integral Data

- Computes “best” data adjustments to minimize differences in computed and measured integral experiments
- Propagates adjustments to application to estimate computational **bias** and **uncertainty**



Summary

- S/U methods can play important role in data assessment for in-reactor as well as ex-reactor components of AFC

- TSUNAMI code system provides unified set of S/U tools for ACF applications
  - Computation of sensitivities with 3D Monte Carlo or 1D discrete ordinates transport theory
  - Determination of implicit sensitivity due to self-shielding
  - Availability of approximate, extended covariance library
  - Computation of uncertainties for in-core and ex-core responses
  - Similarity analysis between proposed facility designs and integral experiments for validation
  - Consolidation of integral /differential data for improved estimates of facility design parameters