IRSN
INSTITUT
DE RADIOPROTECTION
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Uncertainty Assessment for Fast Reactors Based upon Nuclear Data Adjustment

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Outline

- Objectives and motivations
- OECD/NEA WPEC Subgroup 33 adjustment benchmark
- Method and data
  - ✓ Input & output data
  - ✓ One-through and step-wise adjustment algorithms
- Results
  - ✓ Sensitivity coefficients
  - ✓ Adjustment results for one-through and step-wise algorithms
- Conclusions

Objectives and Motivations

- Test performance of the IRSN's methodology for Uncertainty Quantification (UQ)

The methodology is

- ✓ applied for safety needs (IRSN provides technical support to French safety authority)
- ✓ based upon adjustment technique
- ✓ implemented in in-house BERING code

- Test different adjustment algorithms to generate physically justified posteriori cross-correlations for their further use in Total Monte Carlo method for UQ

OECD/NEA WPEC Sg. 33 Benchmark

- Explicitly presented by M. Salvatores (Plenary Session, March 5): "WPEC SG33 on: Methods and Issues for the Combined Use of Integral Experiments"
- Objective: "to study methods and issues of the combined use of integral experiments and covariance data, with the objective of recommending a set of best and consistent practices in order to improve evaluated nuclear data files".
- Input Data: priori C/E and uncertainties, cross sections and covariances
  - Target systems: ABR Oxide, JAEA FBR, ABR Metal, ABR Oxide Recycled
  - 20 well defined integral parameters from 7 fast assembly experiments
  - 11 isotopes: ^{16}O, ^{23}Na, ^{56}Fe, ^{52}Cr, ^{58}Ni, ^{235}U, ^{238}U, ^{239}Pu, ^{240}Pu, ^{241}Pu and ^{10}B
  - 33 energy groups
  - Reactions: Major cross sections, *nu-bar*, mu-bar and fission spectrum
  - Cross-section covariances (COMMARA-2.0 and others)
- Output Data: posteriori C/E and uncertainties, cross sections and covariances

Computations

- *SCALE6.1*

  Nuclear data: CE & 238-group ENDF/B-VI.8 and ENDF/B-VII.0

  Neutron transport: KENOVa and KENOVI

  Sensitivities: TSUNAMI-3D (adjoint-based Monte Carlo technique), TSUNAMI-1D

- ERANOS 2.2

  Nuclear data: 33-group ENDF/B-VI.8

  Neutron transport &

  Sensitivities: BISTRO (Transport solver, RZ geometry)

Code and Data for the Adjustment

- BERING code (IRSN) by E. Ivanov based upon Generalized Linear-Least Square Method (GLLSM)

- Data used for this exercise
  - ✓ Models: Simplified as given in the benchmark specification
  - ✓ Correction factors for simplifications as recommended in the benchmark specification
  - ✓ C/E: SCALE6.1/KENOVa CE
  - ✓ Sensitivities: SCALE/TSUNAMI-3D 238 groups
  - ✓ Experimental correlations: by Makoto Ishikawa (JAEA)
  - ✓ Cross-section covariance libraries: COMMARA-2.0 and JENDL-4.0

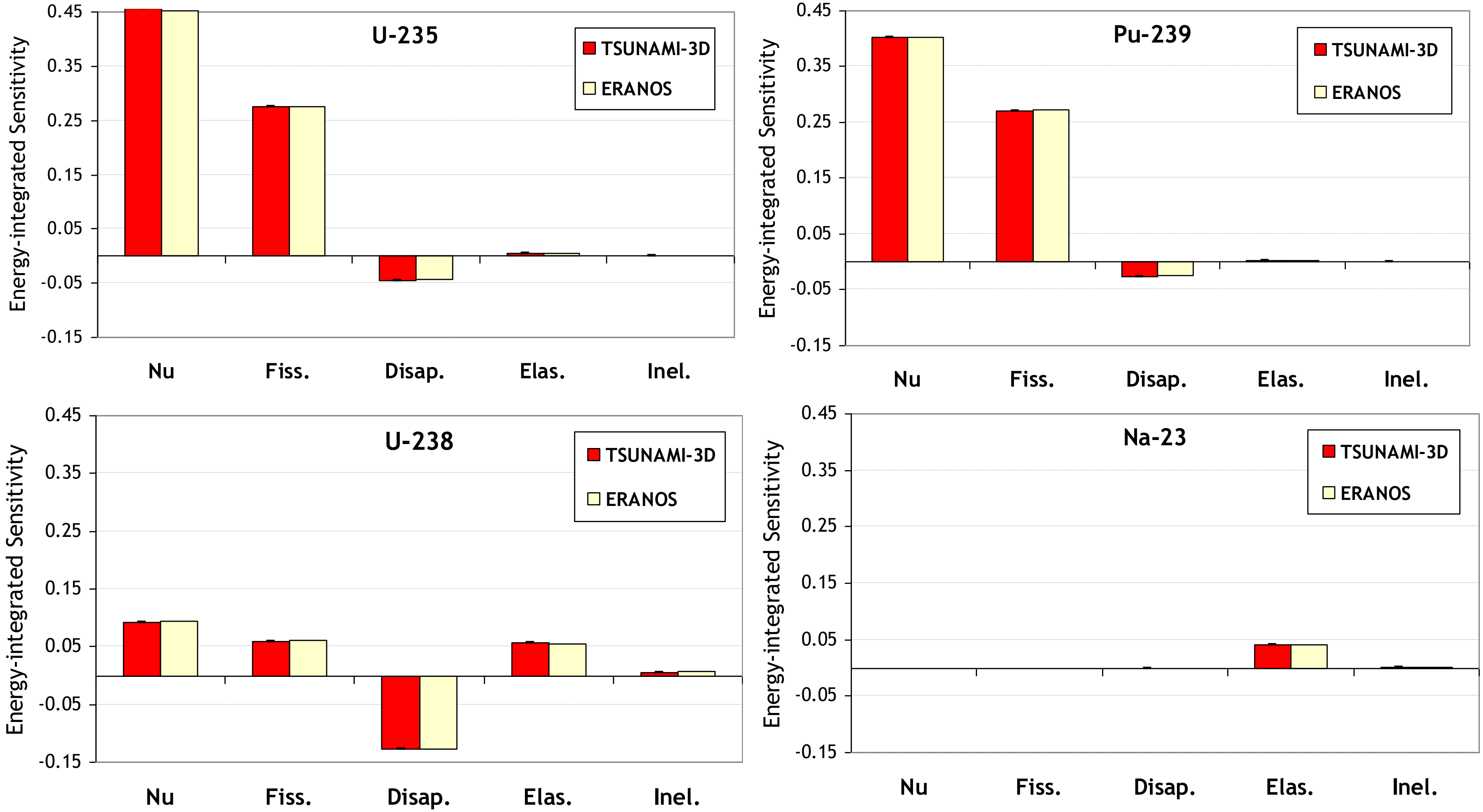
Computations

Computations used in this exercise are shown in red

#	Configuration	Parameter	Parameter calculated with	Sensitivity calculated with
1	JEZEBEL	K-EFF	**KENOVa** & ERANOS	**TSUNAMI-3D** & ERANOS
2	JEZEBEL	F28/F25	KENOVa & ERANOS	TSUNAMI-ID & ERANOS
3	JEZEBEL	F49/F25		
4	JEZEBEL	F37/F25		
5	JEZEBEL Pu240	K-EFF	**KENOVa** & ERANOS	**TSUNAMI-3D**
6	FLATTOP-PU	KEFF	ERANOS	ERANOS
7	FLATTOP-PU	F28/F25		
8	FLATTOP-PU	F37/F25		
9	ZPR6-7	K-EFF	**KENOVa** & KENOVI & ERANOS	**TSUNAMI-3D** & ERANOS
10	ZPR6-7	F28/F25	ERANOS	ERANOS
11	ZPR6-7	F49/F25		
12	ZPR6-7	C28/F25		
13	ZPR6-7 Pu240	K-EFF	**KENOVa** & KENOVI &ERANOS	**TSUNAMI-3D** & ERANOS
14	ZPPR-9	K-EFF		**TSUNAMI-3D** & ERANOS
15	ZPPR-9	F28/F25	ERANOS	ERANOS
16	ZPPR-9	F49/F25		
17	ZPPR-9	C28/F25		
18	ZPPR-9	NAVOID STEP3	KENOVa & KENOVI &ERANOS	TSUNAMI-3D & ERANOS
19	ZPPR-9	NAVOID STEP5		
20	JOYO MK-I	K-EFF	**KENOVa** & & KENOVI ERANOS	**TSUNAMI-3D** & ERANOS

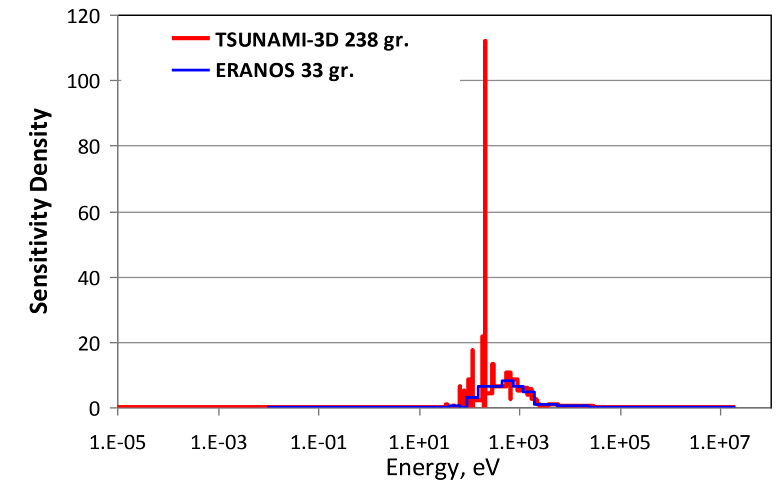
K_{eff} Sensitivity (1/3)

JOYO

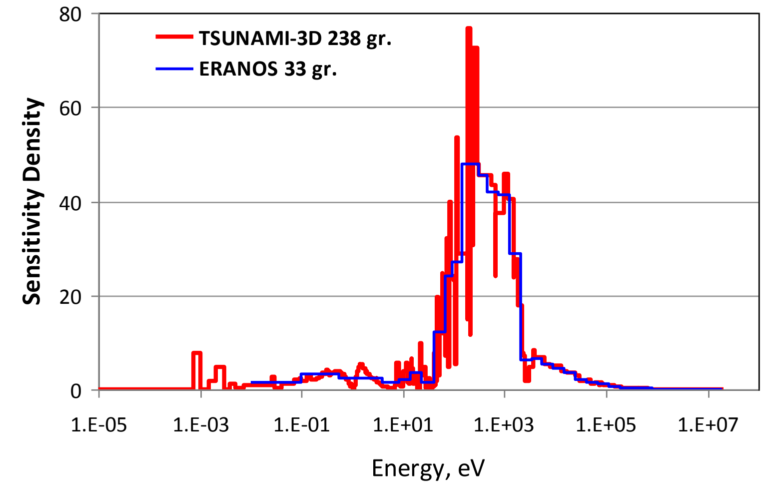


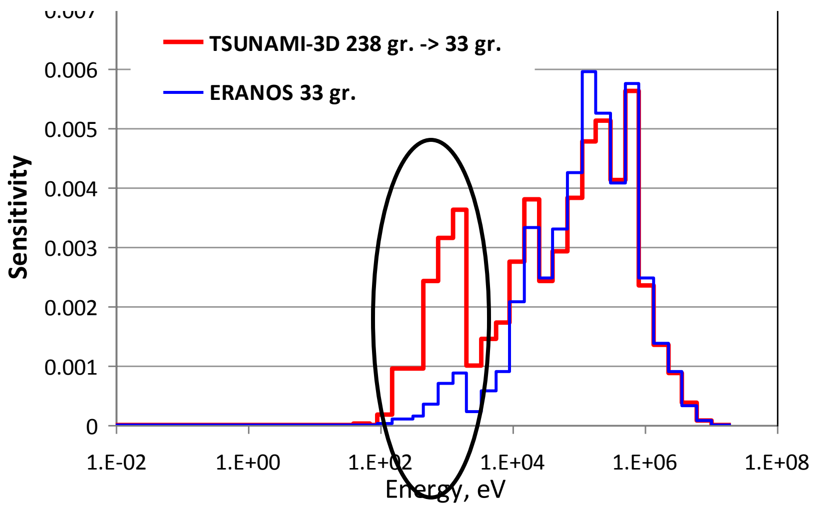
k_{eff} Sensitivity (2/3)

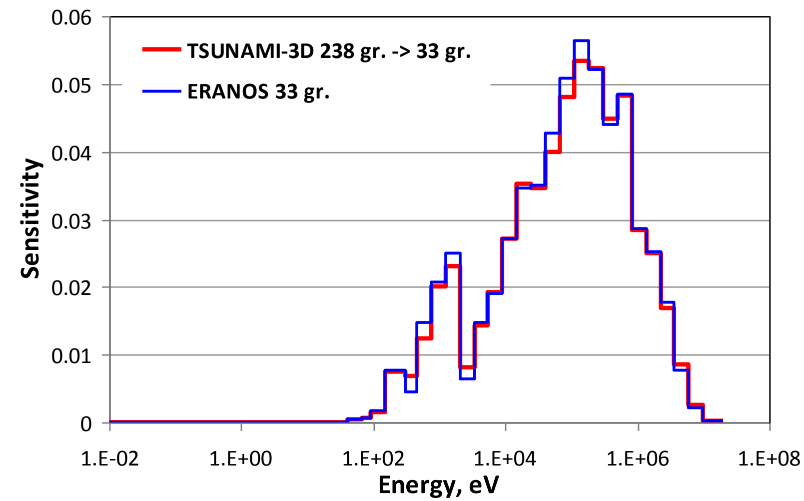
ZPR-6-7 U-238 elastic



ZPPR-9 Pu-239 fission

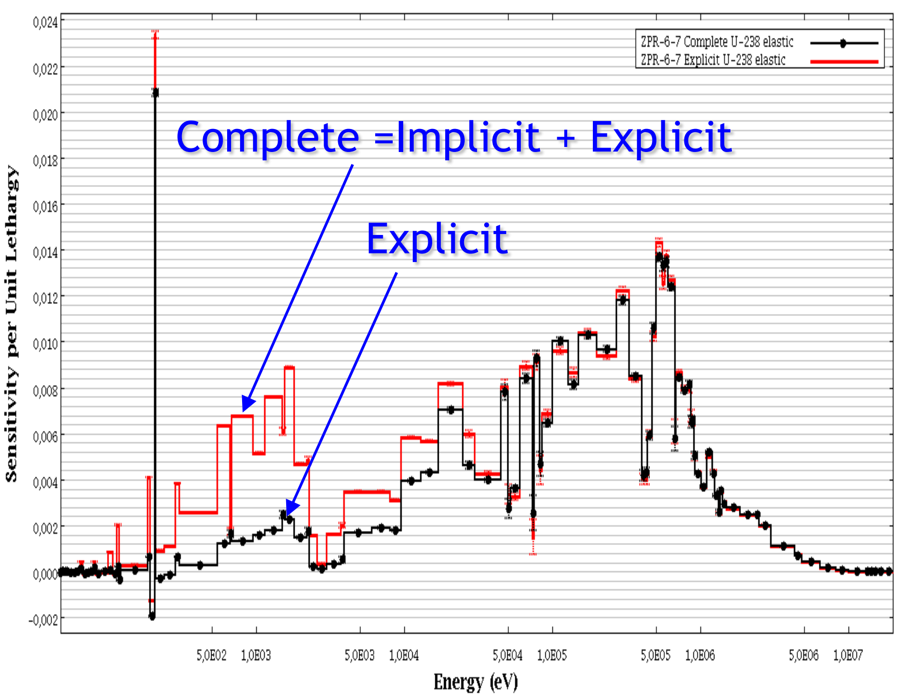




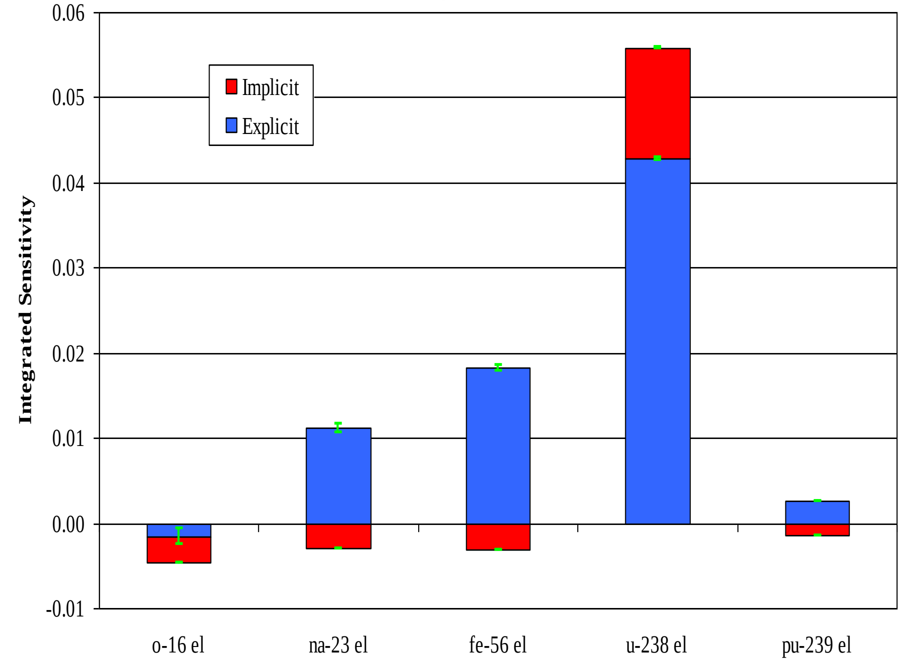


k_{eff} Sensitivity (3/3)

ZPR-6-7 U-238 elastic



ZPR-6-7 Energy-integrated sensitivities with biggest implicit portions



Adjoint-based TSUNAMI-3D technique produces the "complete = implicit + explicit" sensitivity coefficients indicating that a change of a given cross section may also influence the other cross sections through modifications of their shielding factors.

Method and Data (Summary)

W

$$W = \delta\sigma_n \cdot \delta\sigma_m \cdot r_{mn}$$

COMMARA-2.0 33 gr.

JENDL-4.0 33 gr.

Δk

$$\Delta k_i = (k_{c,i} - k_{exp,i})/k_{exp,i}$$

SCALE6.1 KENOVa

ENDF/B-VII CE

H_{exp}, $H_{appl.}$

$$H_{i,n} = \frac{dk_{c,i}/k_{c,i}}{d\sigma_n/\sigma_n}$$

SCALE6.1 TSUNAMI-3D

ENDF/B-VII 238-gr. XS.

Converted into 33 groups.

U

$$U = \delta k_i \cdot \delta k_j \cdot r_{i,j}$$

Integral covariances (JAEA)

$$S^2 = P^t W^{-1} P + (\Delta k + HP)^t U^{-1} (\Delta k + HP)$$

⇩

$$P = (W^{-1} + H^t U^{-1} H)^{-1} (-H^t U^{-1} \Delta k)$$

$$W' = W - WH(V + H^t WH)HW$$

$\chi^2 \approx 1$

YES / **NO**

Results of the adjustment

$\Delta k \pm \delta k'$

$\Delta k = -H\,P$

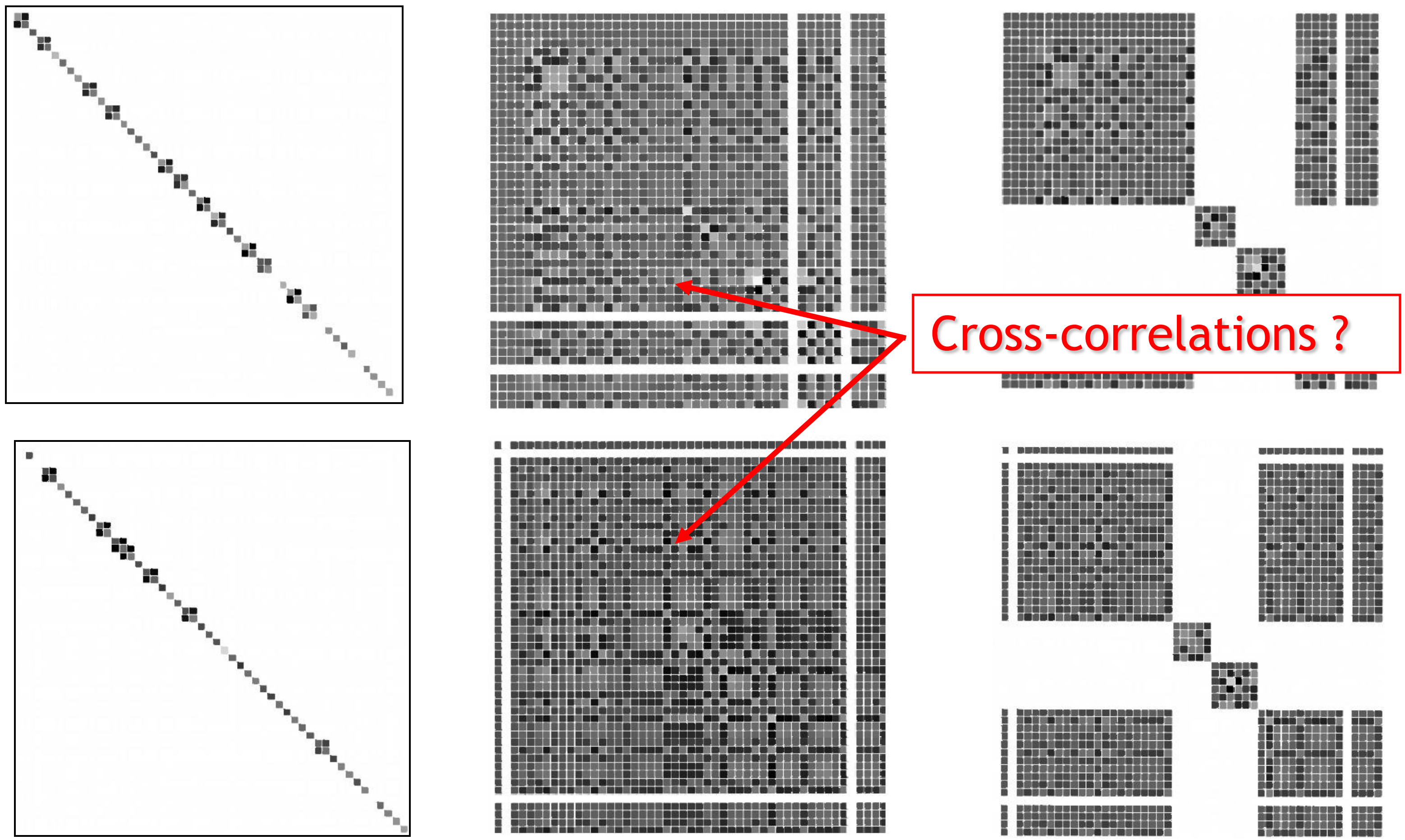
$\delta k' = H\,W'\,H^t$

Cross-section Covariance Matrices

Priori | Posteriori one-through | Posteriori step-wise

COMMARA-2.0

JENDL-4.0



Step-wise Adjustment

The adjustment is conducted as a chain of subsequent steps

$$W = W_0 \cup W_1 \qquad H_k = H_0 \cup H_1$$

- On each step the calculation uncertainty due to the extracted nuclear data is added to the benchmark uncertainty as

$$U_1 = U + H_1^T \cdot W_1 \cdot H_1$$

- Corrections to the neutron cross sections are calculated with the residual matrix

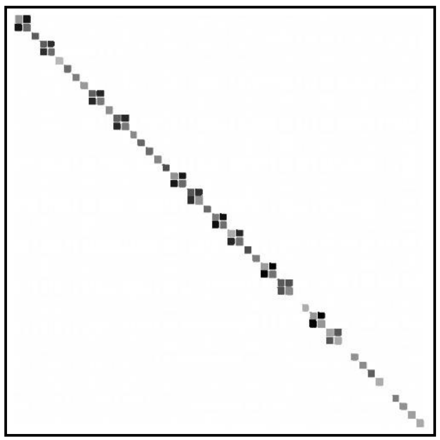
$$P_0 = W_0 \cdot H_0 \cdot \left[U_1 + H_0^T \cdot W_0 \cdot H_0\right]^{-1} \cdot \Delta k$$

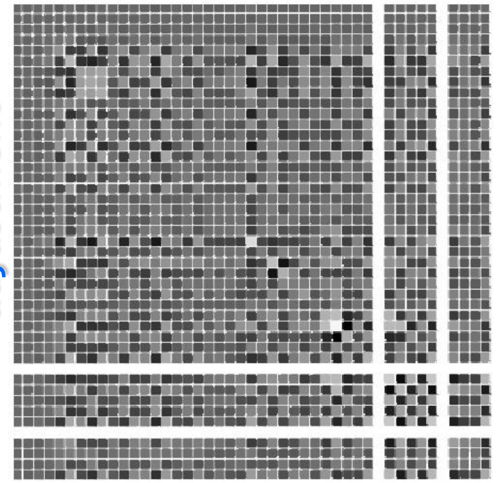
- The reduced cross-section covariance matrix

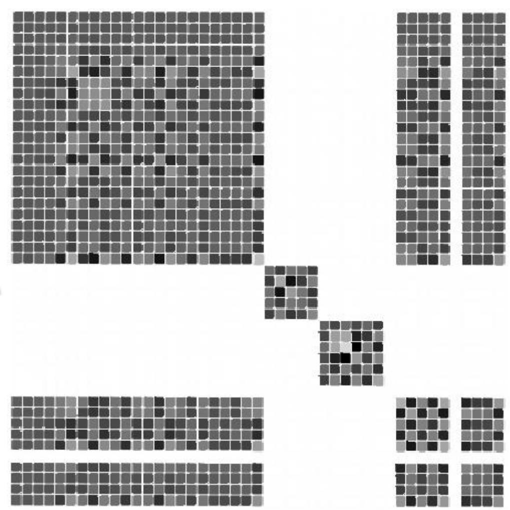
$$W'_0 = W_0 - W_0 \cdot H_0 \cdot \left[U_1 + H_0^T \cdot W_0 \cdot H_0\right]^{-1} \cdot H_0 \cdot W_0$$

$$W' = W_0' \cup W_1' \qquad P = P_0 \cup P_1$$

Adjustment Algorithms







Uncertainties originated from the nuclear data that do not participate in the adjustment are added to the integral data uncertainties

Posteriori Uncertainties

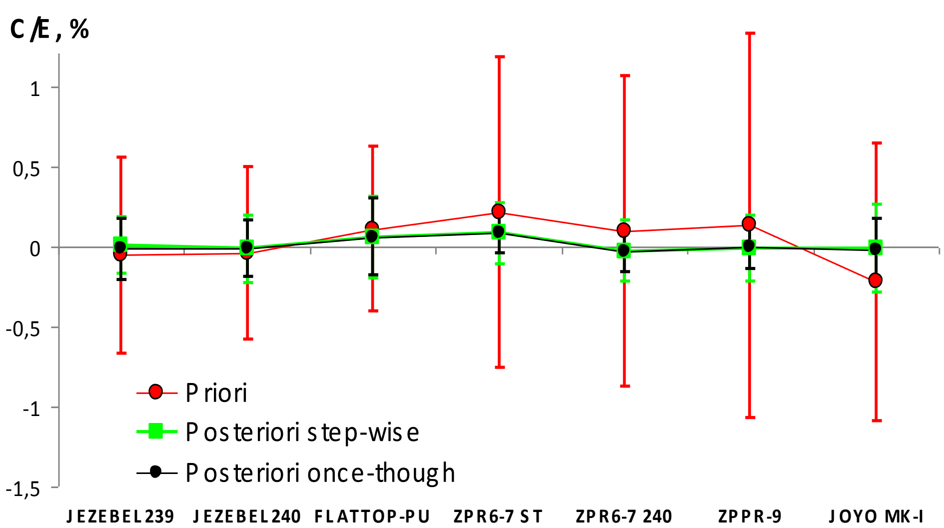
Experimental uncertainties and nuclear data uncertainties before and after the adjustment for benchmark experiments, %

Benchmark Experiment	Experimental Uncertainty	COMMARA-2.0			JENDL-4.0		
		Priori	Posteriori one-through	Posteriori step-wise (3 steps)	Priori	Posteriori one-through	Posteriori step-wise (3 steps)
Jazebel	**0.20**	0.61	**0.19**	**0.17**	0.65	**0.18**	**0.17**
Jazebel-Pu	**0.20**	0.54	**0.18**	**0.13**	0.60	**0.17**	**0.14**
Flattop-Pu	**0.30**	0.52	**0.24**	**0.17**	0.70	**0.26**	**0.17**
ZPR-6-7	**0.23**	0.97	**0.13**	**0.18**	1.10	**0.13**	**0.19**
ZPR-6-7-Pu	**0.22**	0.97	**0.13**	**0.18**	1.08	**0.13**	**0.19**
ZPPR-9	**0.12**	1.20	**0.14**	**0.18**	1.23	**0.13**	**0.20**
JOYO	**0.18**	0.87	**0.20**	**0.09**	0.60	**0.18**	**0.10**

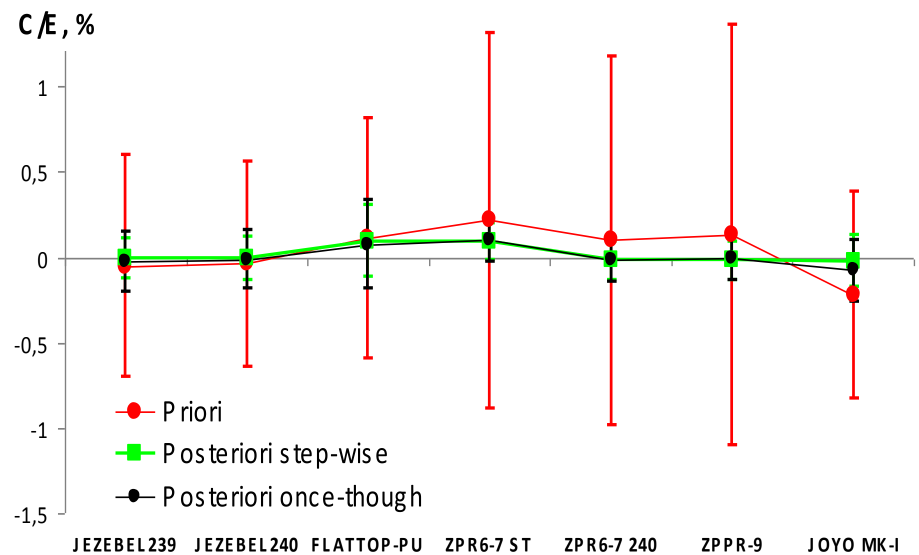
Integral experiments have a key role

C/E and Uncertainties

COMMARA-2.0*



JENDL-4.0*



$$\Delta_m = \left\{ \sum_i \frac{(k_C - k_E)_i}{\sigma_{Ei}^2} \right\} \cdot \left\{ \sum_i \frac{1}{\sigma_{Ei}^2} \right\}^{-1}$$

$$\sigma_m = \sqrt{ \left\{ \sum_i \frac{[(k_C - k_E)_i - \Delta_m]^2}{\sigma_{Ei}^2} \right\} \cdot \left\{ \sum_i \frac{1}{\sigma_{Ei}^2} \right\}^{-1} }$$

	Δ, %	σ,%
EXP	**0.33**	**1.38**
Step-Wise	**0.13**	**0.40**
Once-Through	**0.11**	**0.44**

	Δ, %	σ,%
Experiment	**0.33**	**1.38**
Step-Wise	**0.11**	**0.46**
Once-Through	**0.09**	**0.55**

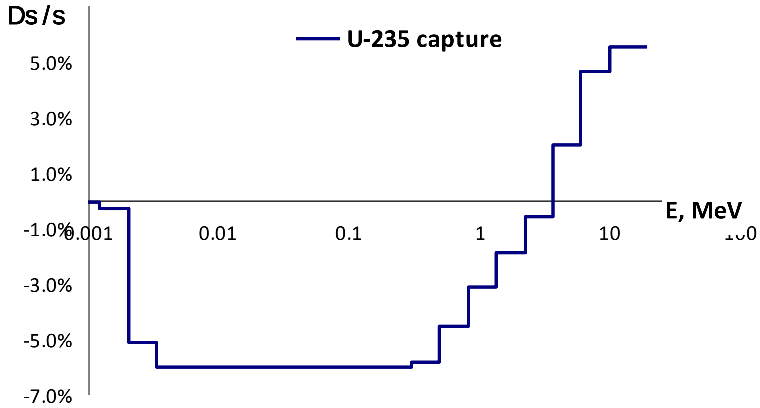
*Input C/E are generated by SCALE/KENOVa code and ENDF/B-VII CE library

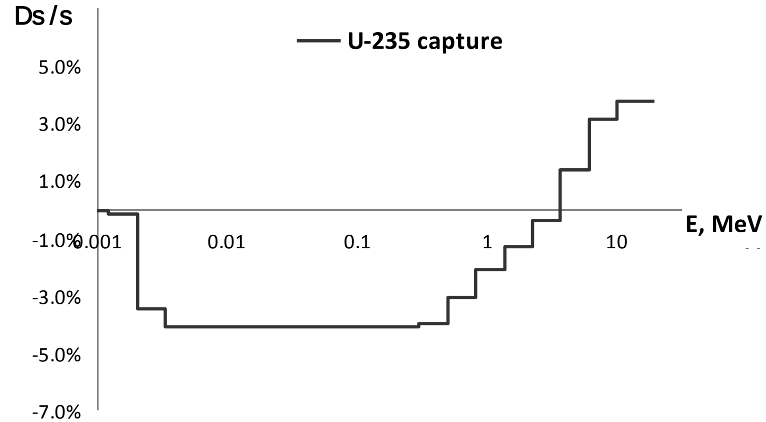
Corrections to Cross Sections

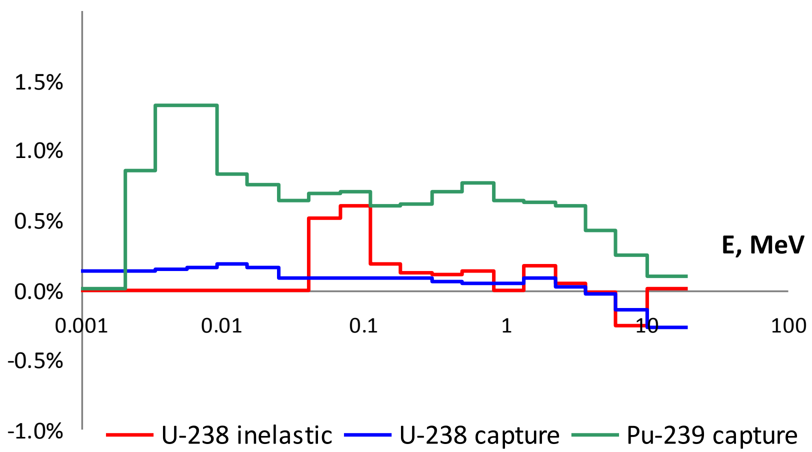
One-through adjustment

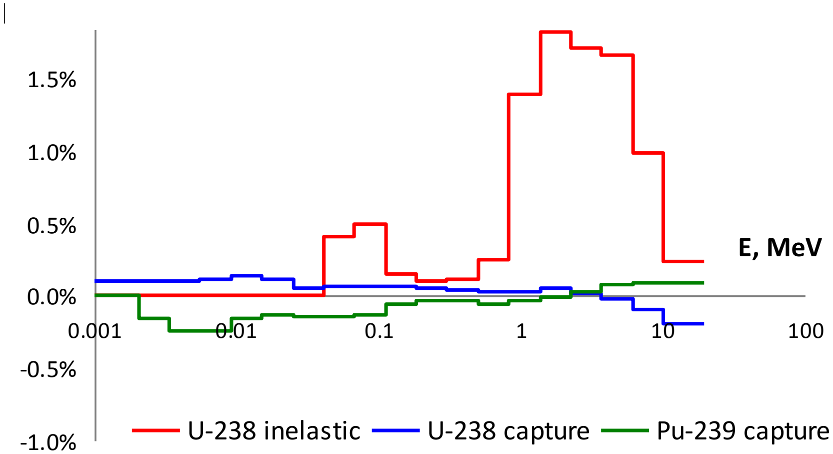
COMMARA-2.0

Step-wise adjustment:
1) ^{238}U, 2)^{239}Pu, 3)Other







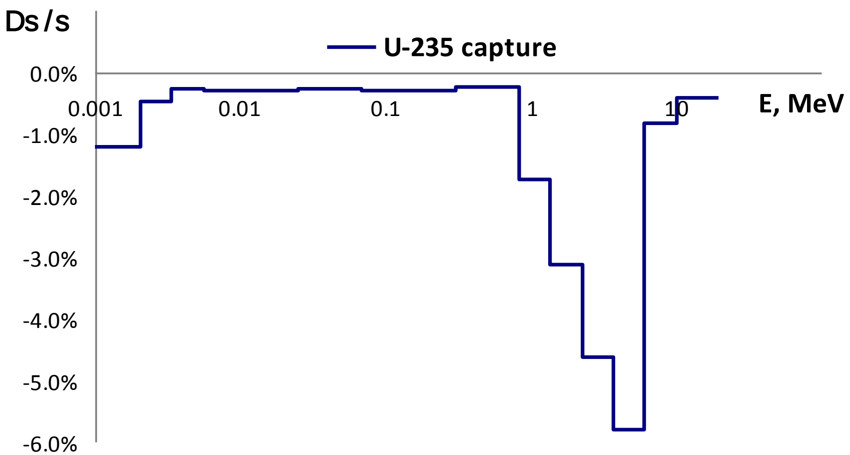


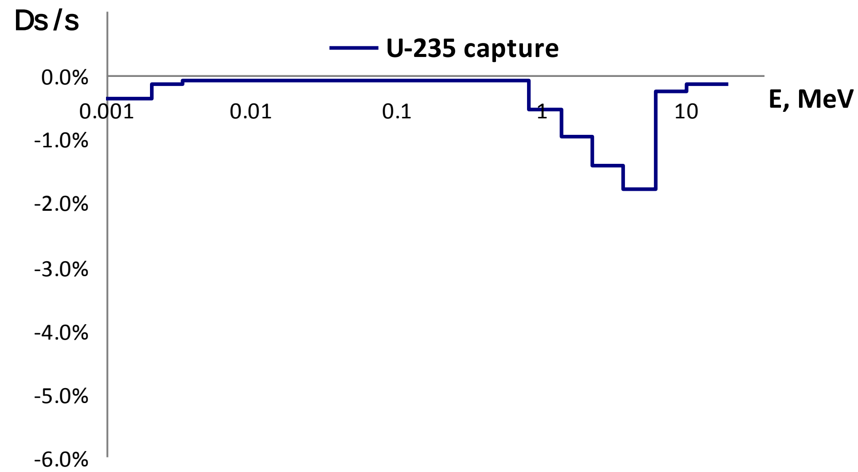
Corrections to Cross Sections

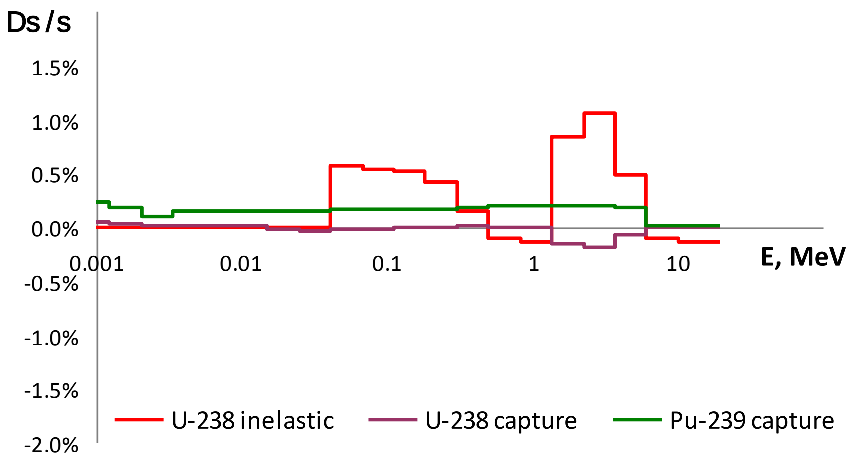
One-through adjustment

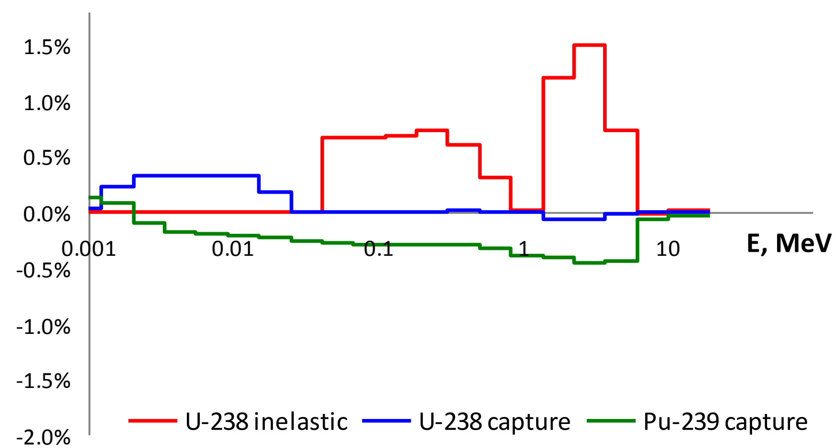
JENDL-4.0

Step-wise adjustment:
1) ^{238}U, 2)^{239}Pu, 3)Other





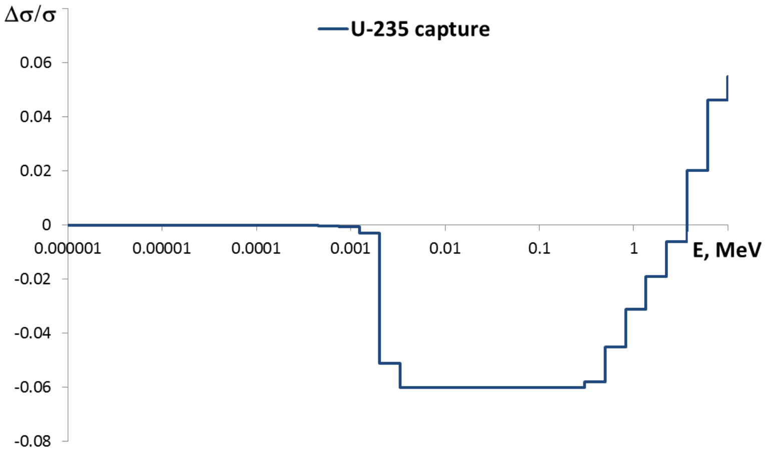


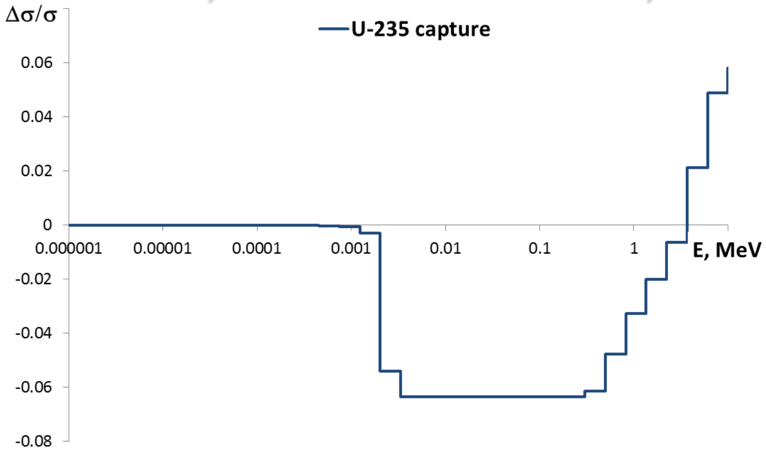


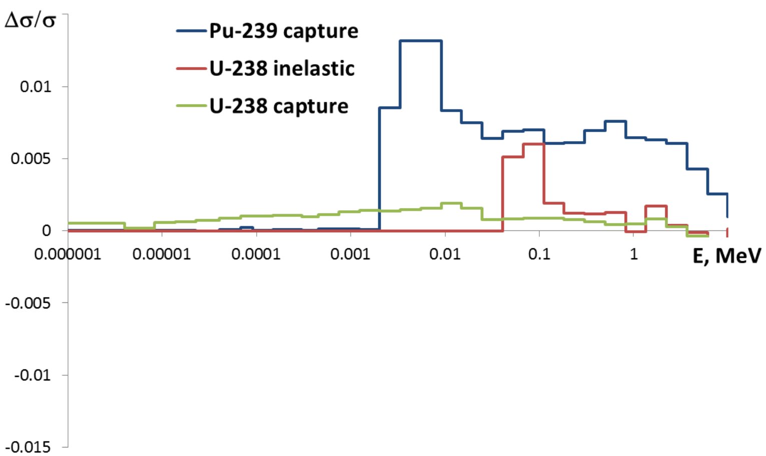
Corrections to Cross Sections

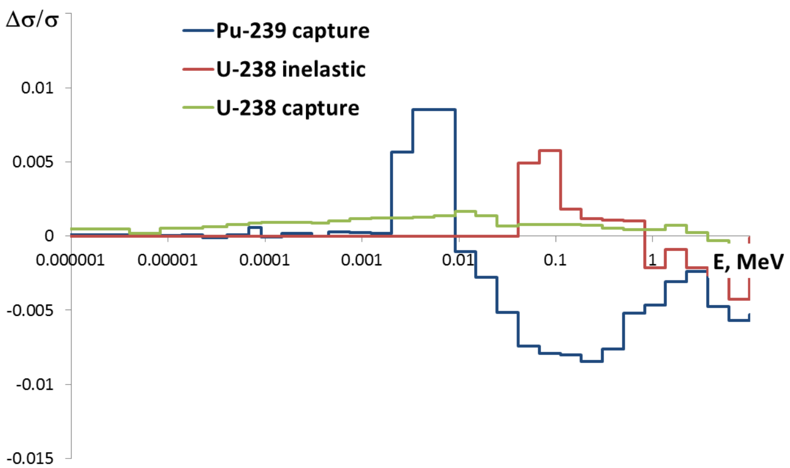
One-through adjustment **COMMARA-2.0**

Step-wise adjustment:
1) $^{238}U+^{239}Pu + ^{235}U$ 2)Other









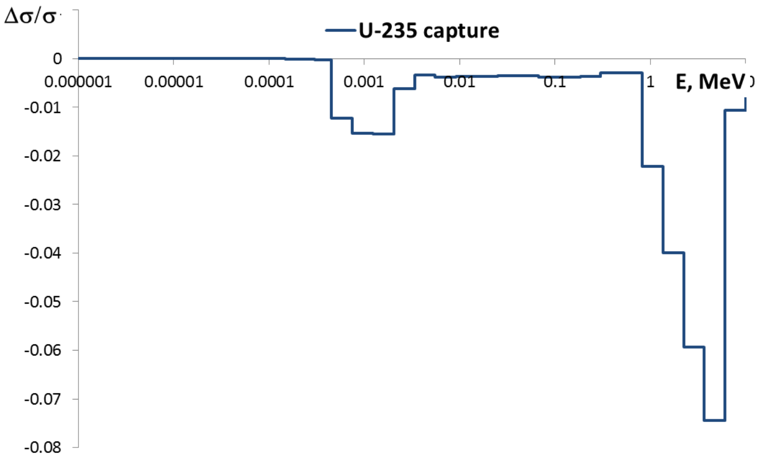
Corrections to Cross Sections

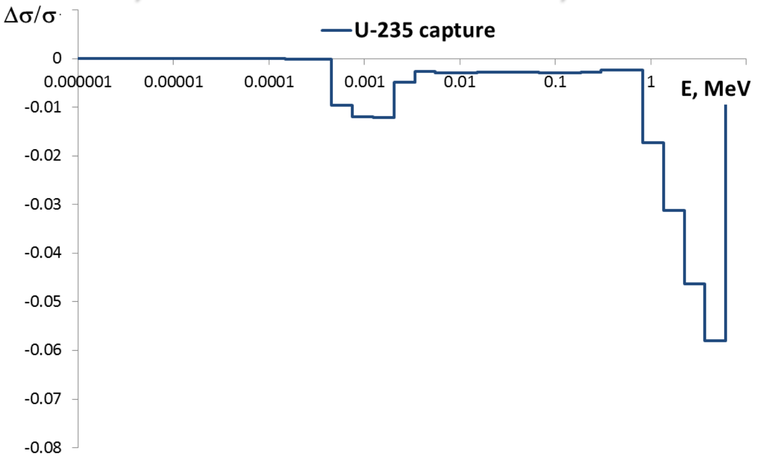
One-through

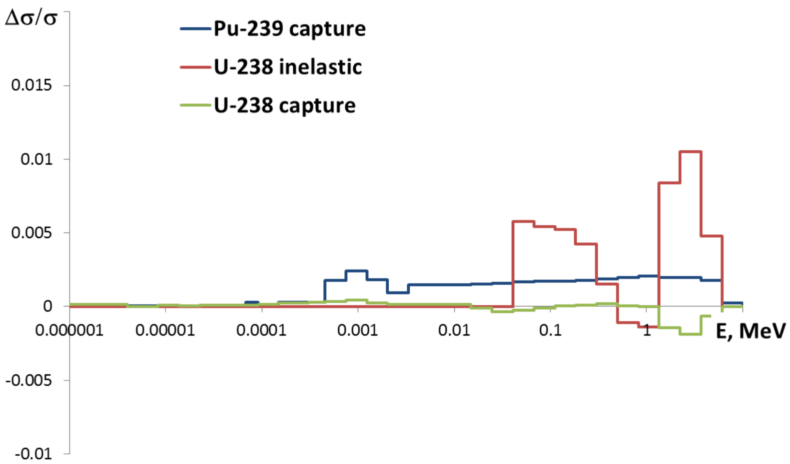
JENDL-4.0

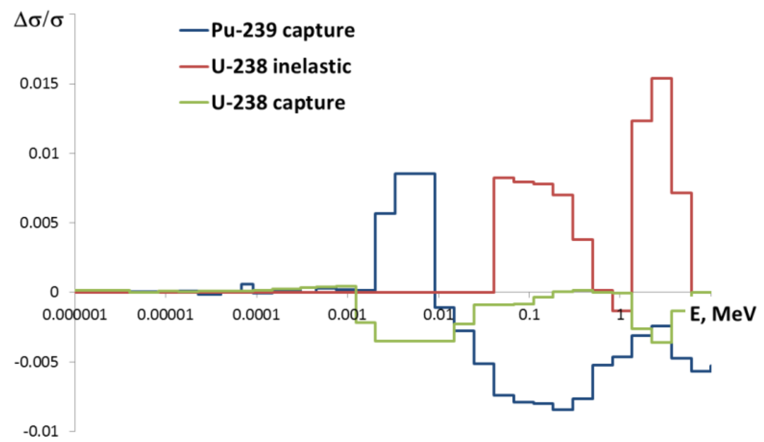
Step-wise adjustment:

1) $^{238}U + ^{239}Pu + ^{235}U$ 2)Other









Conclusions

- Results of the OECD/NE WPEC SG. 33 adjustment exercise have been obtained using in-house BERING code, JENDL-4.0, and ENDF/B-VII.1 covariances and two adjustment algorithms: “classical” one-through and step-wise
- Adjustment with different covariances produces similar posteriori C/E and uncertainties
- Posteriori uncertainties are decreased owing to isotope-isotope reaction-reaction cross-correlations
- The step-wise algorithm is implemented to BERING that allows controlling cross-correlations in posterior cross-section covariance matrices

Conclusions (cont'd)

- The preliminary testing of the step-wise algorithm demonstrates that
  - ✓ it produces reliable C/E and uncertainties and posteriori cross section covariance with desirable cross-correlations
  - ✓ corrections to the cross sections depend on the adjustment algorithm
  - ✓ if correctly applied, the step-wise algorithm can be used to generate physically justified posterior cross section covariance matrices
- Work is ongoing to test the step-wise algorithm for generation of the cross-section covariance matrices

Acknowledgments

The authors would like to gratefully acknowledge the leaders and members of the OECD/NEA WPEC Subgroup 33 for the fruitful exchange within the group that made easier verification of the BERING code.