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PROTEUS FDWR-II (HCLWR) program Contribution to SG-39

WPEC SG39 meeting, Paris, France

Outline

- Reminder of FDWR Experiments at PROTEUS

- Summary of PSI experimental data contribution to SG39
  - K-inf C/E and sensitivities
  - Issue with infinitely dilute inelastic scattering cross sections
  - Elastic scattering sensitivity coefficients

- Additional responses
  - Void coefficients
  - Spectral indices

- Conclusion and outlook

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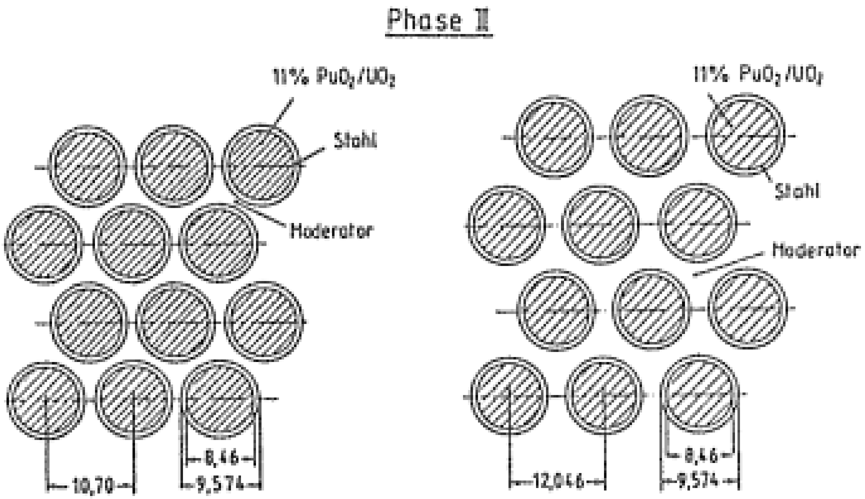
FDWR-II – Experimental Configurations

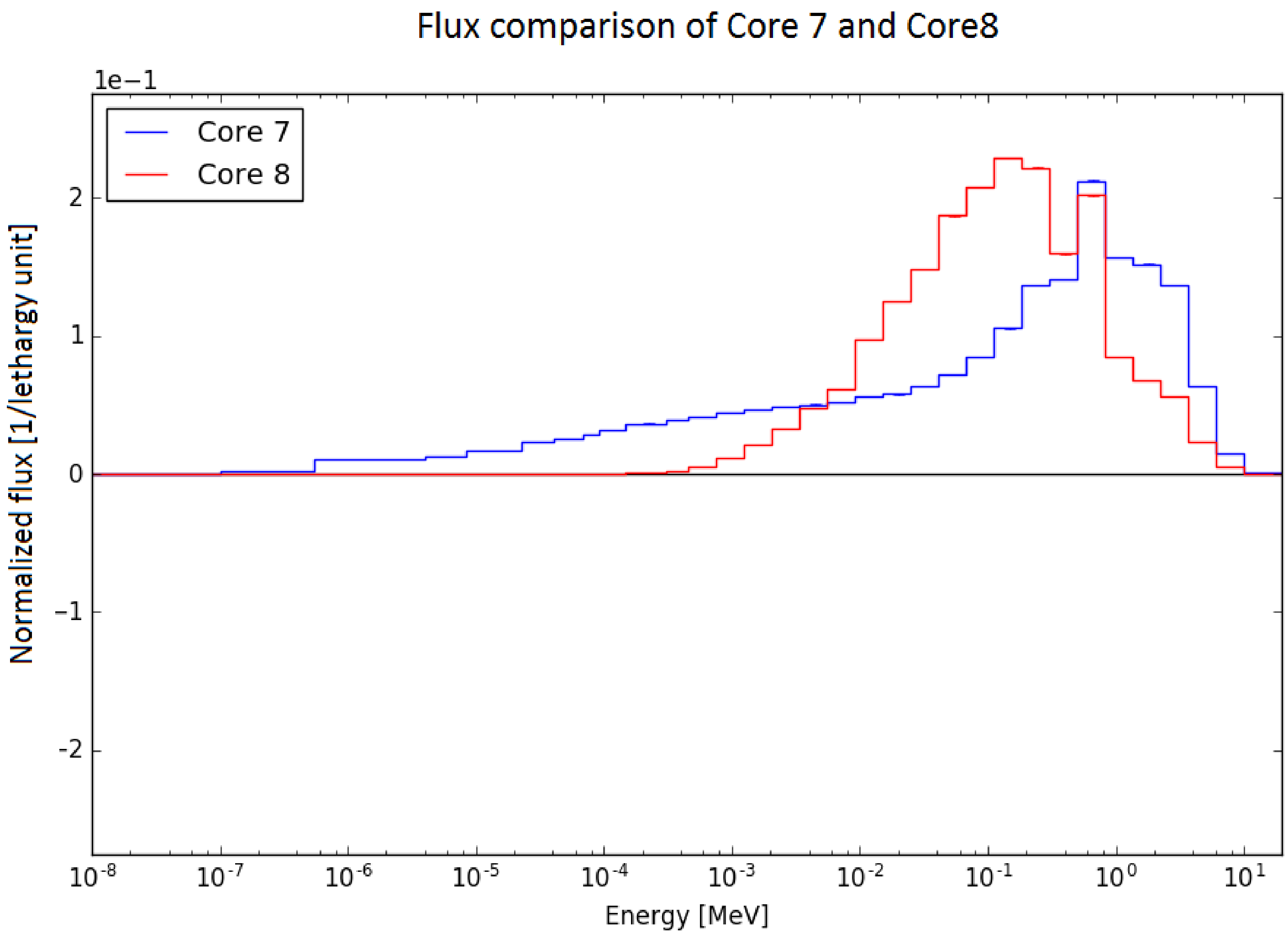


Kern	p/d	V_M/V_F	Moderator	Eff. Moderation
7	1.12	0.48	H_2O	0.48
8	1.12	0.48	ohne	0.00
9	1.12	0.48	Dowtherm	0.28
10	1.12	0.48	Dowtherm	0.28
11	1.12	0.48	ohne	0.00
12	1.12	0.48	H_2O	0.48
13	1.26	0.95	H_2O	0.95
14	1.26	0.95	ohne	0.00
15	1.26	0.95	Dowtherm	0.55
16	1.26	0.95	H_2O	0.95
17	1.26	0.95	ohne	0.00
18	a)	2.07	H_2O	2.07
19	1.26	0.95	H_2O	0.95
20	1.26	0.95	D_2O	-

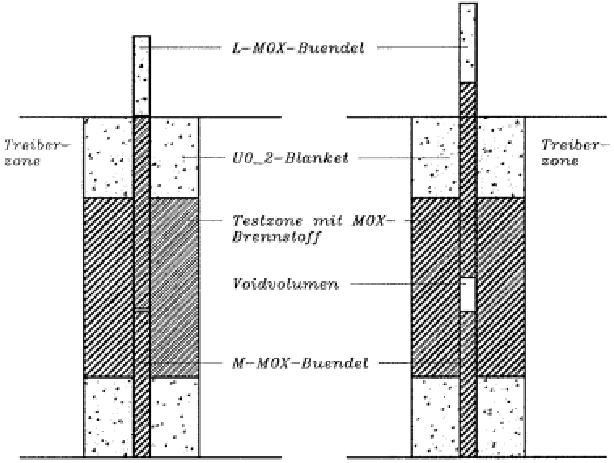
FDWR Phase II

- From 1985 to 1990 in PROTEUS reactor
- PROTEUS is a driven system whose test zone contains the FDWR lattices
- UO_2/PuO_2 pellets with 11% PuO_2
- Pu(8/9/0/1/2): 1%, 64%, 23%, 8%, 4%
- Fuel diameter: 8.46mm
- Fuel total height: 84 cm
- 2 axial blankets:
  - Udep. 0.224w% ^{235}U
  - 28-cm high each

FDWR-II - Spectrum Comparison



FDWR-II – Measurement types

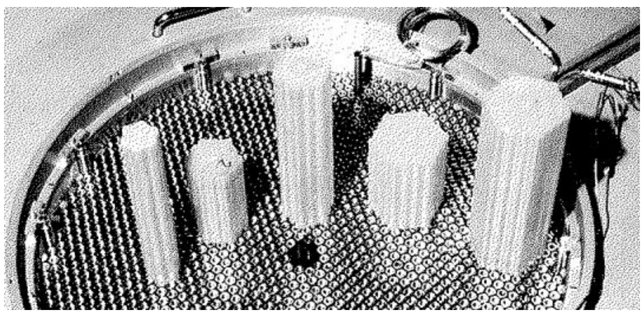


- K∞ measurements

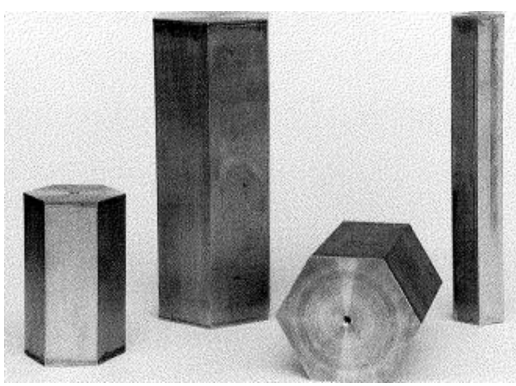
$$k_\infty = 1 + B^2 \cdot M^2$$

$$\frac{\rho_Z}{\rho_S}\frac{S}{R_f} = \bar{\nu}\frac{\overline{\Phi^+}^X}{\overline{\Phi^+}^S}\left(1 - \frac{1}{k^+}\right)$$

  - •Using axial and radial bucklings
  - •Using compensation methods with auto-rod and a ^{252}Cf source

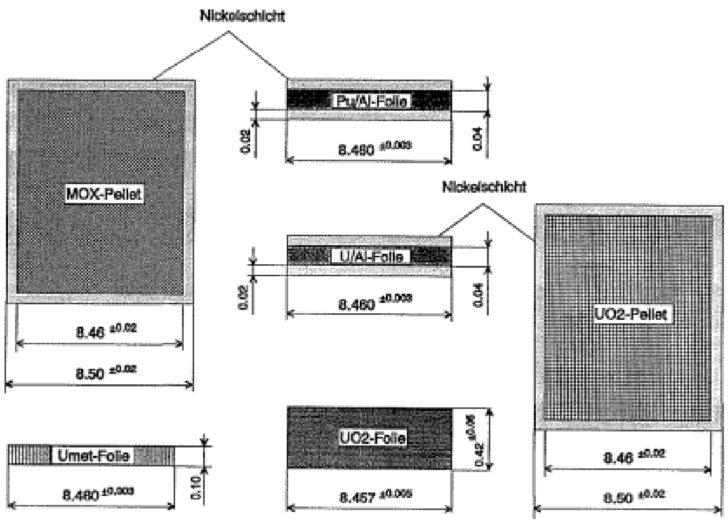


- Reactivity effects
  - Void volume



Absorber	Form	Durchmesser	Cladding	Bemerkung
B_4C(nat)	Pellet	7.473	ja	Referenzabsorber
B_4C(nat)	Pulver	7.430	ja	
B_4C(93%) ^{10}B	Pellet	7.430	ja	
Ag15In5Cd	Legierung	8.830	nein	
Hafnium	Metall	8.350	ja	
Gd_2O_3	Pellet	8.310	ja	
Sm_2O_3	Pellet	7.000	ja	
Tantal	Metall	8.290	ja	
Eu_2O_3	Pellet	8.243	ja	
Zircaloy-2	Legierung	8.300	nein	Strukturmaterial
Stahl	Metall	8.240	nein	Strukturmaterial

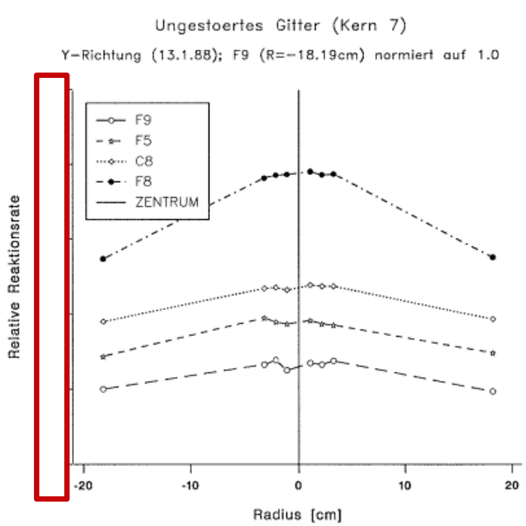
FDWR-II – Measurement types

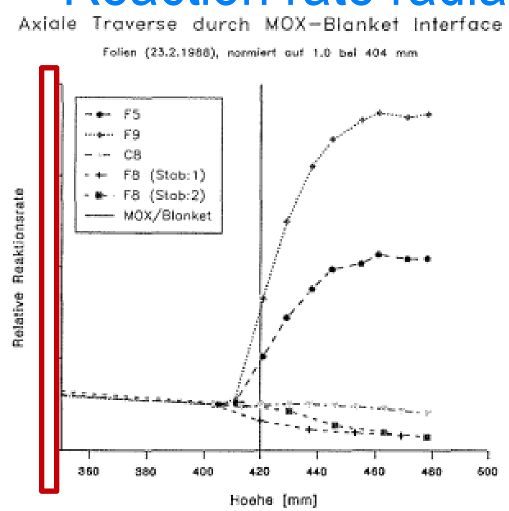


Spectral index measurements (core 7)

- F5/F9 ~0.91 F1/F9 ~ 1.68
- F8/F9 ~1.14e-2 C2/F9 ~ 1.12
- C8/F9 ~7.8e-2
- Typical uncertainties
  F5: 1.8%, F8: 1.9%, F9:1.5%, C8: 1.8%

Reaction rate radial and axial traverses





Data package provided to SG39 members

- C/E for k-inf of Core 7 and 8
  - Data provided
    - Pincell geometry
    - Fuel composition
    - C and E values
  - Calculation: MCNP and pincell models
  - Preferred measurement: cell method b/c smaller uncertainty

- Sensitivity coefficients generated from pincell models
  - MCNP6.1.1 & JEFF-3.1.1
  - Uncertainties are provided
  - Infinitely diluted cross sections are provided

- Sensitivity coefficients tables according to SG33 format
  - Generated with SERPENT-v2.1.15

- **Extra info (P1 moment sensitivities) will be generated with SERPENT-v2.1.19**

Data	Location
Kinf values, C/Es and uncertainties	Section 3
Sensitivity coefficients graphs	Core7.tar.gz Core8.tar.gz
Sensitivity coefficients tables	Core7_SC_MCNP.txt Core8_SC_MCNP.txt
Infinitely diluted cross sections	File J311.dat

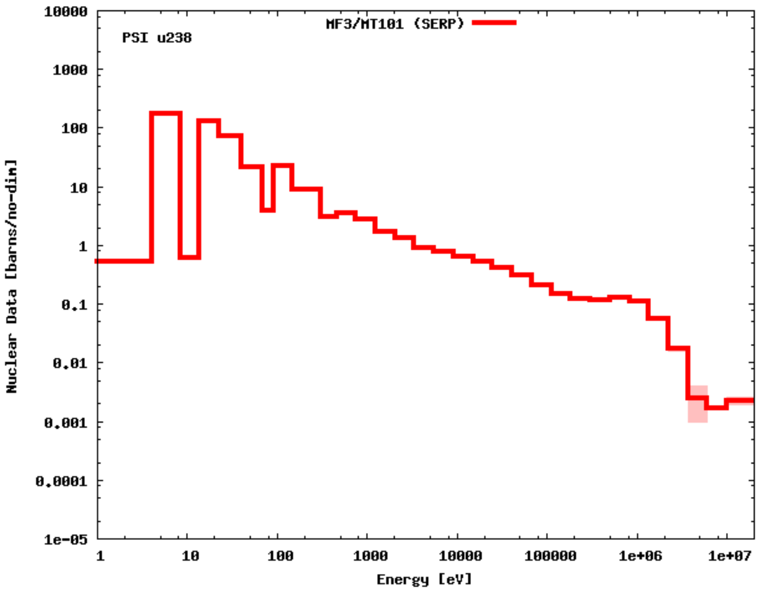
Infinitely Dilute Cross Sections

- 20 MeV homogeneous source in infinite pure graphite medium

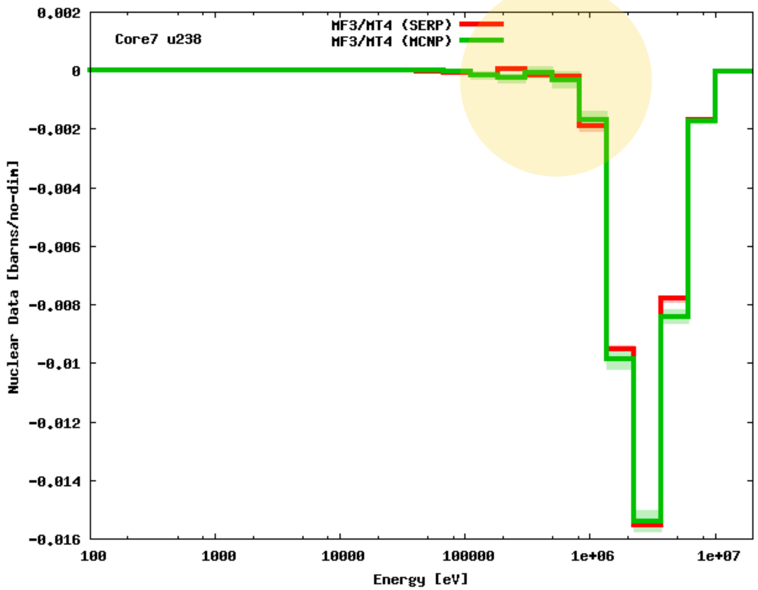
- MCNPX-2.4 & JEFF-3.1.1 library.
  - 10^6 neutrons histories
  - The reaction rates and flux were tallied in the 33-energy group structure

- The cross sections and associated relative uncertainties (1 standard deviation) for the isotopes and reactions of the WPEC Subgroup 33

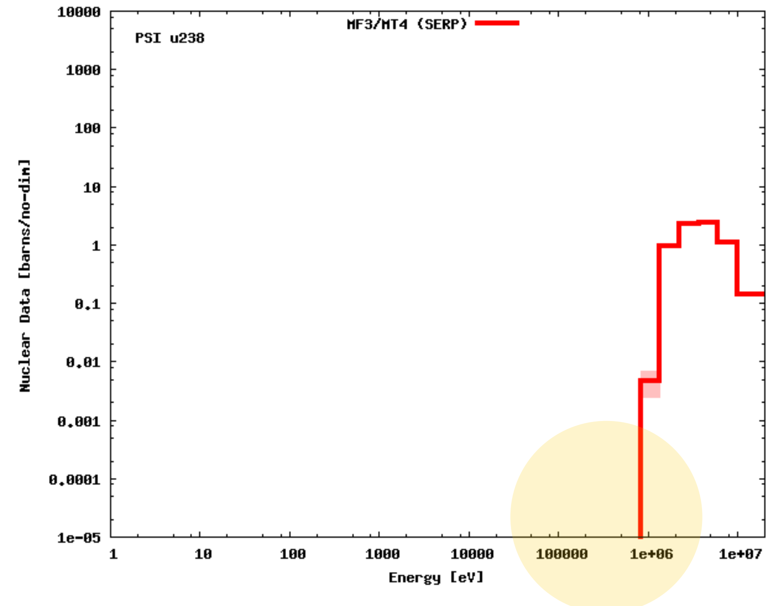
U-238 Capture



Infinitely Dilute Inelastic Cross Sections



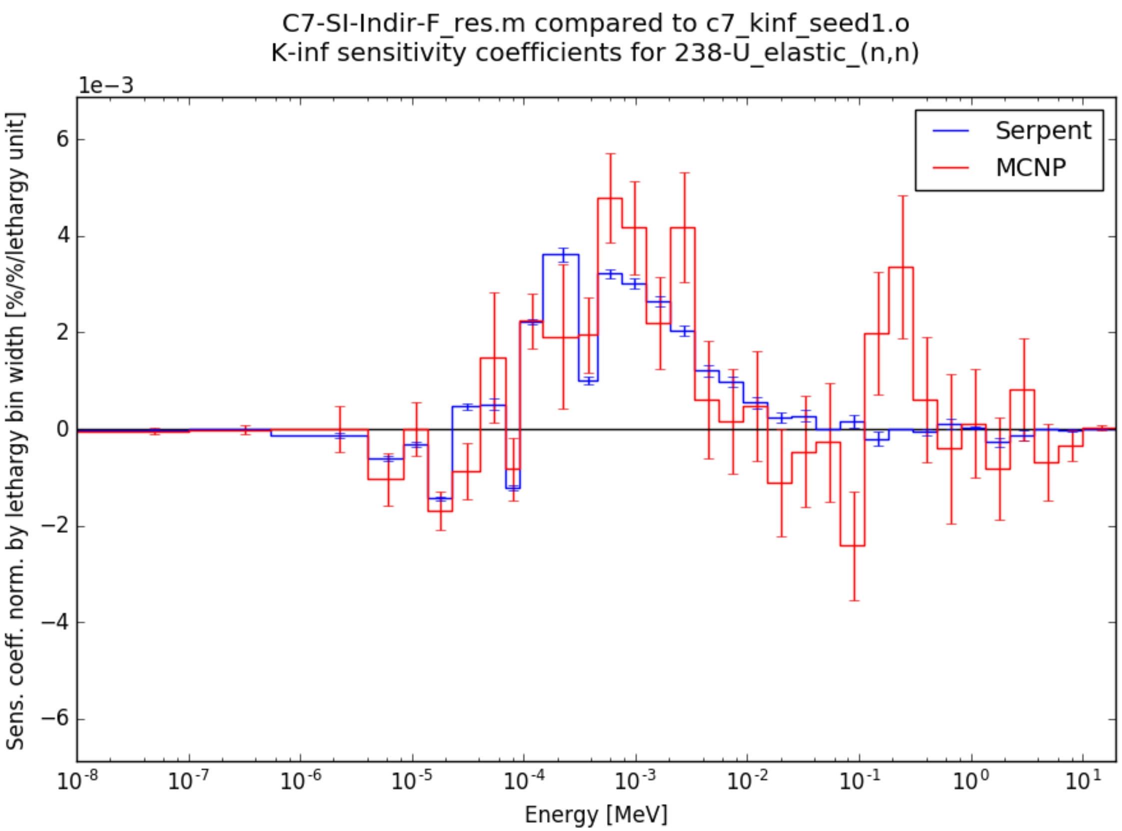
Sensitivity



Infinitely Dilute Cross Sections

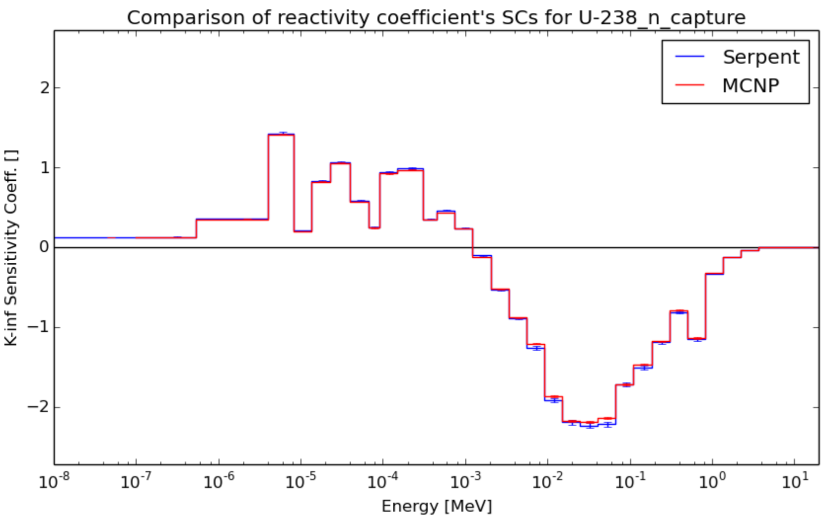
- Stop well above the threshold.
  - Input error: only MT 91 was tallied.
  - MCNP will be rerun
- Sensitivity coefficients are correct though.
- New cross sections will be provided

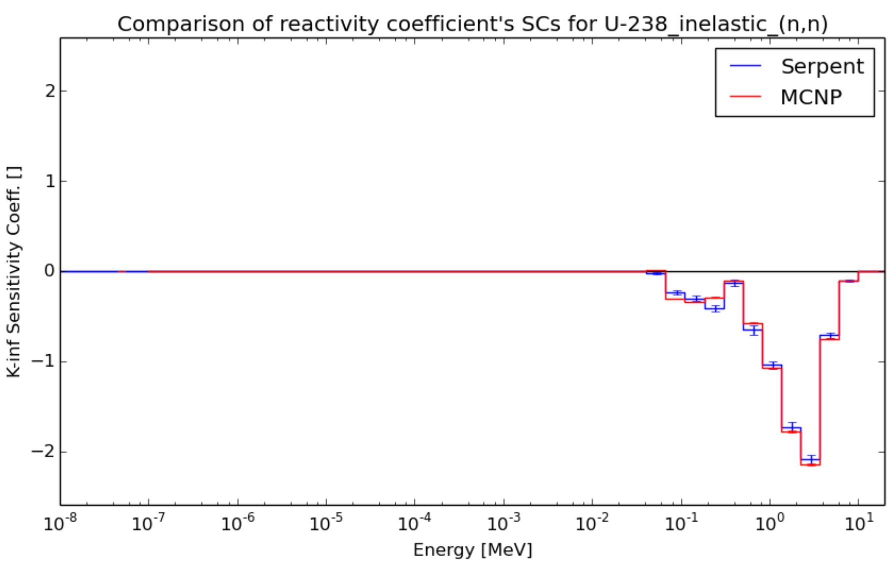
Elastic scattering issue



- Good agreement between codes
  - Previously reported MCNP uncertainty was wrong
- Large uncertainties due to poor convergence of the estimator

Void reactivity Sensitivity Coefficients





$$\Delta\rho = \rho_1 - \rho_0 = \frac{k_1 - k_0}{k_1 k_0}$$

- C/E can be inferred from k-inf results.
- Sensitivity coefficients of void reactivity
  - Computed with EGPT

$$SC(\Delta\rho,\sigma) = \frac{1}{\Delta\rho}\left(\frac{SC(k_1,\sigma)}{k_1} - \frac{SC(k_0,\sigma)}{k_0}\right)$$

  - Issue with MC based sensitivities
  - SERPENT-V2.1.19 will be used in the future

Sensitivity coefficients for spectral indices

A spectral index is a ratio of reaction rates:

$$R = \frac{<\Sigma_1 \phi>}{<\Sigma_2 \phi>}$$

where «1» and «2» are the labels of the considered nuclide-reaction pairs. Brakets are to be intended as integral over the energy range of interest. The sensitivity of the spectral index to a change in a certain cross section (Σ_x) can be expanded as:

$$S_{R,\,x} = \frac{\dfrac{<\frac{\partial \Sigma_1}{\partial \Sigma_x} \phi>}{\Sigma_x}}{<\Sigma_1 \phi>} - \frac{\dfrac{<\frac{\partial \Sigma_2}{\partial \Sigma_x} \phi>}{\Sigma_x}}{<\Sigma_2 \phi>} + \frac{\dfrac{<\Sigma_1 \frac{\partial \phi}{\partial \Sigma_x}>}{\Sigma_x}}{<\Sigma_1 \phi>} - \frac{\dfrac{<\Sigma_2 \frac{\partial \phi}{\partial \Sigma_x}>}{\Sigma_x}}{<\Sigma_2 \phi>}$$

The first two terms are referred to as the direct part of sensitivity coefficient, the last two as the indirect part of it.

Sensitivity coefficients for spectral indices

$$S_{R,x} = \underbrace{\frac{\dfrac{<\frac{\partial \Sigma_1}{\partial \Sigma_x}\phi>}{\Sigma_x}}{<\Sigma_1\phi>} - \frac{\dfrac{<\frac{\partial \Sigma_2}{\partial \Sigma_x}\phi>}{\Sigma_x}}{<\Sigma_2\phi>}}_{S_{R,x}{}^{dir}} + \underbrace{\frac{\dfrac{<\Sigma_1\frac{\partial \phi}{\partial \Sigma_x}>}{\Sigma_x}}{<\Sigma_1\phi>} - \frac{\dfrac{<\Sigma_2\frac{\partial \phi}{\partial \Sigma_x}>}{\Sigma_x}}{<\Sigma_2\phi>}}_{S_{R,x}{}^{indir}}$$

The direct term quantifies the effect of the perturbation of Σ_x on the reaction rate itself. The direct part is zero whenever the cross section that is being perturbed is not Σ_1 or Σ_2.

The indirect term quantifies the effect of the perturbation of Σ_x on the flux, which in turn affects the spectral index.

Serpent sensitivity capability

The modified version of **Serpent 2.1.19** is able to **compute the indirect part** (${S_{R,x}}^{indir}$) of the sensitivity coefficients. The **direct part** of the sensitivity coefficients **has to be computed** separately through a standard SERPENT calculation.

A MATLAB script has been written to generate the direct and indirect parts of the sensitivity based on 2 SERPENT calculations.

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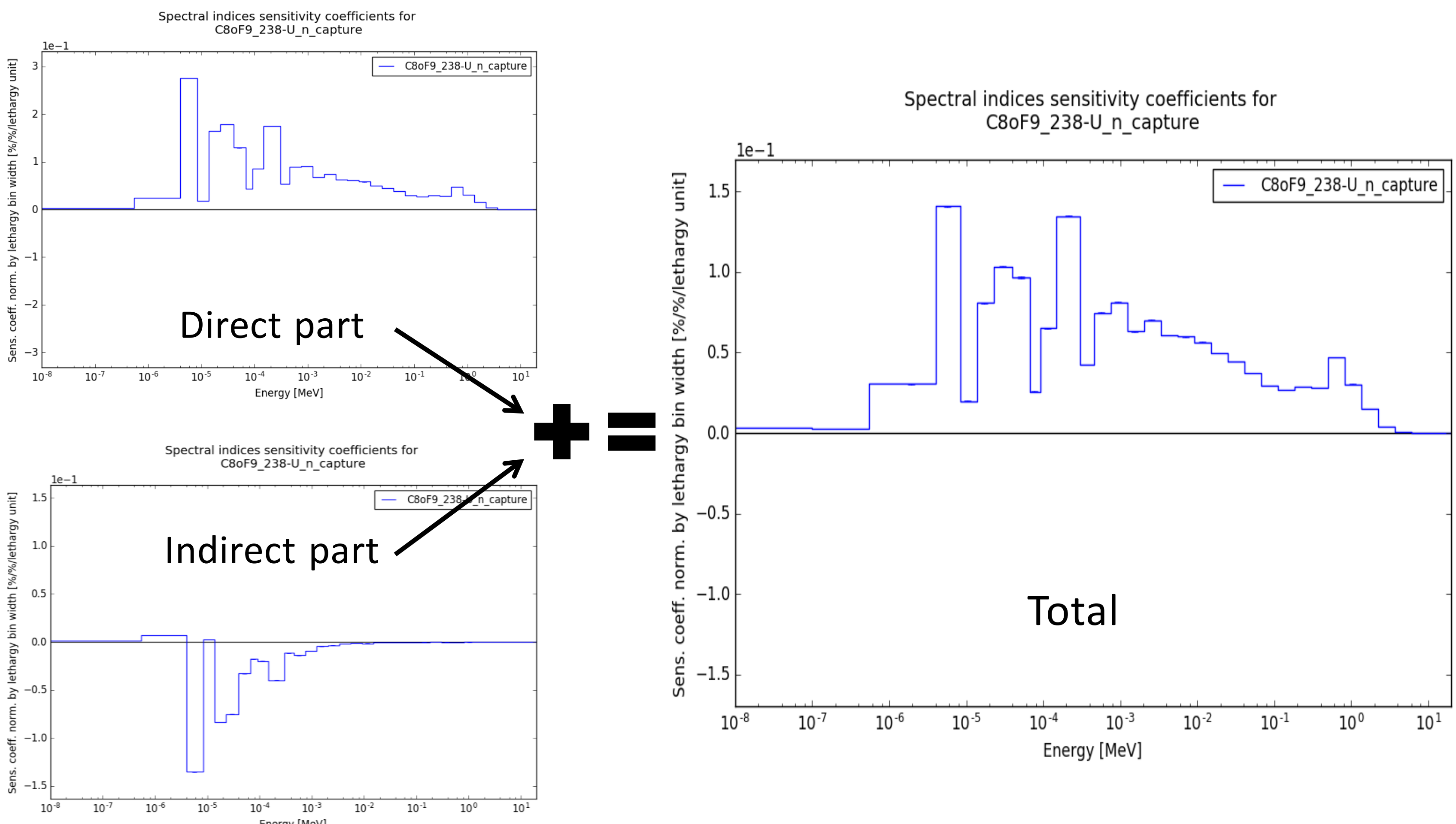
Results for spectral indices sensitivity coeffs.

Example: sensitivity of ^{238}U-capture over ^{239}Pu-fission for a perturbation in the ^{238}U-capture cross section.



Results for spectral indices sensitivity coeffs.

The sensitivity coefficients have been obtained for the following spectral indices:

- ^{235}U-fission over ^{239}Pu-fission
- ^{238}U-capture over ^{239}Pu-fission
- ^{238}U-fission over ^{239}Pu-fission
- ^{241}Pu-fission over ^{239}Pu-fission
- ^{242}Pu-capture over ^{239}Pu-fission

The perturbed cross sections for which sensitivities have been evaluated are all those of nuclides ^{1}H, ^{16}O, ^{235}U, ^{238}U, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu for the reactions of elastic scattering, inelastic scattering, capture, total fission and the parameter ν_T.

Outlook of Re-analysis work at PSI

- Master student currently working on HCLWR re-analysis
  - Sensitivity work on 1D models almost complete
    - K-inf
    - Void coefficient
    - Spectral indices
  - About to start the development of 3D models

- Previous delivery will be updated
  - Fixing infinitely dilute inelastic cross sections
  - Addition of sensitivities to P1 scattering moments
  - C/E + senstivities for spectral indices

- Feedbacks on Data Delivery
  - Was it used?
  - Is it useful in terms of data assimilation?

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Wir schaffen Wissen – heute für morgen

Serpent sensitivity capability

The modified version of **Serpent 2.1.19** is able to **compute the indirect part** (${S_{R,x}}^{indir}$) of the sensitivity coefficients. The **direct part** of the sensitivity coefficients **has to be computed separately**.

Assume that the direct part of the energy-resolved sensitivity coefficient of $R = \frac{<\Sigma_1 \phi>}{<\Sigma_2 \phi>}$ to a perturbation of Σ_1 is needed. Then, within a standard Serpent 2 input:

- Define **integral** detector for $<\Sigma_1 \phi>$ (assume name is «R1»)
- Define **energy resolved** detector for $<\Sigma_1 \phi>$ (assume name is «R1E»)
- Add «dt 3 R1» option (i.e. divide by values of R1) to the «R1E» detector

The score of the «R1E» detector will be ${S_{R,1}}^{dir}$ and will normalize to 1.