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Combined use of k-effective and beta-effective measurements for nuclear data validation and improvement

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ND-2016, Bruges

PURPOSE

- Mainly criticality benchmarks are used for ND validation and adjustment studies. However, k_{eff} is a very global parameter;
- Validation against other type of measurements provides a complementary view and wider scope validation;
- The following experimental measurements can be useful for ND validation & adjustment:
  - Critical benchmarks
  - **Kinetics measurements**
  - Shielding benchmarks

Motivation:

- Uncertainty in the effective delayed neutron fraction β_{eff} was studied in the in the scope of **UAM project of OECD/ NEA since ~2010**.
- β_{eff} is important for:
  - dynamic behaviour of a reactor and safety analysis ($): present and future reactor design (GEN-IV, ADS)

- **CHANDA project**: k_{eff} and β_{eff} sensitivity & uncertainty analyses of the **MYRRHA reactor**.
- **WPEC-SG39**

Effective delayed neutron fraction b-eff

$$\beta_{eff} = \frac{\nu_d}{k_{eff}} \frac{\partial k_{eff}}{\partial \nu_d}$$

$$= \int \Phi^+(\vec{r}, E', \Omega') \chi_d(E') dE' d\Omega' \int \nu_d(E) \Sigma_f(\vec{r}, E) \Phi(\vec{r}, E, \Omega) dE d\Omega d\vec{r}$$

- **b$_{eff}$ can be easily calculated using deterministic and Monte Carlo GPT codes;**
- **Sensitivity of b$_{eff}$ can be obtained as a 2nd derivative of *k$_{eff}$* (Monte Carlo codes).**

I. Kodeli, Sensitivity and Uncertainty in the Effective Delayed Neutron Fraction (b$_{eff}$), *Nuclear Instruments and Methods in Physics Research A* **715** (2013)70-78.

Bretscher‘s Prompt k Ratio Method for determining b-eff

$$\beta_{eff} = 1 - \frac{k_p}{k}$$

k: usual multiplication factor
k_p: multiplication factor with delayed neutrons not taken into account

Sensitivity of b-eff can be obtained as a (properly weighted) difference between two standard sensitivity terms:

$$\frac{\sigma}{\beta_{eff}} \frac{\partial \beta_{eff}}{\partial \sigma} = \frac{1-\beta_{eff}}{\beta_{eff}} \left(S_k - S_{kp} \right)$$

I. Kodeli, Sensitivity and Uncertainty in the Effective Delayed Neutron Fraction (b_{eff}), *Nuclear Instruments and Methods in Physics Research A* **715** (2013)70-78.

Sensitivity/uncertainty analysis - XSUN-2016 computational tool

- **PARTISN**: 1D, 2D, 3D S_N transport solver (deterministic);
- **Cross sections:**
  - **ENDF/B-VII.1 33-group** cross-sections for **110 isotopes,** T= 300 to 850 K: processed by **NJOY-99** in MATXS format, self-shielded case dependent XS prepared by **TRANSX**;
- **SUSD3D** sensitivity-uncertainty calculations,
- **Covariance matrices:**
  - **JENDL-4.0** (delayed nu-bar), COMMARA-2, SCALE-6.0, ENDF/B-VII.1
- Validation against M/C:
  - Winfried Zwermann: XSUSA
  - Manuele Aufiero: SERPENT2 GPT extended

- I. Kodeli, W. Zwermann, Evaluation of Uncertainties in β_{eff} by Means of Deterministic and Monte Carlo Methods. *Nuclear Data Sheets.* 118 (2014)

SUSD3D b_{eff} S/U analysed benchmarks from ICSBEP and IRPhE

- **SNEAK-7A** & **-7B**: MOX fuel reflected by metallic depleted U.
- **Jezebel**: bare sphere of ^{239}Pu metal, 6.385-cm radius
- **Skidoo** (Jezebel-23): bare ~98.1% ^{233}U sphere;
- **Popsy** (Flattop-Pu): ~20-cm natural U reflected ^{239}Pu sphere;
- **Topsy** (Flattop-25): ~20-cm natural U reflected ^{235}U sphere;
- **Flattop-23**: ~20-cm natural U reflected ^{233}U sphere;
- **Big Ten**: 10% enriched U with U-reflector, cylinder r=41.91cm, h=96.428cm;
- **ZPPR-9**: MOX core with sodium cooling, depleted U blanket.
- **MYRRHA**: ADS

- I. Kodeli, Sensitivity and uncertainty in the effective delayed neutron fraction (β_{eff}), *Nuclear Instruments and Methods in Physics Research A* ***715*** *(2013)70-78*

Calulated & measured b-eff

Benchmark	Measured (pcm)	Calculated (pcm)		
		SUSD3D	Prompt k-ratio	
			PARTISN	MCNP
SNEAK 7A	395±5.15%	373	379	369
SNEAK 7B	413±6%	419	429	415
Jezebel	195±5%	185	186	186
Jezebel-^{233}U	290±3.5%	296	297	
Flattop-Pu	276±2.5%	277	278	284
Flattop-^{235}U	665±2%	688	690	
23 Flattop	360±2.5%	374	375	
Big-ten	720±1%	720	734	
ZPPR-9P	/	360	362	
MYRRHA	/	322	323	

FLATTOP-23: Total uncertainty in b-eff: 5.5/6.9 %

(b_{exp} = 395 pcm)

b (pcm):
^{233}U: 260
^{235}U: 650
$^{238}U_f$: 1480

MAT	Sensitivity (%/%)						
	elastic	inelastic	(n,f)	(n,γ)	$\bar{\nu}_d$	$\bar{\nu}_p$	$\bar{\nu}_t$
^{233}U	-0.005	-0.034	**-0.230**	-0.016	**0.697**	**-0.882**	**-0.184**
^{234}U	$2 \cdot 10^{-5}$	-0.001	-0.001	$-2 \cdot 10^{-4}$	0.007	-0.009	-0.002
^{235}U	0.001	-0.001	0.015	-0.001	0.015	0.002	0.017
^{238}U	0.074	**-0.129**	**0.166**	-0.033	**0.273**	**-0.104**	0.170

MAT	Uncertainty (%)								
	elastic	inelastic	(n,f)	(n,γ)	$\bar{\nu}_d$	$\bar{\nu}_p$	χ_p	χ_d	Total
JENDL-4.0m									
^{233}U	0.089	0.584	0.209	0.217	**5.097**	0.657	0.304	0.762	5.27
^{235}U	0.004	0.009	0.063	0.001	0.048	0.002	0.017	0.001	0.06
^{238}U	0.318	1.293	0.103	0.073	0.916	0.061	0.045	0.110	1.63
Sum	0.33	1.42	0.24	0.23	5.18	0.81	0.31	0.77	5.5
COMMARA-2									
^{233}U	0.298	0.432	0.195	0.227	**6.444**	0.197	0.227	N/A	6.47
^{235}U	0.003	0.004	0.006	0.010	N/A	0.001	0.013	N/A	0.01
^{238}U	1.770	2.430	0.088	0.046	N/A	0.122	0.036	N/A	2.44
Sum	1.77	2.47	0.21	0.23	6.44	0.23	0.23	N/A	6.9

SNEAK-7B: Uncertainty in b_{eff} (TOTAL~3 %)

SNEAK-7B	Sensitivity (%/%)						
MAT	elastic	inelastic	(n,f)	(n,γ)	ν_{del}	ν_{pmt}	ν
U-235	$-2 \cdot 10^{-4}$	-0.002	0.060	-0.001	0.111	-0.052	0.059
U-238	-0.018	**-0.160**	**0.261**	0.011	**0.550**	**-0.326**	0.224
Pu-239	-0.001	-0.008	**-0.228**	-0.001	**0.292**	**-0.565**	**-0.273**

SNEAK-7B	Uncertainty (%)								
MAT.	elastic	inelast.	(n,f)	(n,γ)	ν_{del}	ν_{pmt}	χ_p	χ_d	TOTAL
	JENDL 4.0m								
U-235	~0	0.023	0.079	0.005	0.329	0.011	0.071	0.086	0.35
U-238	0.051	1.701	0.112	0.067	1.848	0.196	0.046	0.469	2.57
Pu-239	0.003	0.086	0.055	0.012	1.162	0.099	0.489	0.195	1.29
SUM	0.17	1.72	0.18	0.07	2.21	0.22	0.50	0.52	2.9
	COMMARA-2								
U-235	0.009	0.010	0.028	0.011	N/A	0.005	0.051	/	0.06
U-238	2.863	2.991	0.139	0.046	N/A	0.385	0.018	/	3.01
Pu-239	0.105	0.148	0.108	0.070	N/A	0.044	0.323	/	0.38
SUM	2.87	2.99	0.18	0.06	N/A	0.39	0.33	/	3.0

b (pcm):

^{235}U: ~650

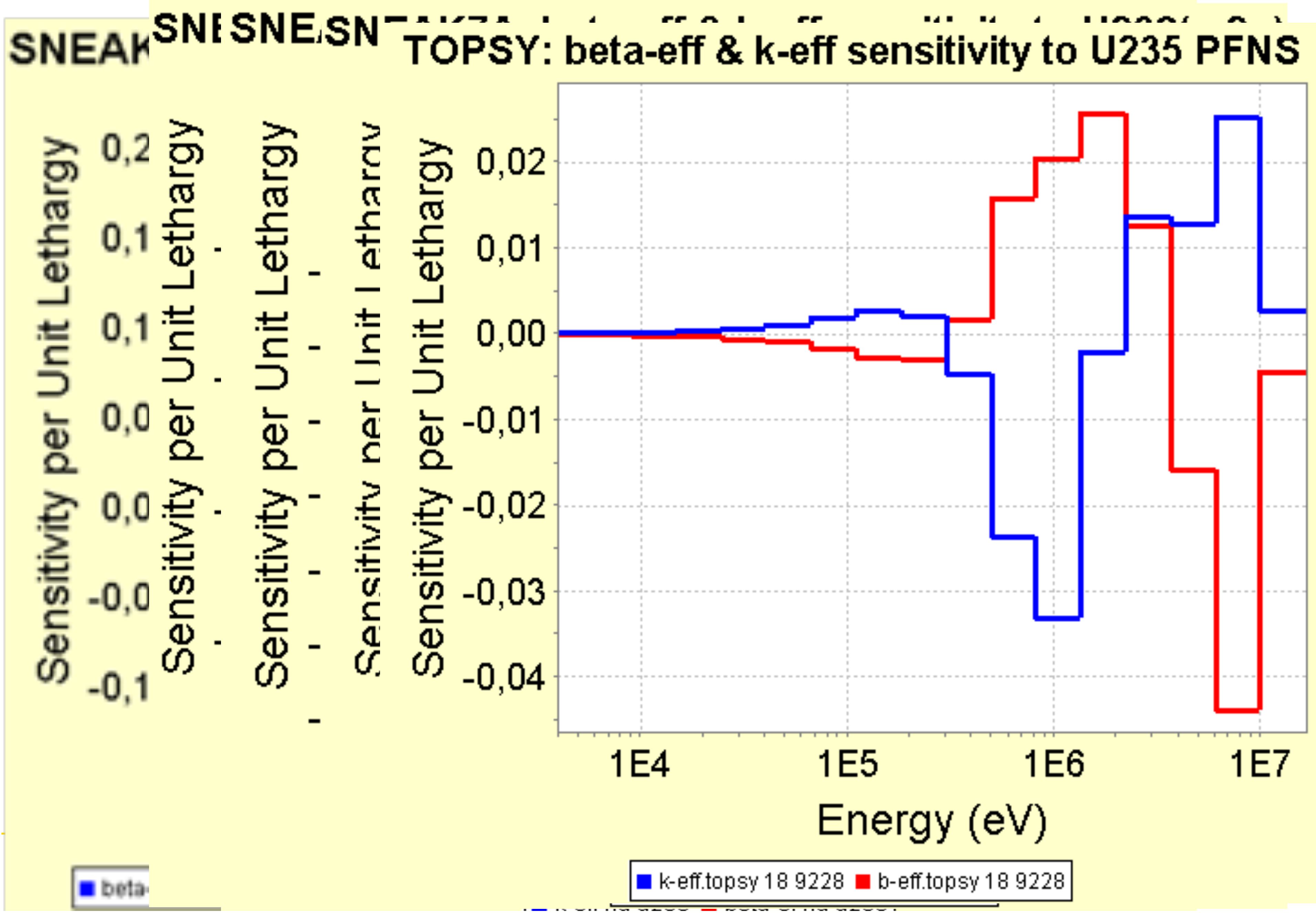
$^{238}U_f$: ~1480

^{239}Pu: ~210

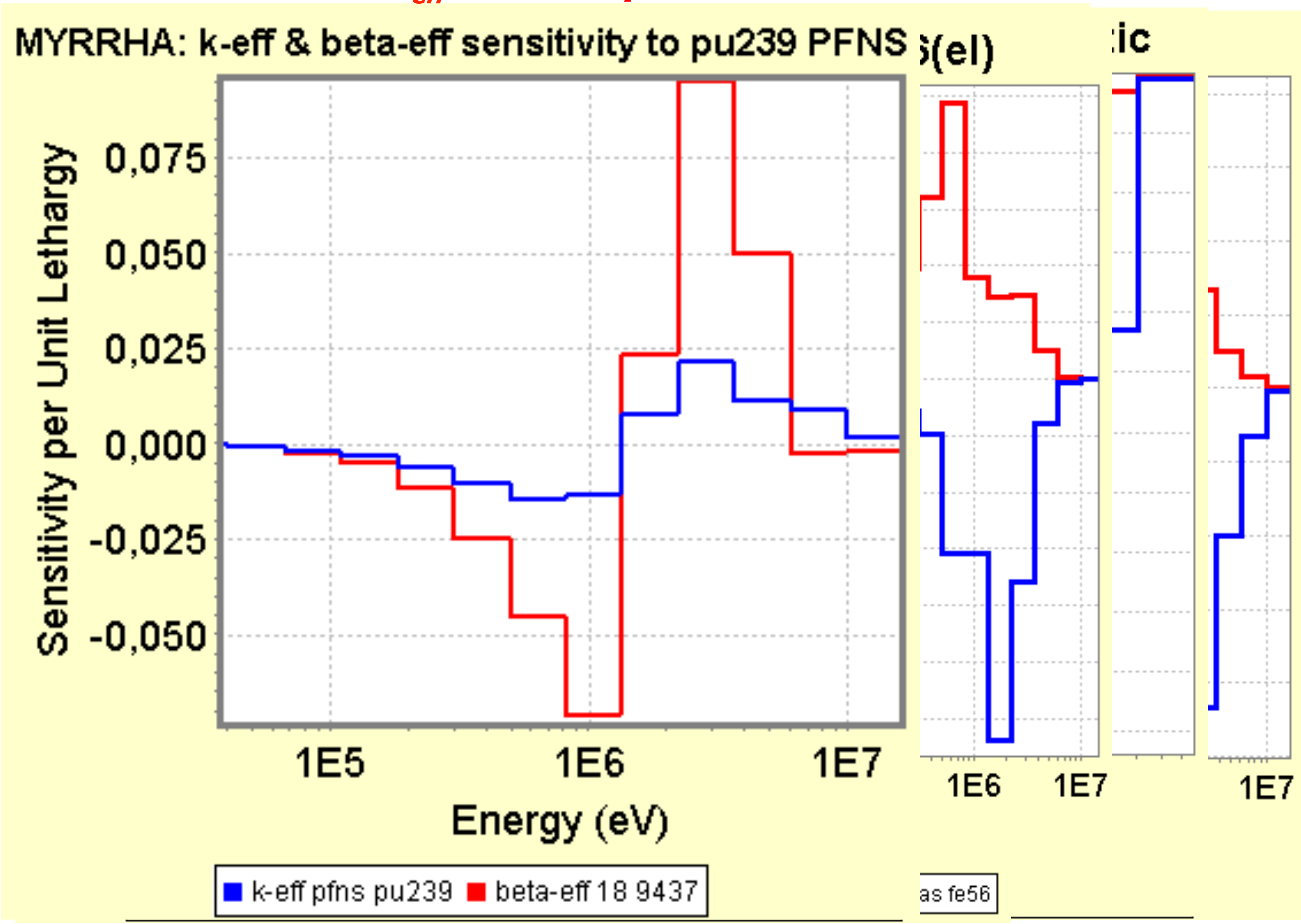
^{240}Pu: ~270

^{241}Pu: ~490

Differences in sensitivity profiles of b_{eff} and k_{eff}



MYRRHA b_{eff} sensitivity / CHANDA



Calculated uncertainties k_{eff} vs. b_{eff} (%)

Assembly	Covariances	SUSD3D	
		k_{eff}	b_{eff} no/full corr.
SNEAK-7A	JENDL-4.0m	0.6144	2.7 / 3.8
	ENDF/B-VII.1	0.7671	
	SCALE6.0m	1.0897	
FLATTOP-Pu	JENDL-4.0m	0.7013	2.6 / 3.3
	ENDF/B-VII.1	0.5483	
	SCALE6.0m	1.2003	
JEZEBEL	JENDL-4.0m	0.6034	2.5 / 2.7
	ENDF/B-VII.1	0.5646	
	SCALE6.0m	1.3477	

Conclusions

- **Use of shielding, criticality & kinetics benchmarks offers a more complete picture needed for ND validation.**
- Powerful codes for nuclear data **sensitivity and uncertainty analysis**, both based on deterministic and Monte Carlo methods are available which, **combined with benchmark experiments, offer an efficient tool for evaluation and testing of nuclear data.**
- The application of sensitivity and uncertainty tools to the effective delayed neutron fraction demonstrated the potential benefits of integrating the kinetics benchmarks into the nuclear data evaluation and validation schemes.
- **Sensitivities of k_{eff} and b_{eff} show complementary features, suggesting that a combined use of both measurements can be optimal for the validation and improvement of modern nuclear data.**

CONCLUSIONS

- According to **JENDL-4.0m covariances,** the β_{eff} uncertainty is predominantly due to n_d uncertainties. In some cases (Popsy, SNEAK-7A, -7B, ZPPR-9, MYRRHA) the **inelastic & elastic scattering, (n,f),** n_p**,** $?_p$ and $?_d$ play an important role.
- Uncertainty due to ^{238}U inelastic XS are almost twice as large using COMMARA-2 covariances (1.5–1.7% vs. 2.5–3%).
- **Total uncertainty in β_{eff} is ~3%** (up to 5 - 7% for Flattop 23 due to ^{233}U uncertainties).
- Due to their high sensitivity and different shapes of sensitivity profiles the β_{eff} experiments can provide a complementary information to critical experiments for validation of e.g. on ^{238}U inelastic, elastic, fission, PFNS, in addition to n_d.
- **Chalanges:**
  - **β_{eff} experimental uncertainty: 1 – 5% ??????**
  - **Improved covariance matrices needed: n_d + correlations among isotopes, DFNS .....**