Potential Use of beta-eff and other Benchmarks for Adjustment

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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.

- 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 β-eff

Benchmark	Measured (pcm)	Calculated (pcm)		
		SUSD3D	Prompt k-ratio (Eq.7)	
		(eq. 6)	DANTSYS	MCNP
SNEAK 7A	$395 \pm 5.15\%$	373	379	369
SNEAK 7B	$413 \pm 6\%$	419	429	415
Jezebel	$194 \pm 5\%$	185	186	186(191)
Skidoo Jezebel-U233	$290 \pm 3.5\%$	296	297	
Popsy Flattop-Pu	$276 \pm 2.5\%$	277	278	284
Topsy Flattop-U235	$665 \pm 2\%$	688	690	
23 Flattop	$360 \pm 2.5\%$	374	375	
Big-ten	$720 \pm 1\%$	720	734	
ZPPR-9	355	360	362	

Analysis of benchmarks from ICSBEP and IRPhE

- SUSD3D sensitivity-uncertainty calculations,
  - PARTISN/DANTSYS (1D, 2D, 3D),
  - ENDF/B-VII.0 33-group cross-sections (TRANSX)
  - JENDL-4.0m (delayed nu-bar), COMMARA-2 & SCALE-6.0 covariance matrices;
- Validation against M/C:
  - Winfried Zwermann: XSUSA
  - Manuele Aufiero: SERPENT2 GPT extended

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

(β_{exp} = 395 pcm)

β (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

FLATTOP-Pu (POPSY)

Popsy: sensitivity of β_{eff} relative to nuclear data.

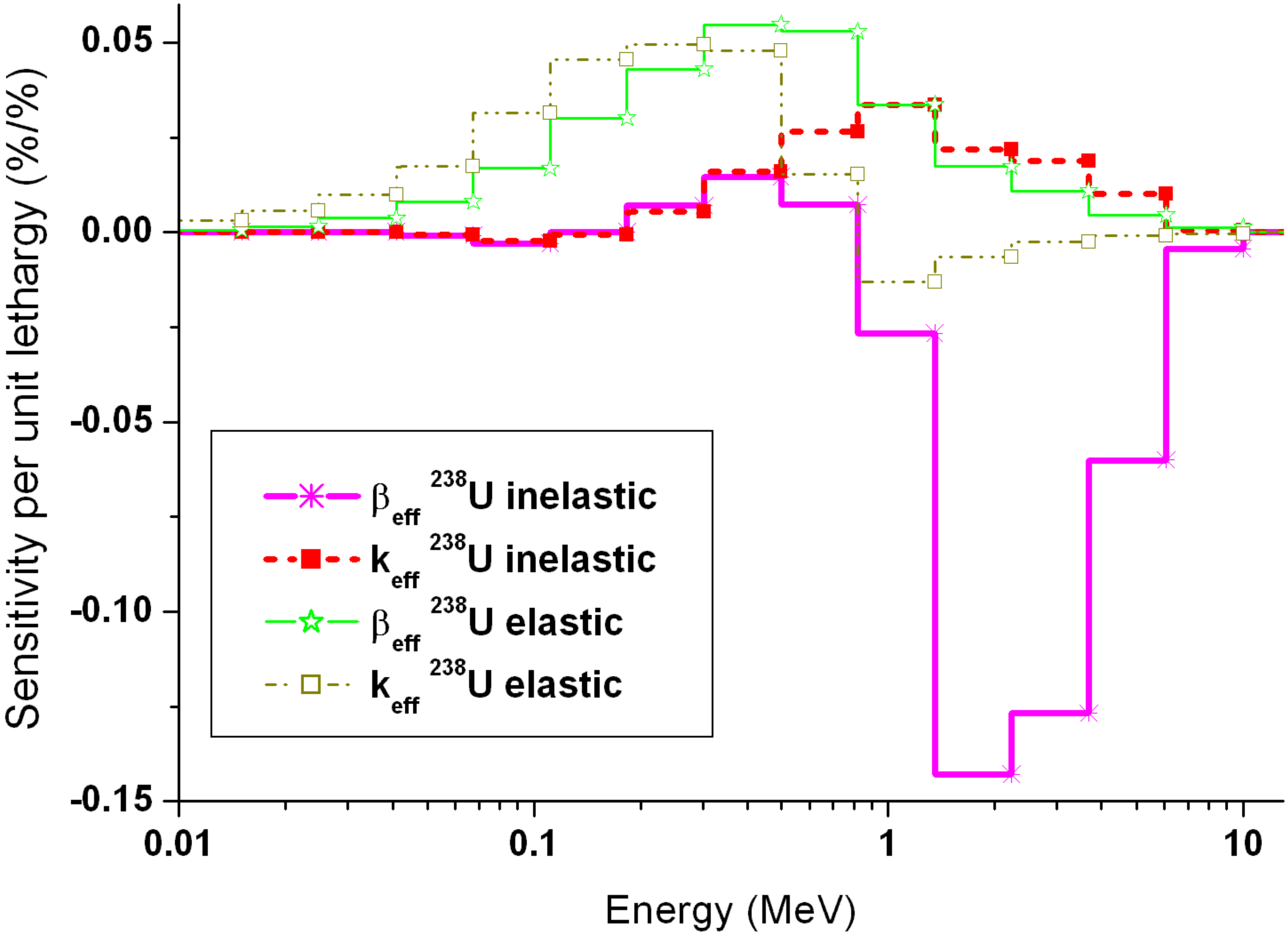
MAT	Sensitivity (%/%)						
	Elastic	Inelastic	(n,f)	(n,γ)	$\overline{\nu}_d$	$\overline{\nu}_p$	$\overline{\nu}_t$
^{235}U	0.001	−0.001	0.027	−0.001	0.020	0.010	0.030
^{238}U	**0.103**	**−0.170**	**0.261**	−0.050	**0.361**	−0.083	**0.278**
^{239}Pu	−0.010	−0.042	**−0.305**	−0.017	**0.588**	**−0.879**	**−0.292**
^{240}Pu	-3×10^{-4}	−0.002	−0.015	−0.001	0.024	−0.043	−0.019
^{241}Pu	-4×10^{-5}	-1×10^{-4}	0.002	-5×10^{-5}	0.005	−0.002	0.002

FLATTOP-Pu (POPSY)

Popsy: variance penalties and total uncertainty in β_{eff} relative to nuclear data uncertainties. Note that the $\overline{\nu}_d$ covariances are not available in the COMMARA-2 evaluation.

MAT	Uncertainty (%)								
	Elastic	Inelastic	(n,f)	(n,γ)	$\overline{\nu}_d$	$\overline{\nu}_p$	χ_p	χ_d	Total
JENDL-4.0m									
^{235}U	0.004	0.011	0.100	0.002	**0.066**	0.003	0.030	0.011	0.08
^{238}U	0.380	**1.712**	0.029	0.103	**1.191**	0.048	0.094	0.098	2.13
^{239}Pu	0.034	0.414	0.184	0.107	**1.347**	0.265	0.172	0.073	1.47
^{240}Pu	0.002	0.017	0.163	0.005	0.114	0.008			0.12
^{241}Pu	~0	0.003	0.055	~0	0.022	0.001			0.02
Sum	0.38	1.76	0.27	0.15	1.80	0.05	0.20	0.12	**2.6**
COMMARA-2									
^{235}U	0.009	0.006	0.011	0.015	N/A	0.001	0.022	N/A	0.02
^{238}U	1.645	**3.273**	0.136	0.066	N/A	0.096	0.079	N/A	3.30
^{239}Pu	0.622	0.657	0.273	0.131	N/A	0.102	0.045	–	0.73
^{240}Pu	0.054	0.058	0.026	0.005	N/A	0.101			0.12
^{241}Pu	~0	0.004	0.002	0.001	N/A	0.001			0.004
Sum	1.76	3.34	0.31	0.15	N/A	0.17	0.09	–	**3.4**

Comparison of β_{eff} and k_{eff} sensitivities with respect to inelastic and elastic cross-sections of ^{238}U (**Popsy - FLATTOP-Pu**)



The fact that an important part of the total k_{eff} and β_{eff} uncertainty comes from the ^{238}U inelastic cross-section uncertainty makes such benchmarks potentially suitable for the validation of these nuclear reaction data. **Due to the different shapes of the sensitivity profiles it is expected that the combined use of criticality and β_{eff} measurements would provide a better insight and an efficient validation of these nuclear data in the energy range above ~1 MeV.**

SNEAK-7A: Sensitivity to k_{eff} and β_{eff}

β (pcm):
^{235}U: 650
$^{238}U_f$: 1480
^{239}Pu: 210
^{240}Pu: 270
^{241}Pu: 490

k-eff	Sensitivity (%/%)					
MAT	elastic	inelastic	(n,f)	(n,γ)	ν_{del}	ν_{pmt}
U-235	0.001	$-2\cdot10^{-4}$	**0.037**	-0.005	$3\cdot10^{-4}$	0.056
U-238	**0.102**	-0.017	**0.087**	**-0.156**	0.002	**0.137**
Pu-239	0.006	-0.001	**0.540**	**-0.058**	0.002	**0.779**

β-eff	Sensitivity (%/%)						
MAT	elastic	inelastic	(n,f)	(n,γ)	ν_{del}	ν_{pmt}	ν
U-235	$-2\cdot10^{-4}$	-0.001	**0.052**	-0.001	**0.080**	**-0.025**	0.055
U-238	-0.011	**-0.151**	**0.276**	-0.017	**0.488**	**-0.233**	**0.255**
Pu-239	-0.002	-0.012	**-0.252**	-0.006	**0.402**	**-0.700**	**-0.298**

SNEAK-7A: Uncertainty in β_{eff} (TOTAL~3 %)

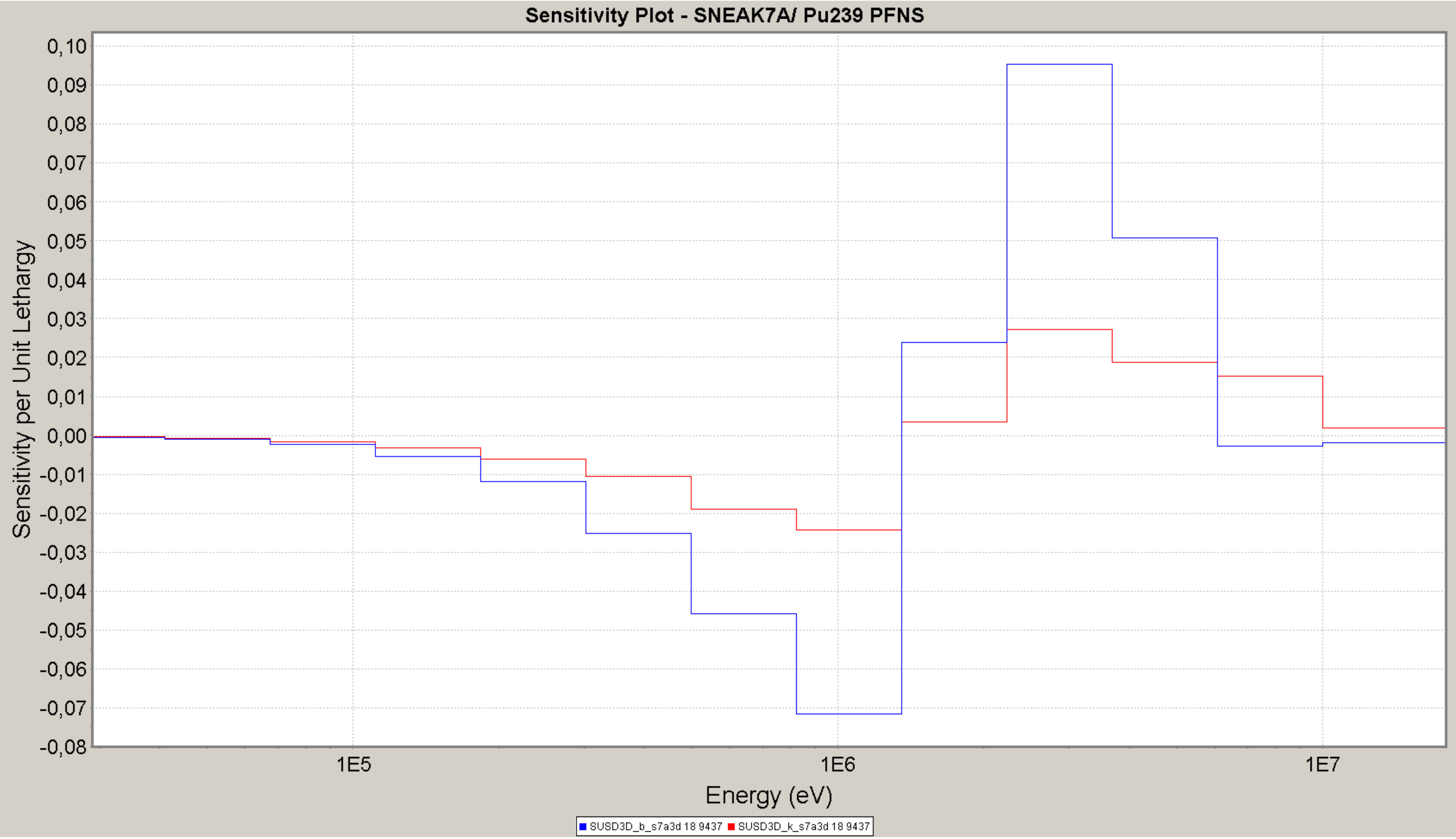
SNEAK-7A	Uncertainty (%)								
MAT.	elastic	inelast.	(n,f)	(n,γ)	ν_{del}	ν_{pmt}	χ_p	χ_d	TOTAL
	JENDL 4.0m								
U-235	~0	0.017	0.074	0.004	**0.218**	0.006	0.050	0.044	0.23
U-238	**0.051**	**1.425**	**0.101**	**0.066**	**1.610**	**0.138**	0.025	**0.279**	**2.18**
Pu-239	0.008	**0.120**	**0.074**	**0.018**	**1.529**	**0.122**	**0.523**	**0.091**	**1.63**
SUM	0.13	**1.44**	0.19	0.07	**2.23**	0.18	**0.53**	0.30	**2.7**
	COMMARA-2								
U-235	0.008	0.008	0.025	0.017	**N/A**	0.002	0.036	/	0.05
U-238	**2.515**	**2.595**	**0.144**	**0.045**	**N/A**	**0.270**	0.017	/	**2.62**
Pu-239	**0.169**	**0.216**	**0.126**	**0.055**	**N/A**	0.051	**0.341**	/	**0.43**
SUM	**2.52**	**2.60**	0.19	0.07	**N/A**	0.28	0.35	/	**2.6**

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

SNEAK-7B	Sensitivity (%/%)						
MAT	elastic	inelastic	(n,f)	(n,γ)	ν_{del}	ν_{pmt}	ν
U-235	$-2\cdot10^{-4}$	-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**

Sensitivity of β-eff to and k-eff to nuclear data



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CONCLUSIONS

- According to the available covariance data the total uncertainty in β_{eff} was found to be in general around 3%, but up to 7% in the ^{233}U reactor systems.
- The β_{eff} uncertainty is in most cases predominantly due to the uncertainties in delayed neutron yields, contributing in the Jezebel, Skidoo, Topsy, Big-ten and Flattop 23 benchmarks over 90% to the total uncertainty. In some cases (Popsy, SNEAK-7A, -7B and ZPPR-9) the **inelastic and elastic scattering** (contributing with few %), **fission** cross-sections (~0.2%) and **prompt neutron yields** (~0.2%), as well as prompt and delayed **fission spectra** (roughly 0.5%) play an important role.
- **Due to their high sensitivity and different shapes of sensitivity profiles the β_{eff} experiments can provide a complementary information to critical experiments for the validation of nuclear data (other than ν_d). ^{238}U inelastic and elastic scattering (&fission, PFNS) are particularly interesting examples where β_{eff} measurements could contribute to the improved nuclear data evaluations.**
- Sensitivity profiles for **SNEAK-7A,** & **-7B**, **Jezebel, Skidoo** (Jezebel-23), **Popsy** (Flattop-Pu), **Topsy** (Flattop-25), **Flattop-23**: **Big Ten**: **ZPPR-9** were evaluated in 33 groups and could be made available for adjustment purposes.

SINBAD

- FNS-Liquid Oxygen
- PCA REPLICA (new 3D TORT model prepared by M. Pescarini)
- ASPIS Iron (old benchmark, but could provide sensitivities to fast reaction rates
- Other ASPIS benchmarks...