SA and UQ work for the VENUS-F facility using the SANDY code

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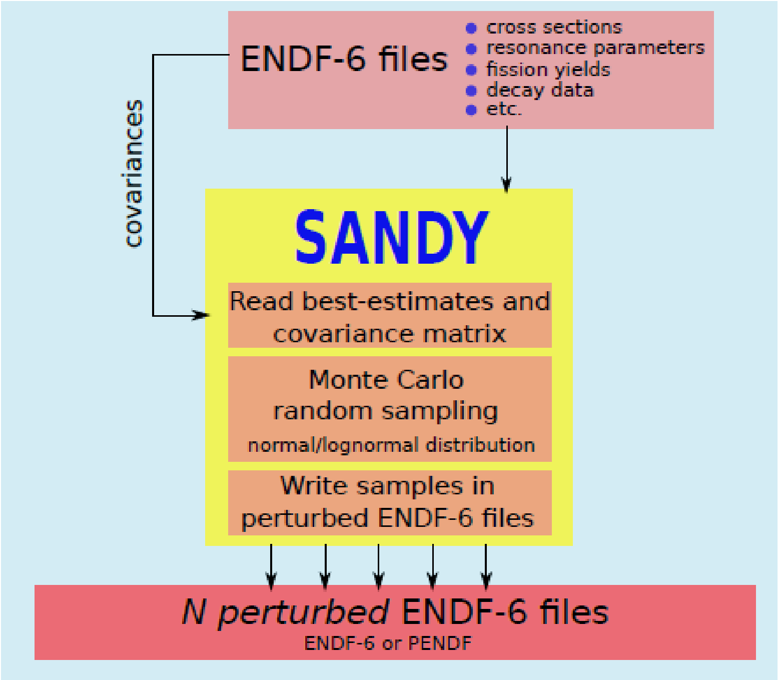
What is SANDY?

- Numerical tool for nuclear data uncertainty quantification
- Based on Monte Carlo sampling
  - Input parameters random samples are generate according to best-estimate data and covariances
  - Normal or LogNormal multivariate PDF
  - Not dependent on the model and on the model solver (black box)
  - No linerarity assumption
  - Accuracy related to the number of samples



- Compatible with ENDF-6 format
- Pointwise parameters (no multi-group assumption)
- Flexibility: many libraries, many codes (MCNP)
- SANDY was tested for linear models against TSUNAMI and perturbation theory obtaining analogous results.

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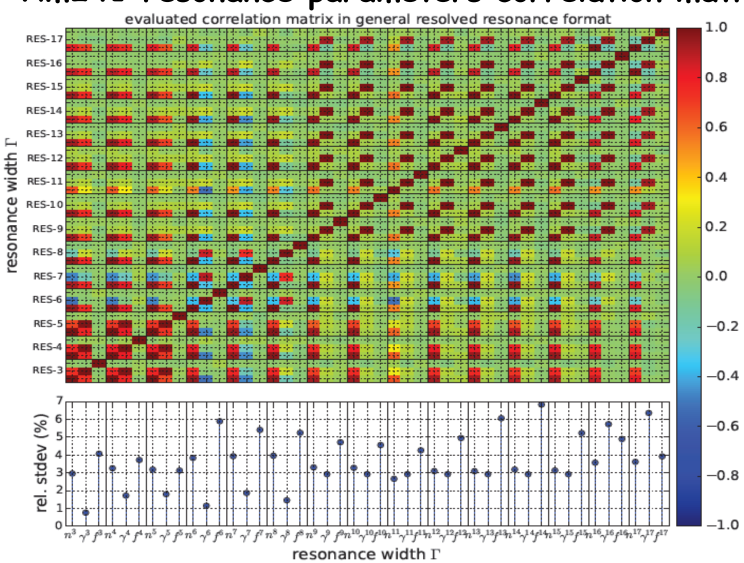
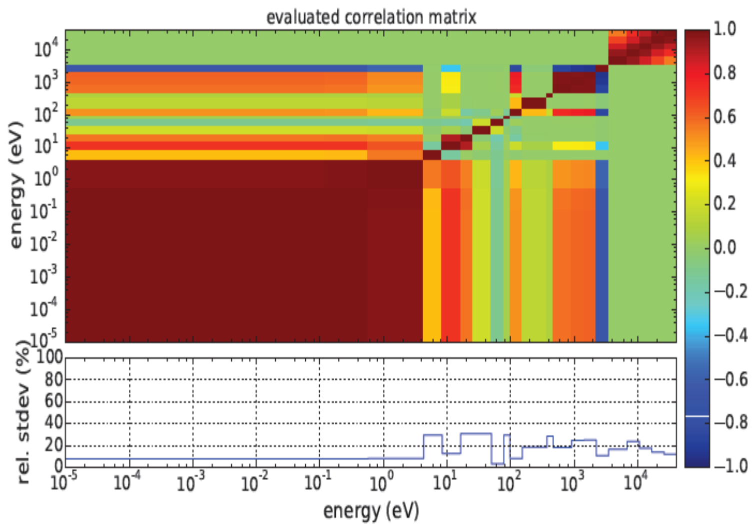
What is SANDY?

- SANDY can propagate uncertainties for:
  - Cross sections (background and resonances) [MF=32, 33]
  - Energy and angular distribution of secondary particles [MF=34, 35]
  - Fission neutron multiplicities (ν) [MF=31]
  - Independent, cumulative and spontaneous neutron fission yields [MF=8]
  - Radioactive decay data (decay constants, branching ratios, energy,…) [MF=8]

Am241 resonance parameters correlation matrix



U238 cross section correlation matrix



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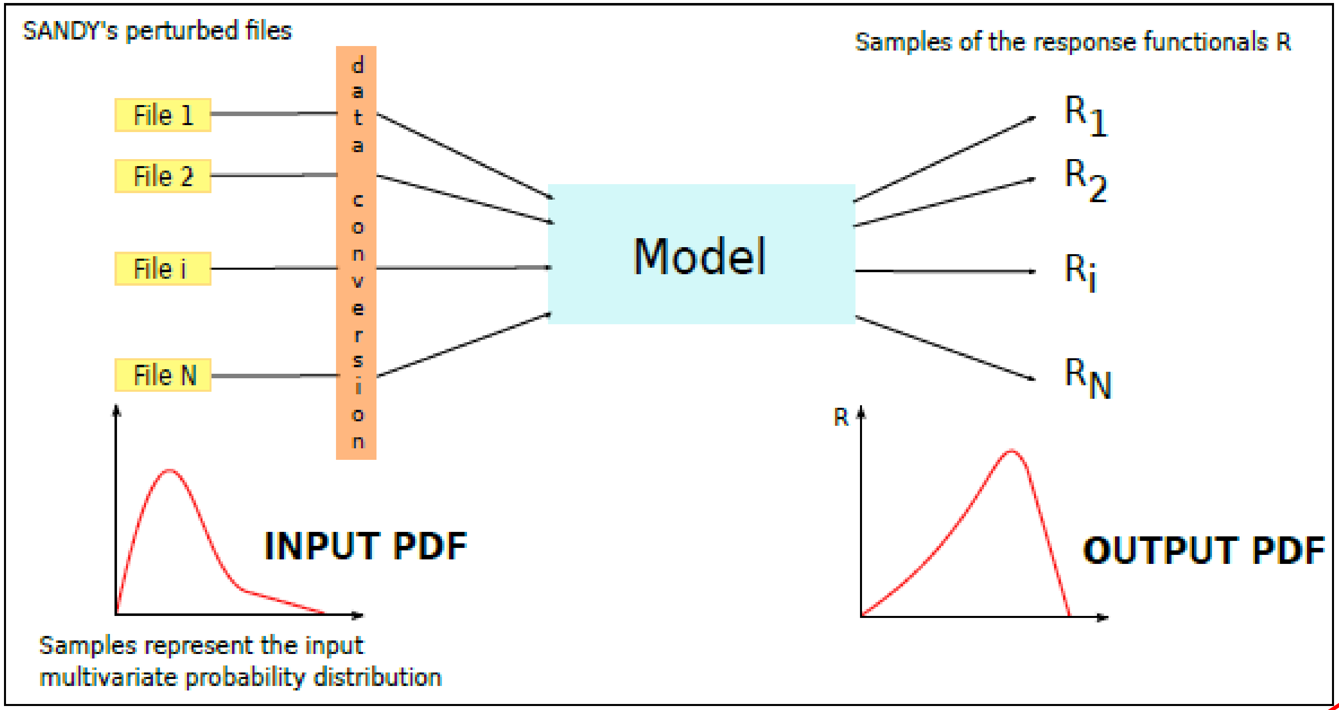
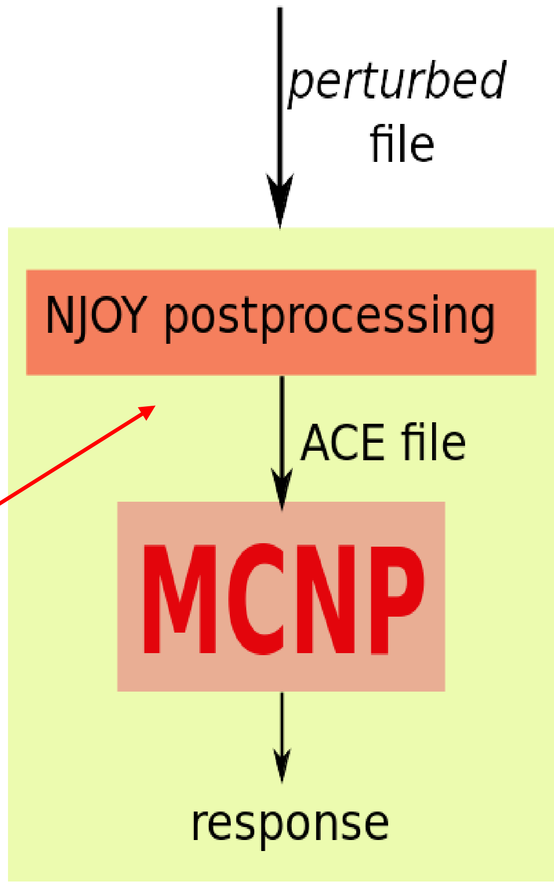
SANDY uncertainty propagation





ENDF-6 files can be converted into different formats

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SANDY's variance decomposition

- According to ANOVA, the response variance can be decomposed amongst its contributors (reaction cross sections, resonance parameters, parameters within an energy range, ...)

$$V_y = \sum_{i=1}^{n} V_i + \sum_{i=1}^{n} \sum_{j>i}^{n} V_{ij} + \cdots + V_{1,\ldots,n}$$

UNCORRELATED PARAMETERS

- SANDY estimates global sensitivity indices:
  - *Individual sensitivity index* $$S_i = \frac{V_i}{V_y}$$
  - *Total sensitivty index* $$S_{T_i} = S_i + \sum_{j \neq i}^{n} S_{ij} + \cdots + S_{1,\ldots,i,\ldots,n}$$
- Correlated parameters must first be decorrelated

$$p(\mathbf{x}) = p(x_1)p(x_2|x_1)\ldots p(x_n|\mathbf{x}_{-n})$$

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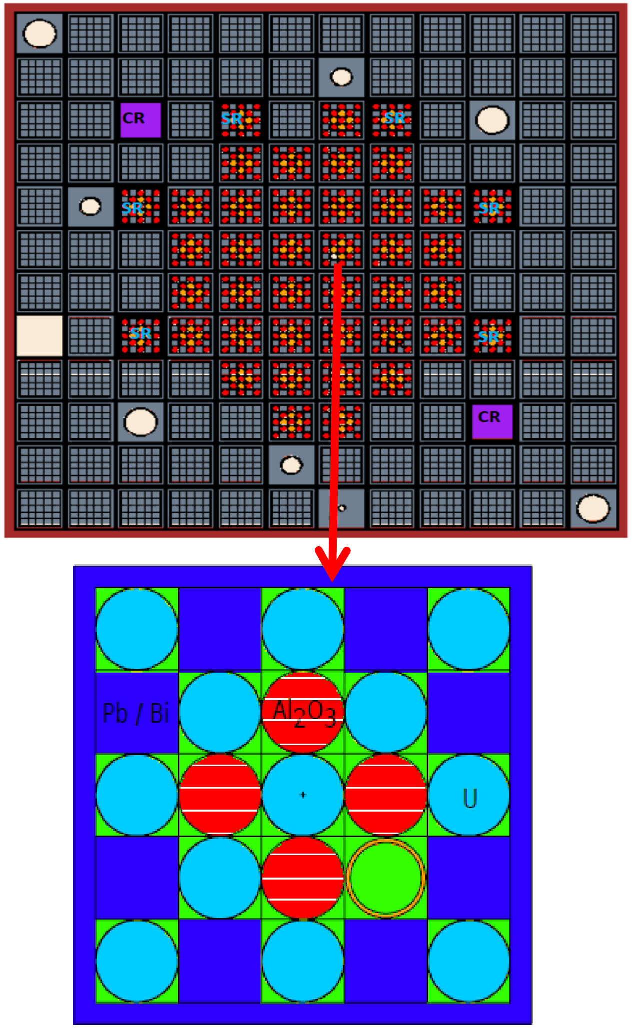
VENUS-F model

- VENUS-F full core
  - 12x12 lattice
  - 41 fuel assemblies
  - Pb plates
- VENUS-F fuel assembly
  - 5x5 lattice
  - ~30 wt.% $^{235}U + Al_2O_3$
- Pb replaced with Bi according to the new VENUS configuration



Correlation between VENUS-F full core and fuel assembly

$$\rho_{X,Y} = \frac{\mathbb{E}[(X-\mathbb{E}[X])(Y-\mathbb{E}[Y])]}{\sigma_X \sigma_Y} = 0.995$$

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Sensitivity coefficients calculated with MCNP (KSEN)

Rank #	Nuclide	Reaction	Sensitivity	Rel. unc.
1	^{235}U	$\bar{\nu}_p$	9.06×10^{-1}	0.0002
2	^{235}U	(n,f)	3.49×10^{-1}	0.0011
3	^{238}U	(n,γ)	-1.42×10^{-1}	0.0008
4	^{235}U	(n,γ)	-1.12×10^{-1}	0.0009
5	^{238}U	$\bar{\nu}_p$	8.69×10^{-2}	0.0018
6	^{238}U	(n,n*)	-4.66×10^{-2}	0.0163
7	^{238}U	(n,f)	2.95×10^{-2}	0.0022
8	^{235}U	(n,n*)	-1.99×10^{-2}	0.0288
9	^{16}O	(n,n)	-1.95×10^{-2}	0.0642
10	^{209}Bi	(n,n*)	-1.19×10^{-2}	0.0164
11	^{27}Al	(n,n)	-6.83×10^{-3}	0.14
12	^{209}Bi	(n,n)	-4.52×10^{-3}	0.4667
13	^{209}Bi	(n,γ)	-3.51×10^{-3}	0.0009
14	^{238}U	(n,n)	-3.18×10^{-3}	0.6168
15	^{235}U	(n,n)	-2.92×10^{-3}	0.8655

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k_{eff} uncertainty quantification with SANDY

Isotope	uncert. k_{eff} (pcm) (ENDF/B-VII.1)	Reaction	Variance decomposition	uncert. K_{eff} (pcm) (JENDL-4.0)
Bi-209 (XS)	201 ± 34	(n,elastic)	55 ± 17	-
		(n,inelastic)	133 ± 38	-
		(n,gamma)	143 ± 41	-
U-235 (XS)	5511 ± 1233	(n,elastic)	35 ± 11	-
		(n,inelastic)	273 ± 86	-
		(n,fission)	264 ± 83	-
		(n,gamma)	5477 ± 1734	-
U-238 (XS)	1161 ± 183	(n,elastic)	49 ± 16	-
		(n,inelastic)	1065± 337	-
		(n,fission)	53± 19	-
		(n,gamma)	326 ± 103	-
U-235 (ν_p)	179 ± 57	-	-	367± 116
U-238 (ν_p)	189± 60	-	-	99± 31

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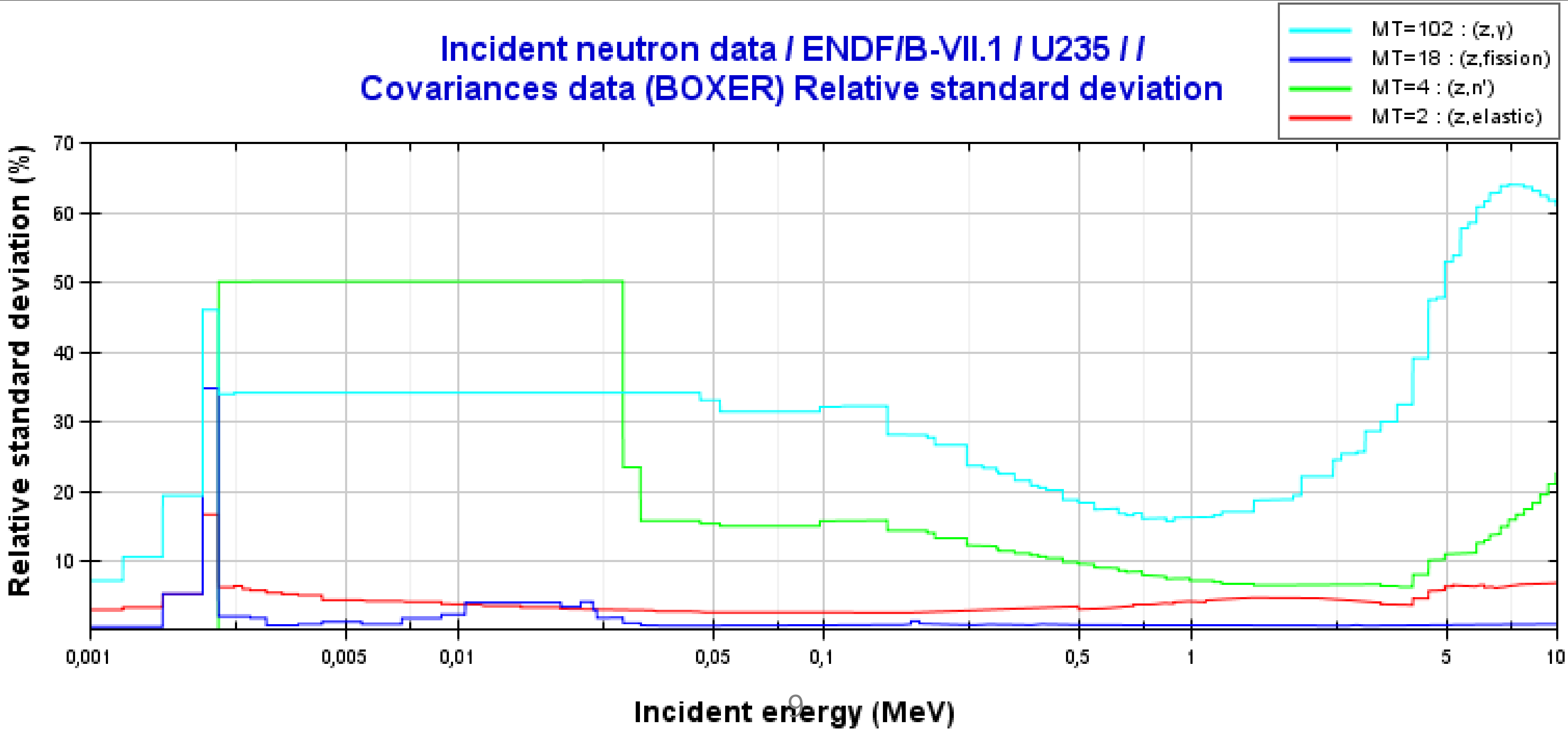
U-235

U-235 (XS)	5511 ± 1233	(n,elastic)	35 ± 11	-
		(n,inelastic)	273 ± 86	-
		(n,fission)	264 ± 83	-
		(n,gamma)	5477 ± 1734	-



U-238

U-238 (XS)	1161 ± 183	(n,elastic)	49 ± 16	-
		(n,inelastic)	1065± 337	-
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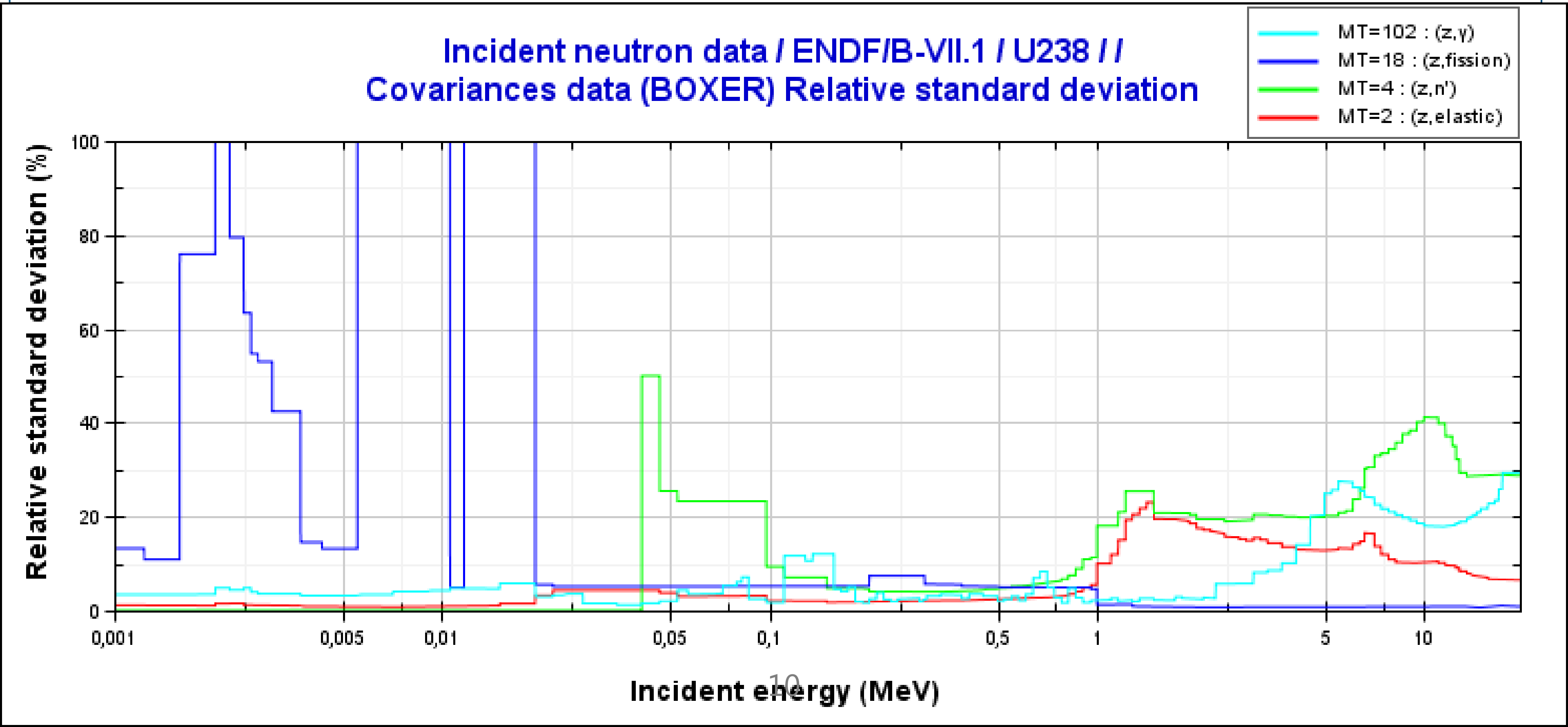
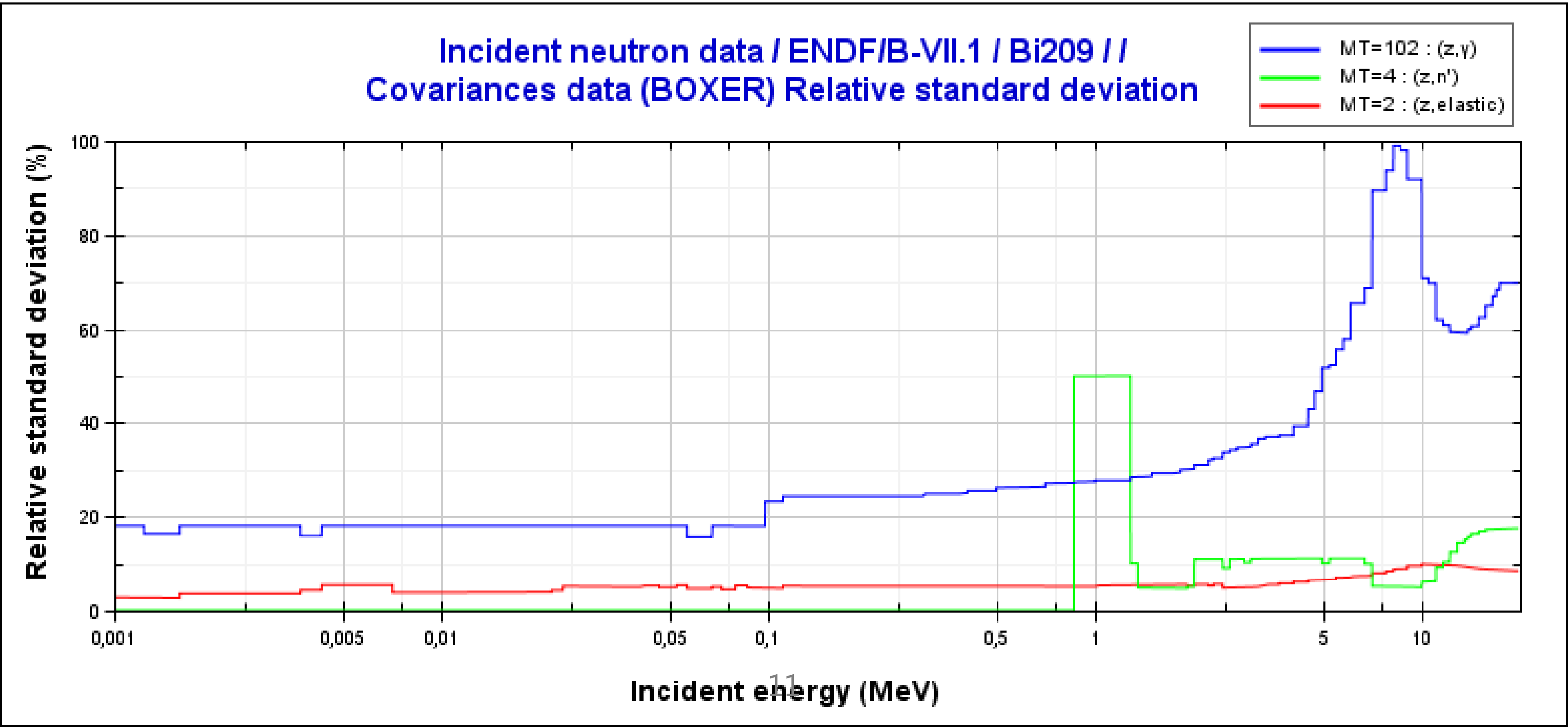


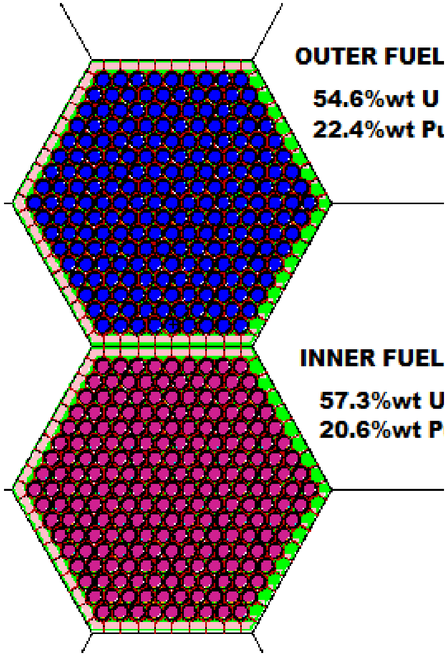
Bi-209

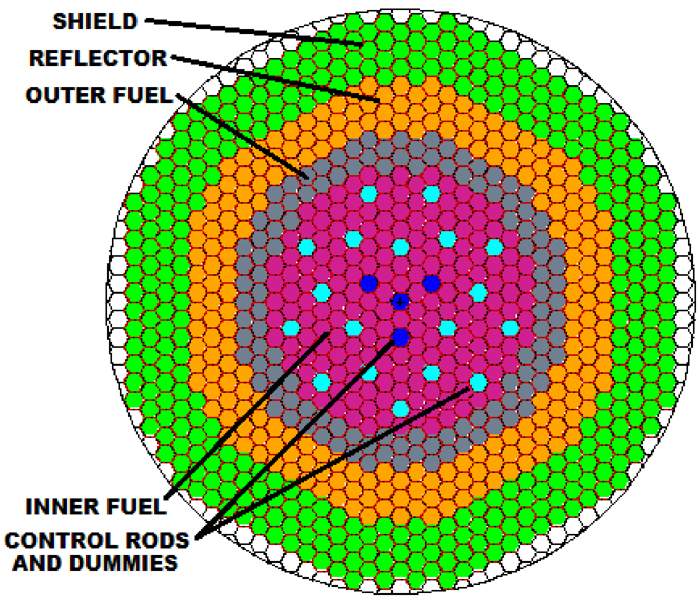
Bi-209 (XS)	201 ± 34	(n,elastic)	55 ± 17	-
		(n,inelastic)	133 ± 38	-
		(n,gamma)	143 ± 41	-

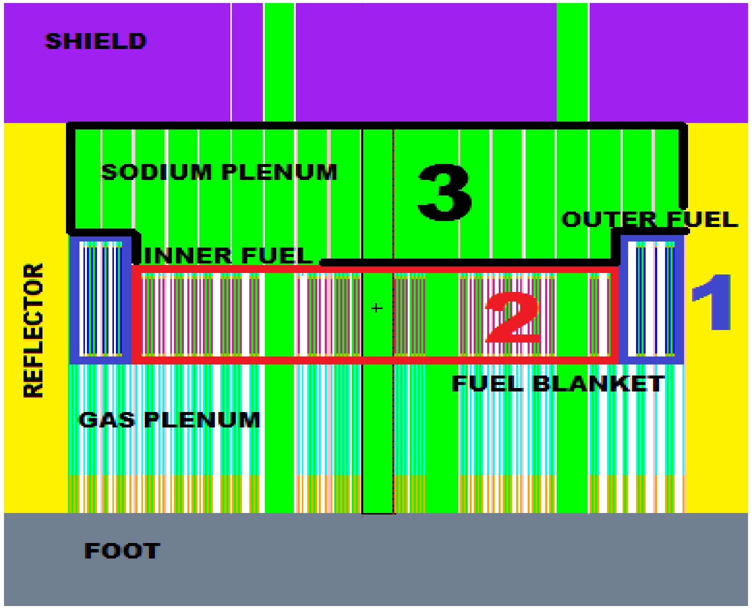


Nuclear data uncertainty propagation on SFR: MCNP model

- Reference specifications for core model: ASTRID CFV-V1 scaled down to 1200MWth and loaded with 10%wt Minor Actinides (MAs)
- Keff (1.01406) and void coefficient uncertainty are calculated







- Voided zones and values:
  - -inner fuel only (2) +5$
  - -outer fuel only (1) +1.7$
  - -all fuel + sodium plenum (1+2+3) -1.2$
- Perturbed isotopes: U-238, Pu-239, Am-241, Am-243, Fe-56, Na-23

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Nuclear data uncertainty propagation on SFR: Keff

- MCNP simulations run with standard deviation on the Keff of approximately 40pcm
- Where possible, variance decomposition for different reactions was calculated.

perturbed isotope	reaction	Keff uncertainty [pcm]			
		global	+ / -	decomposed	+ / -
Am-243	capture	133	38	86	25
	fission			99	28
	scattering			18	5
Am-241	capture	229	53	118	34
	fission			192	61
	scattering			56	18
Pu-239	capture	267	64	240	76
	fission			202	64
	scattering			293	93
U-238	capture	1280	296	201	64
	fission			472	135
	scattering			58	18
Fe-56	inelastic	228	61	213	67
	elastic			208	67
Na-23	inelastic	121	35	109	31
	elastic			52	15

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Nuclear data uncertainty propagation on SFR: one group XS

- The same analysis is applied to the cross section tallies as provided by MCNP
- The values represent the flux averaged cross section of different perturbed reactions

perturbed isotope	reaction	one group reaction rate [b]		
		value	uncertainty	relative
Am-243	capture	1.48	7.59E-02	5.14%
	fission	0.25	2.10E-02	8.52%
Am-241	capture	1.64	2.65E-02	1.61%
	fission	0.33	4.38E-03	1.33%
Pu-239	capture	0.41	2.13E-02	5.15%
	fission	1.76	1.08E-02	0.62%
U-238	capture	0.25	3.36E-03	1.33%
	fission	0.06	2.66E-03	4.76%
Fe-56	inelastic	0.12	1.21E-03	0.98%
	elastic	3.75	2.70E-02	0.72%
Na-23	inelastic	4.21	1.95E-02	0.46%
	elastic	4.40	2.00E-02	0.46%

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Nuclear data uncertainty propagation on SFR: Void coefficient

- For each perturbation, an entire batch in normal condition is compared to a batch in voided conditions, total correlation assumed.

$$\Delta f(x_1, \ldots, x_n) \approx \sqrt{\sum_{i=1}^{n}\left(\frac{\partial z}{\partial x_i}\Delta x_j\right)^2 + 2\sum_{i\neq j}^{n}\frac{\partial z}{\partial x_i}\frac{\partial z}{\partial x_j} corr(x_i, x_j)\Delta x_i \Delta x_j}$$

- The coefficient is defined as follows and expressed **in pcm**

$$C_v = \frac{K^v_{eff} - K_{eff}}{K_{eff}}$$

Isotope	voided zone	uncertainties [pcm]		
		corr=100%	+ / -	corr=0%
Am-241	core + plenum	34	10	301
	inner fuel	44	12	302
	outer fuel	40	11	300
U-238	core + plenum	92	26	1736
	inner fuel	73	21	1725
	outer fuel	29	8	1693
both	core + plenum	62	18	120
	inner fuel	58	17	116
	outer fuel	18	5	102

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Conclusions and further work

- SANDY is a new tool for nuclear data uncertainty propagation
- SANDY is compatible with the ENDF-6 format and with any code and data post-processors using it (including MCNP)
- SANDY is not limited to first order perturbation theory
- SANDY uses a variance decomposition approach to assess each parameter's correlated and/or uncorrelated contribution to the response uncertainty
- Results were tested against TSUNAMI returning a good agreement
- SANDY was used for the SA/UQ of VENUS-F with Bi
- SANDY is currently being used for the UQ/SA of SFR benchmarks
- SANDY is used to produce multigroup covariances for derived cross sections, e.g. dpa and KERMA

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