Uncertainties in Generation IV Reactors and Nuclear Data

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05.10.2025

Outline

- Generation IV and Uncertainties
- Sensitivity and Uncertainty Analysis
- Uncertainty Propagation for Generation IV Reactors
- Nuclear Data Needs for Generation IV Reactors
- Summary

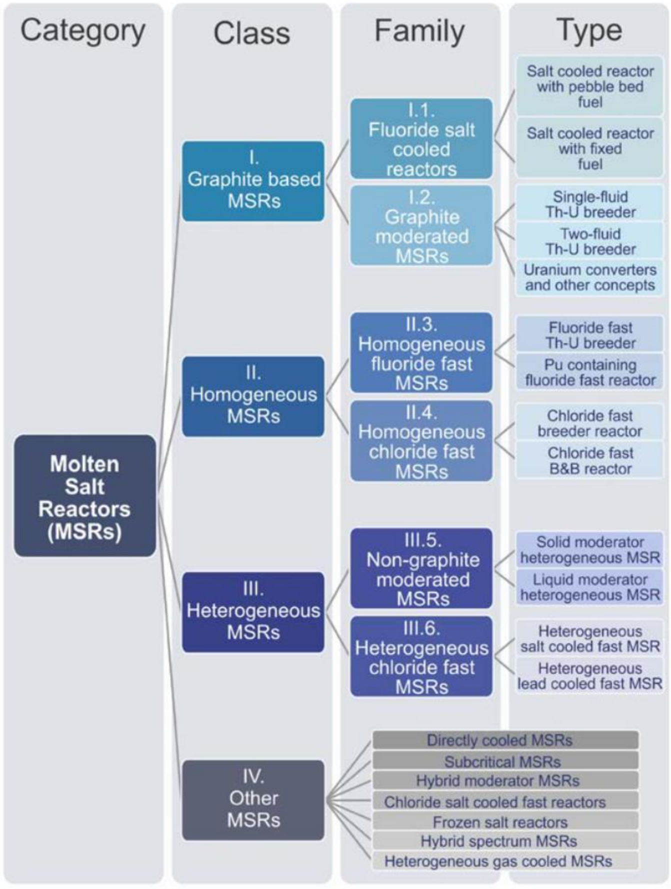
Generation IV and Uncertainties

Relevance

- Worldwide interest in different Generation IV realizations
- Some Gen-IV reactors are under construction
- Interest in Best Estimate Plus Uncertainty (BEPU)

Challenges:

- Accurately predict the core behavior
- Different from LWRs physics (materials, geometry, temperatures, fuel, spectra, etc.)
- Limited nuclear data (basis for every neutron transport simulation!!!)
- Limited material property data
- Limited experimental (validation) base



Example of an MSR classification [1]

[1] IAEA, 2023. Status of molten salt reactor technology (No. STI/DOC/010/489). International Atomic Energy Agency, Vienna, Austria.

Uncertainties in Generation IV

Uncertainty Sources

Uncertainty Types:

- Modeling
- Numerical
- Nuclear data

Nuclear data are considered as a main uncertainty source

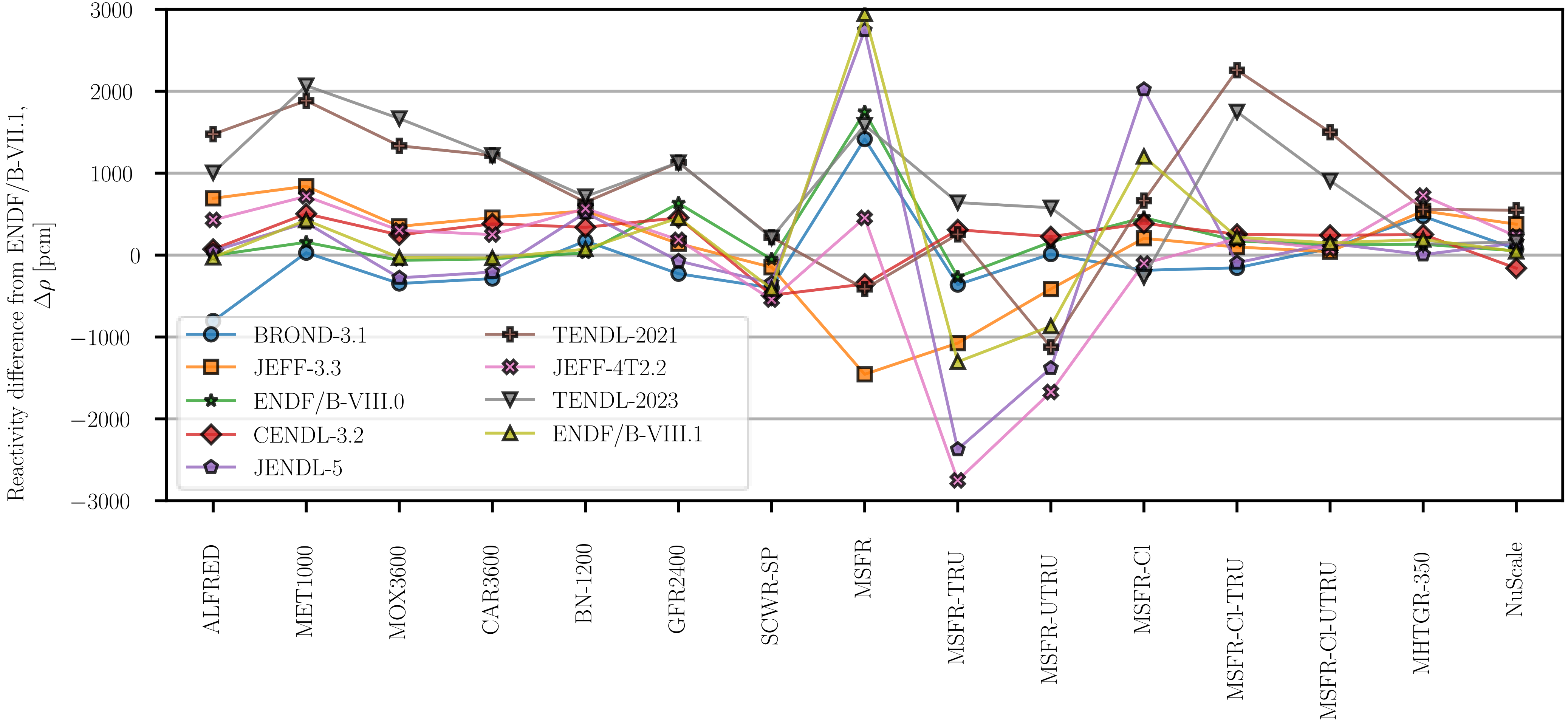
Sensitivity and uncertainty analysis with respect to nuclear data

Eigenvalue of MOX3600 with different nuclear data via OpenMC

Library	k	$\Delta\rho$ [pcm]
ENDF/B-VII.1	1,01198(6)	(ref)
BROND-3.1	1,00844(6)	-347(8)
JEFF-3.3	1,01559(5)	351(8)
ENDF/B-VIII.0	1,01131(5)	-65(8)
CENDL-3.2	1,01451(6)	246(8)
JENDL-5	1,00914(5)	-278(8)
TENDL-2021	1,02583(6)	1334(8)
JEFF-4T2.2	1,01508(5)	302(8)
TENDL-2023	1,02935(6)	1667(8)
ENDF/B-VIII.1	1,01167(6)	-30(8)
JEFF-4	1,01780(6)	565(8)

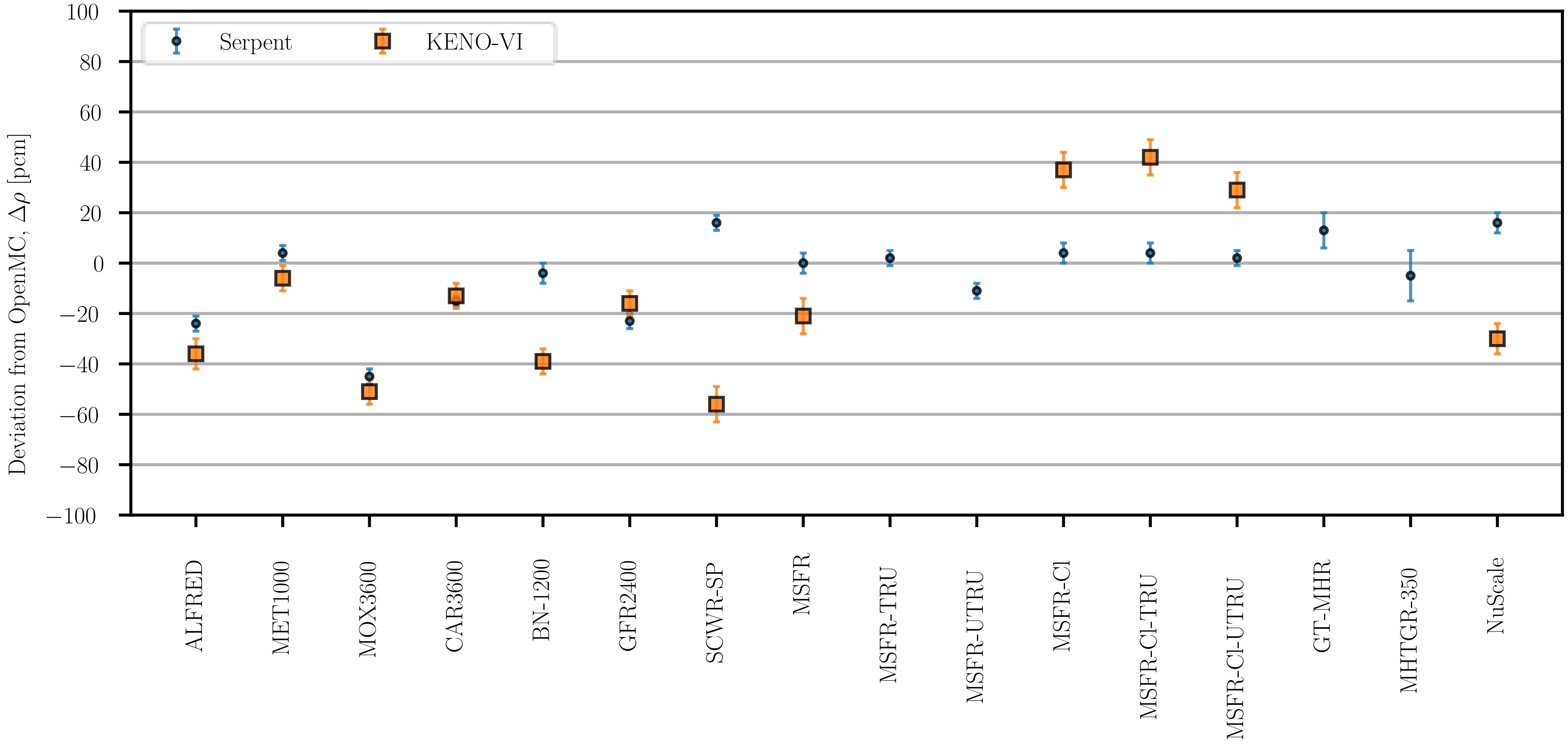
Effect of different libraries in simulation for k

Eigenvalue deviation with different libraries from ENDF/B-VII.1



Effect of different tools in simulation for k

Eigenvalue deviation for Serpent and SCALE/KENO-VI from OpenMC



The influence of difference in stochastic transport codes is < 0,05% — significantly lower than one of ND

Sensitivity and uncertainty analysis

Perturbation-based Approach

- provides the uncertainties of chosen responses (eigenvalues, reactivity coefficients, etc.) to ensure appropriate safety margins are set
- provides the sources of the uncertainties
- allows assessing nuclear data performance
- allows identifying data requiring the attention
- allows finding the current nuclear data gaps

Sensitivity Analysis

$$S(R,\alpha) \equiv \frac{\alpha}{R}\frac{\mathrm{d}R}{\mathrm{d}\alpha}$$

Perturbation Theory*

$$S(k,\alpha) = \frac{\alpha}{k}\frac{\mathrm{d}k}{\mathrm{d}\alpha} = -\alpha\frac{\left\langle \psi^*, \left(\frac{\partial \hat{A}}{\partial \alpha} - \frac{1}{k}\frac{\partial \hat{F}}{\partial \alpha}\right)\psi\right\rangle}{\left\langle \psi^*, \frac{1}{k}\hat{F}\psi\right\rangle} + \mathcal{O}(\delta\psi)$$

Uncertainty Analysis

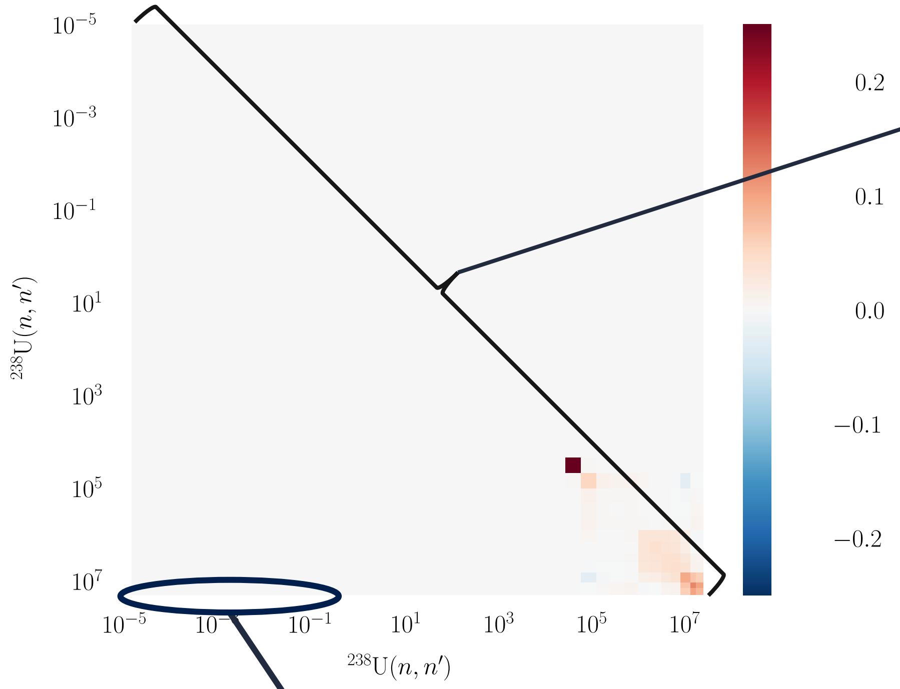
$$\delta R(\alpha) = \sqrt{SCS^T}$$

C — the covariance matrix

*An example for the eigenvalue k

Covariance Matrices

An example of covariance matrix for $^{238}\mathrm{U}(n,n')$ from ENDF/B-VII.1

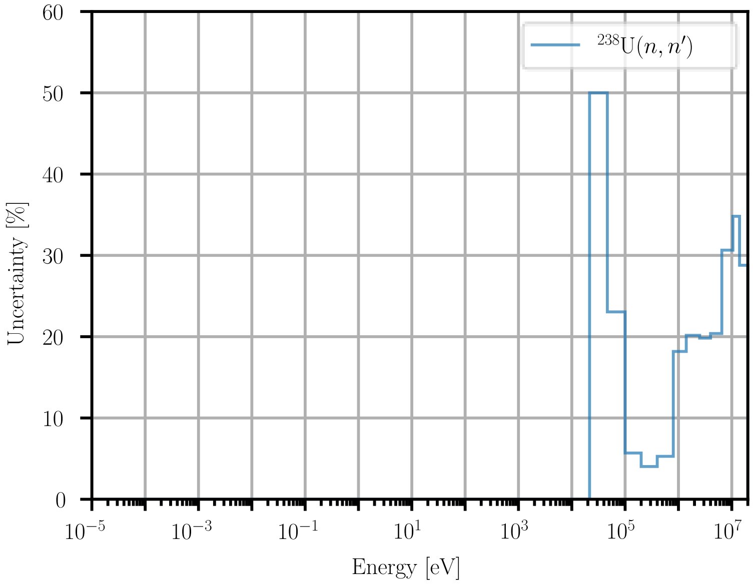


Diagonal=Variances

$\mathrm{var}(\sigma_{\mathrm{U238}(n,f),g})$

Uncertainty

$\sqrt{\mathrm{var}(\sigma_{\mathrm{U238}(n,n'),g})}$



Covariance between g=28 and g=1 for $^{238}\mathrm{U}(n,n')$

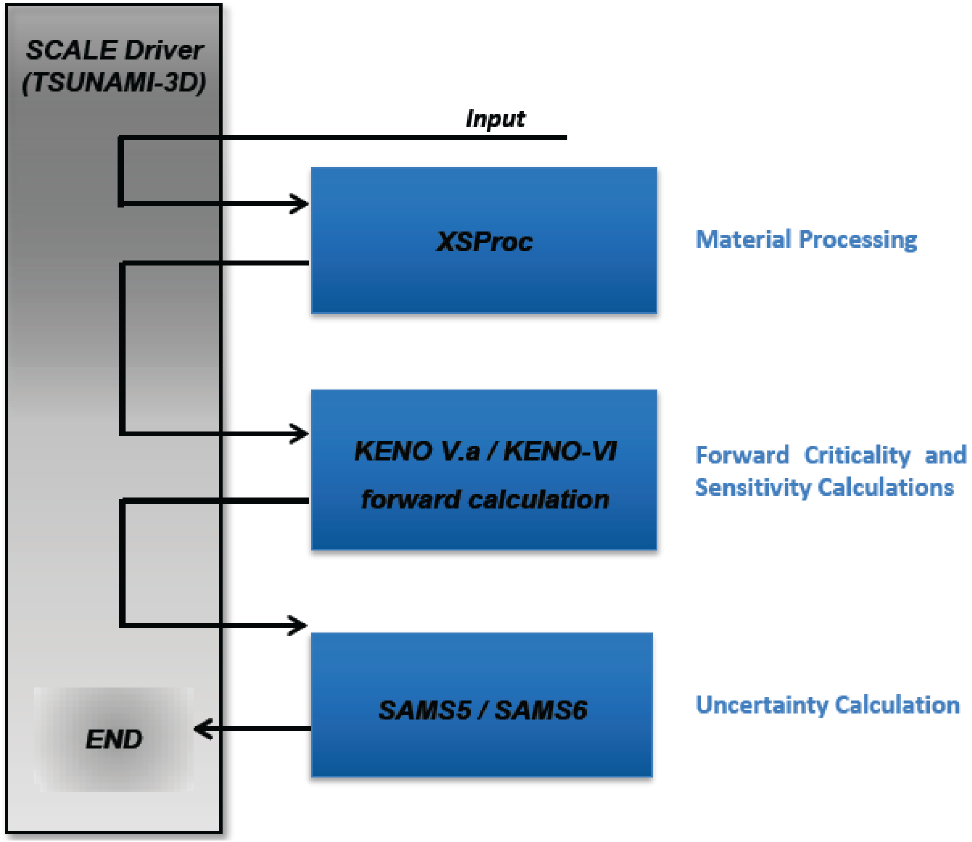
Tools for Computing Sensitivities

SCALE

- SCALE has a set of modules/sequences for sensitivity and uncertainty analyses (see TSUNAMI-3D example
- Pre-prepared covariance data

Serpent

- Serpent is only capable of computing sensitivity (though it is able to use AMPX covariance data)
- No openly available covariance data (including SCALE's)
- One must prepare covariance data from ENDF-6 files

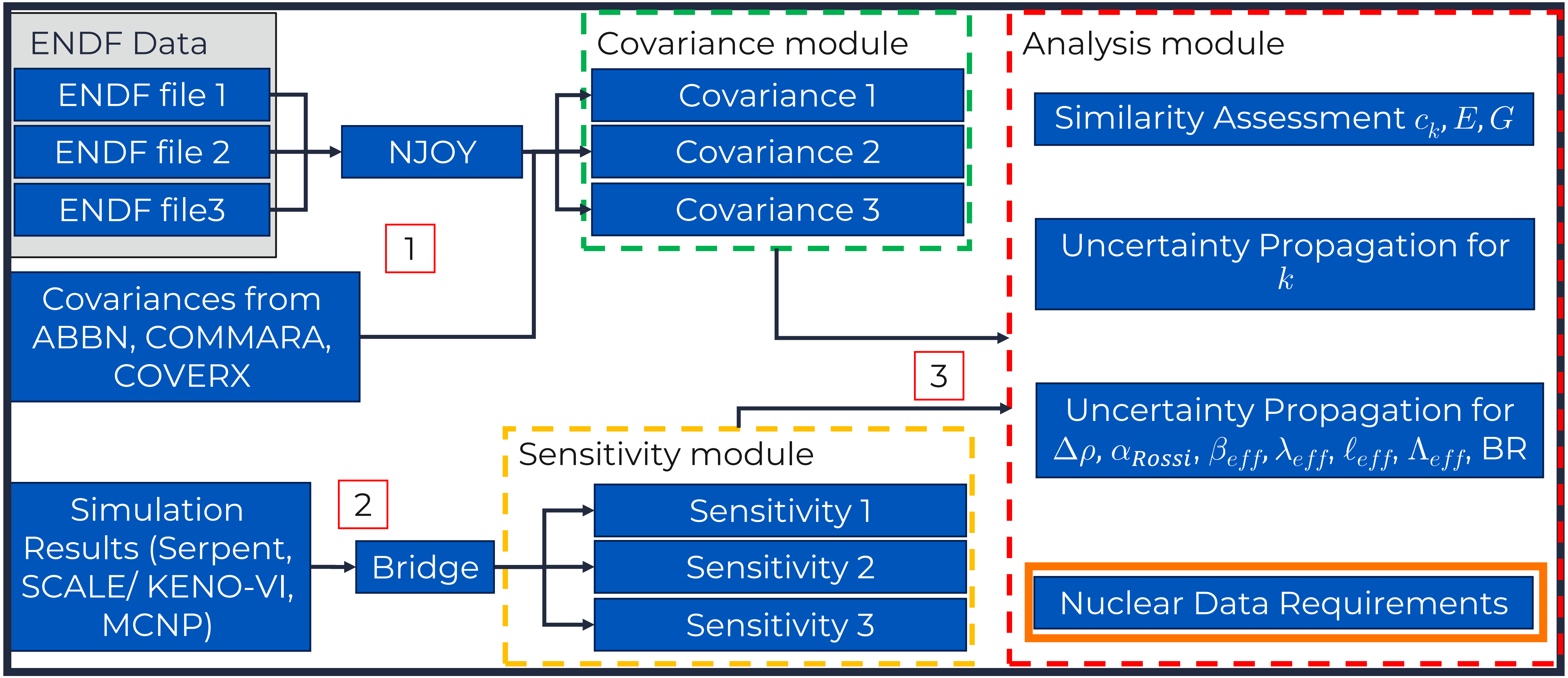


Sensitivity and uncertainty analysis sequence of SCALE/TSUNAMI-3D (CE) [1]

[1] SCALE Code System, ORNL/TM-2005/39, Version 6.2.4, Oak Ridge National Laboratory, Oak Ridge, TN, US. Available from Radiation Safety Information Computational Center as CCC-834.

SAUNA (Sensitivity And UNcertainty Analysis)

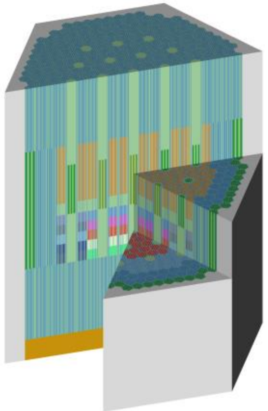
SAUNA: A Python package for Systematic Sensitivity and Uncertainty Analysis



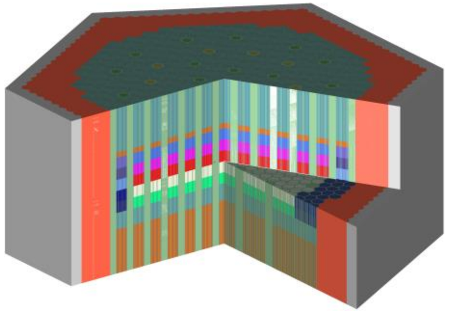
Advanced Nuclear Reactors (16 models)

The models were developed for SCALE (KENO-VI), Serpent, and OpenMC

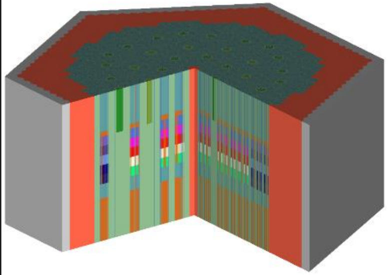
SFR (4)



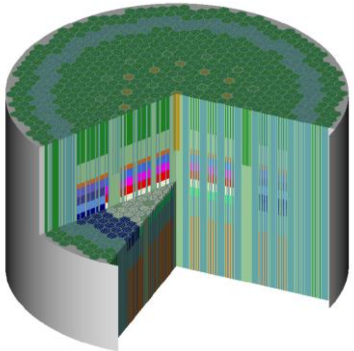
MET1000 $(\mathrm{U-TRU-Zr})$



CAR3600 (UPuC)

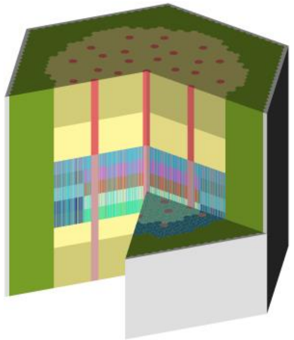


MOX3600 (MOX)



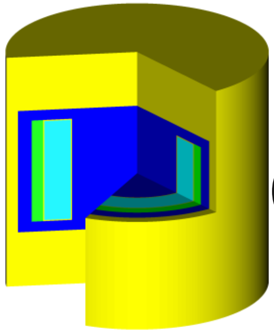
БН-1200 (UPuN)

GFR (1)



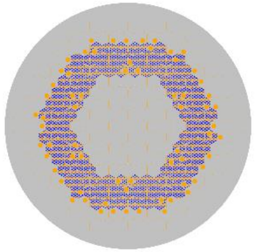
GFR2400 (UPuC)

MSR (6)

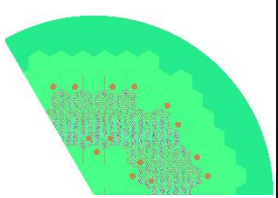


MSFR
MSFR-Cl
$(\mathrm{TRU-Th})$
$(\mathrm{UTRU-Th})$
$(^{233}\mathrm{U-Th})$

VHTR (2)

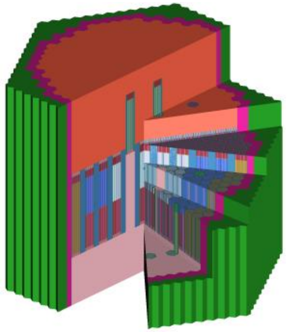


GT-MHR (PuC)



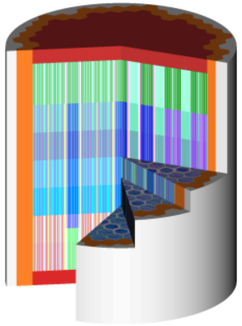
MHTGR-350 (UOC)

LFR (1)



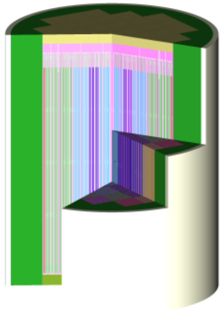
ALFRED (MOX)

SCWR (1)



SCWR-SP (MOX)

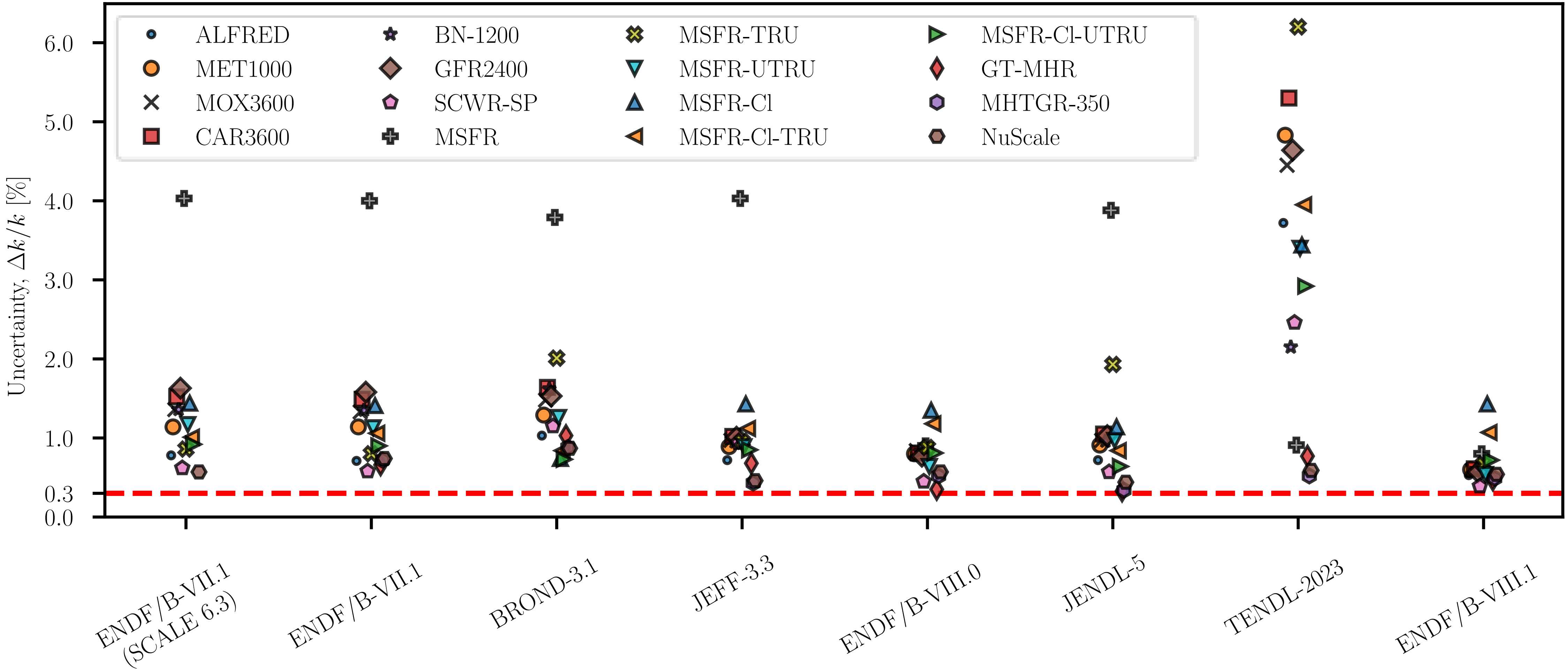
SMR (PWR) III+ (1)



NuScale $(\mathrm{UO_2})$

Uncertainty Propagation for k

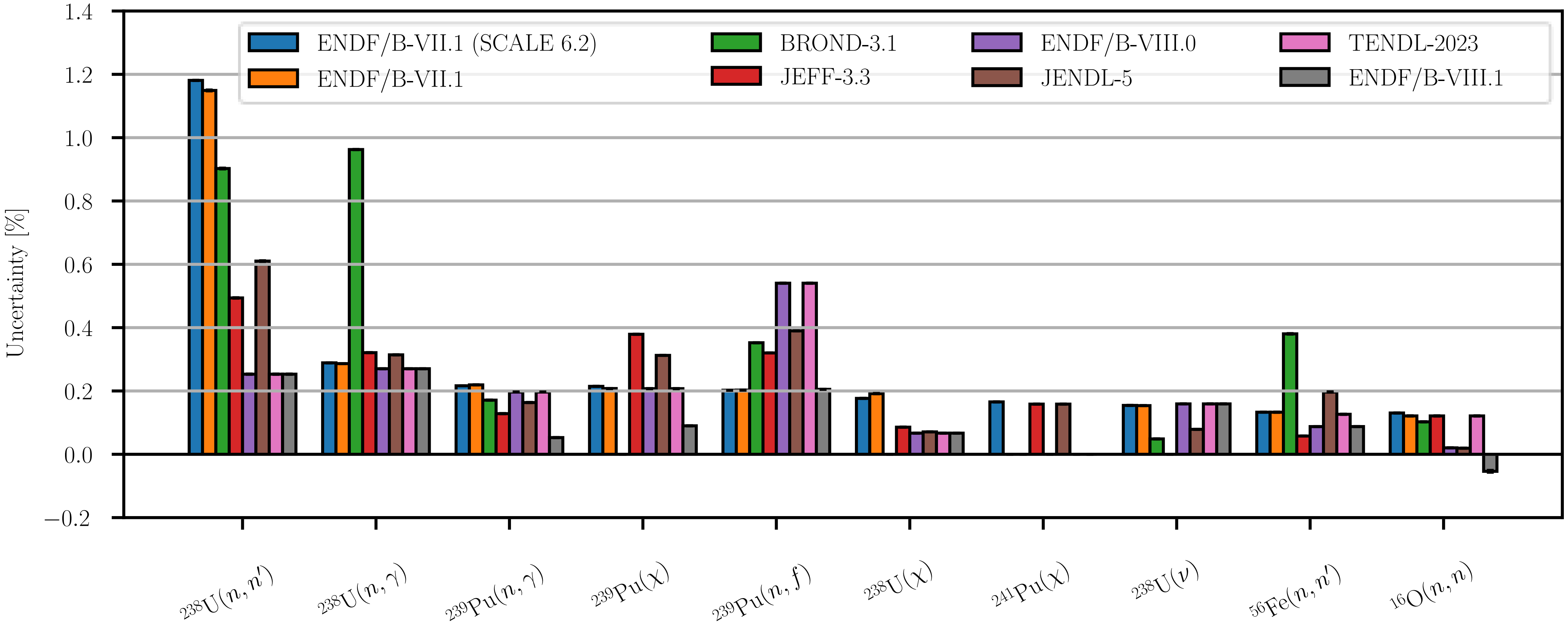
Nuclear data uncertainty for advanced nuclear reactor systems



Target Accuracy Requirements for k ~0,3% (Nikolaev, 2013, Andrianov et al., 2023, Cabellos et al., 2024)

Nuclear Data Uncertainty Sources for k

An example of uncertainty breakdown for the MOX3600 model



The target accuracy requirement (TAR) problem

The optimization problem

$$\begin{cases} \min\limits_{\delta\alpha_i} \sum\limits_{i=1} \dfrac{\lambda_i}{\delta\alpha_i^2} \\ \delta R_j(\alpha) \le \delta R_{j,TAR} \\ (\delta\alpha_i)_{min} \le \delta\alpha_i \le (\delta\alpha_i)_0 \end{cases}$$

Parameter costs from WPEC/SG26

Nuclides	Reaction	λ_i
^{235}U, ^{238}U, ^{239}Pu	$(n,\gamma), (n,f), (\nu)$	1
Fuel	$(n,\gamma), (n,f), (\nu)$	2
Non-fuel	(n,γ)	1
All	(n,n)	1
The others	The others	3

λ_i — the cost parameter

$\delta\alpha_i$ — the uncertainty of parameter i (cross sections,...)

$\delta R_{j,TAR}$ — the target uncertainty of output j

$(\delta\alpha_i)_{min}$ — the minimum achievable uncertainty of parameter i

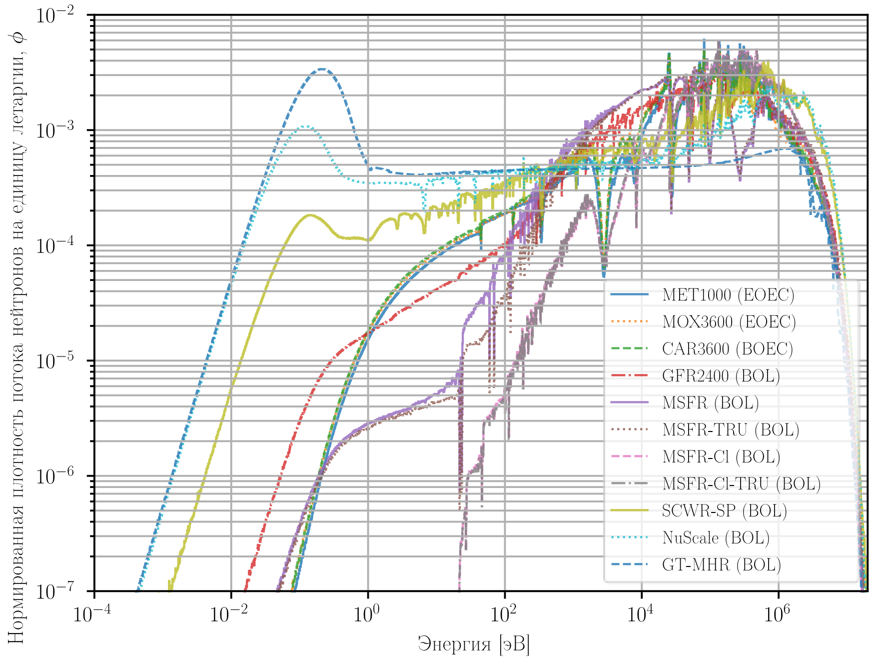
$(\delta\alpha_i)_0$ — the initial uncertainty of parameter i

The problem is solved in the 7-group approximation of WPEC/SG46

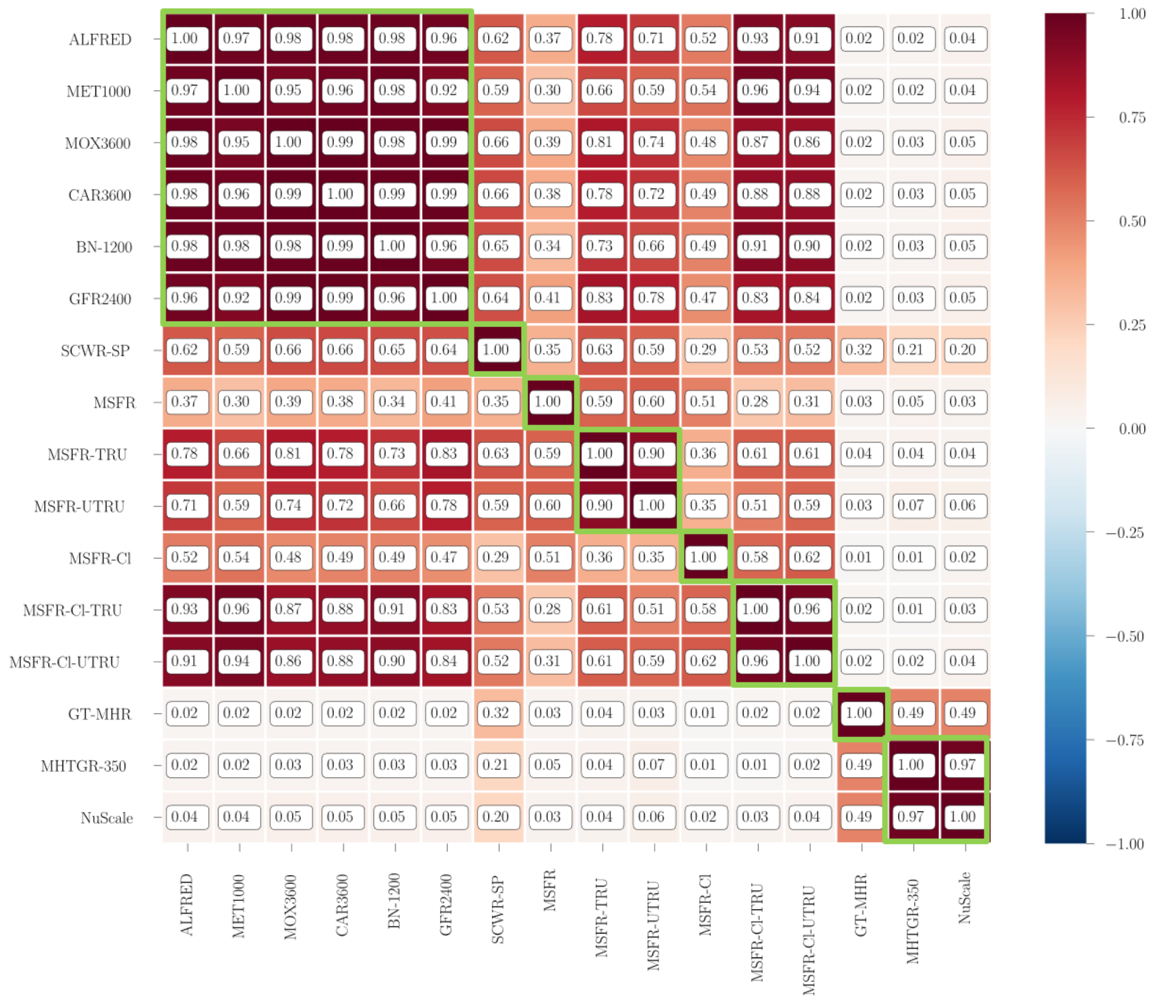
WPEC – Working Party on International Nuclear Data Evaluation Co-operation (NEA/OECD)

Generalize the Nuclear Data Needs

Selecting Models for the Analysis



Neutron Flux per Unit Lethargy ϕ_u



Correlation Index E (average cosine between two sensitivity vectors) for the Eigenvalue k

Target Accuracy Requirements

The solution of the optimization problem

Target Accuracy Requirements for MOX3600 as an example

Reaction	**Uncertainty, $\Delta k/k$ [%]**	
	Initial	Target
$^{238}\mathrm{U}(n,n')$	1,04	0,07
$^{238}\mathrm{U}(n,\gamma)$	0,24	0,12
$^{239}\mathrm{Pu}(n,\gamma)$	0,21	0,05
$^{239}\mathrm{Pu}(\chi)$	0,21	0,05
$^{239}\mathrm{Pu}(n,f)$	0,20	0,20
Total	1,20	0,31*

*Only top 20 matrices were tweaked

Target Accuracy Requirements

TARs for Fast Reactors with UPu Fuel

Reaction	Group	Uncertainty [%]	
		Initial	Target
$^{238}\mathrm{U}(n,n')$	2	16,9	0,8
	1	19,3	0,8
$^{238}\mathrm{U}(n,\gamma)$	4	1,6	0,5
$^{239}\mathrm{Pu}(n,\gamma)$	4	8,2	1,3
$^{56}\mathrm{Fe}(n,n')$	2	11,6	1,6
$^{14}\mathrm{N}(n,\alpha)$	1	23,6	1,4
$^{14}\mathrm{N}(n,p)$	1	31,5	2,3
	2	24,8	1,6

This reduces the contribution from the $^{238}\mathrm{U}(n,n')$ uncertainties in groups 1 and 2 by 38 and 34 раз times: from 0,58% to 0,02%

TARs for Thermal Reactors with U Fuel

Reaction	Group	Uncertainty [%]	
		Initial	Target
$^{238}\mathrm{U}(n,\gamma)$	7	1,8	0,5
$^{235}\mathrm{U}(\nu)$	7	0,7	0,2
$^{235}\mathrm{U}(n,\gamma)$	7	1,6	0,4
$^{1}\mathrm{H}(n,\gamma)$	7	2,6	0,8

The TARs for thermal systems are rather too optimistic and can be further reduced via integral experiments

Summary

1. Countries develop Gen-IV systems
2. Uncertainty quantification is crucial for designing new generation system in the frame of lack in experience
3. A series of models has been developed to systematically assess the influence of nuclear data in Gen-IV nuclear reactors
4. Nuclear data uncertainties were propagated; it is shown that they introduce uncertainties larger than ones from tools
5. Uncertainty propagation results provided the base for nuclear data needs for Gen IV reactors via SAUNA

Thank you for your attention!