Joint UPM and CIEMAT contribution: Progress on European Sodium Fast Reactor (ESFR)

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Outline

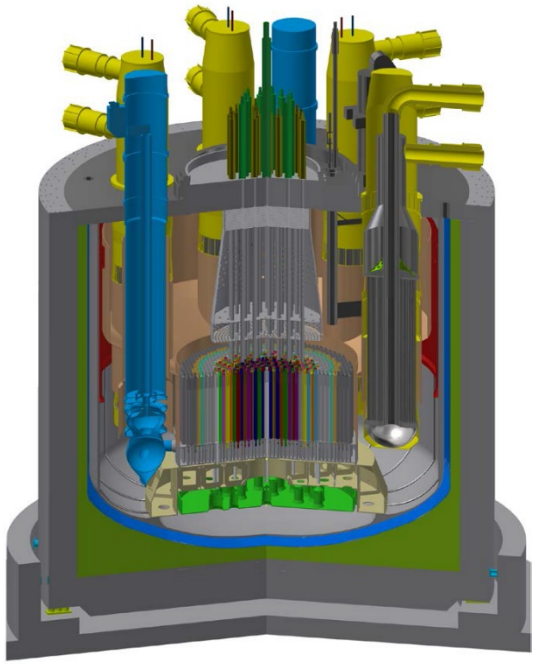
1. Introduction
2. Computational tools
3. Models
4. S/U analyses
5. Data assimilation
6. Outlook

1. Introduction

- **WP1.2: Normal operation of the ESFR-SMART**
  - T1.2.2: Uncertainties in the mapping of Doppler and void reactivity for the EoC ESFR core

S/U and data assimilation for the co-development of nuclear data and ESFR

- S/U for main integral parameters
- Selection of useful integral experiments
- Data assimilation (ongoing)



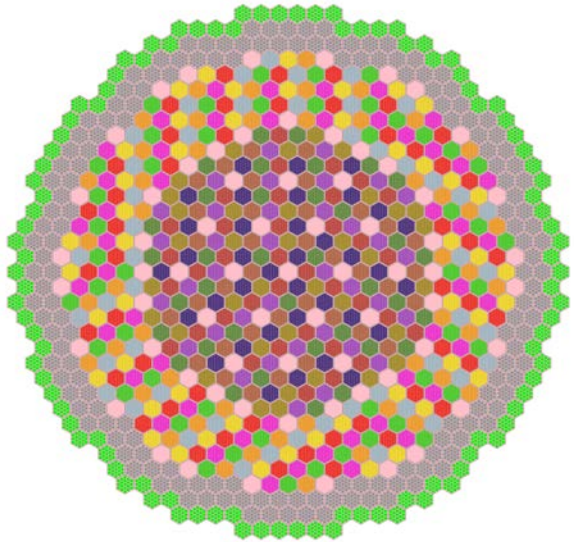
2. Computational tools

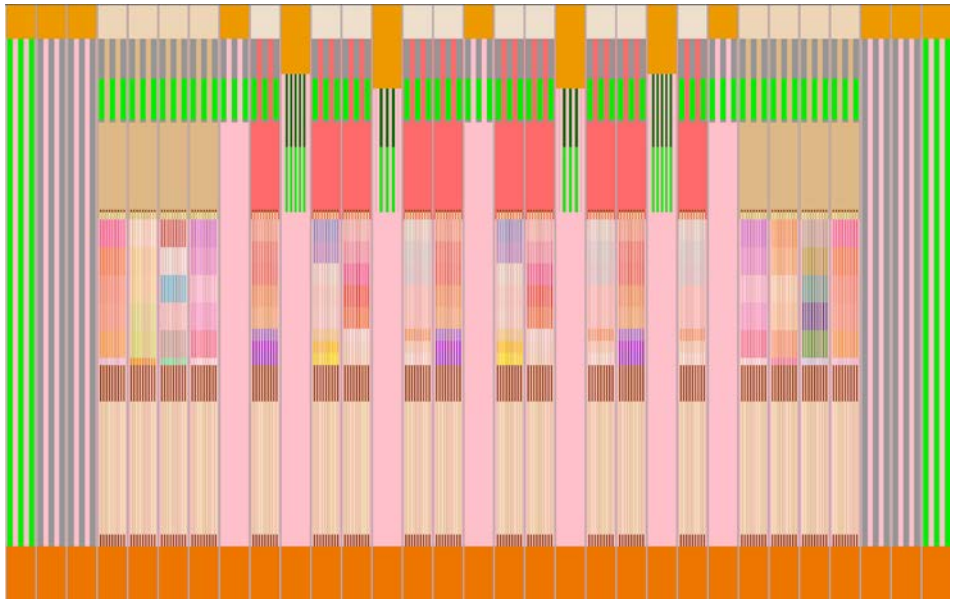
- **SCALE 6.2.3**
  - **TSUNAMI-3D continuous energy (CE) as reference module**
    - Linear perturbation theory
    - Transport solver KENO-VI
    - Eigenvalue sensitivities: CLUTCH
    - CE JEFF-3.1 XS data (AMPX-processed at UPM)
    - Covariance data: SCALE6.2-56g (ENDF/B-VII.1 based), JEFF-3.3 and ENDF/B-VIII.0
  - **TSAR module**
    - Reactivity response sensitivity: eigenvalue-difference response + 1st order perturbation theory
- **Data assimilation with SUMMON (DAWN)**
  - Based on Bayesian inference and GLS technique

3. Models: actual ESFR core

Heterogeneous 3D ESFR core

- 3600 MWth sodium cooled fast reactor
- MOX-fueled inner core (216 hex. assemblies) and outer core (288 hex. assemblies)
- Multibatch core model containing 84 burnable regions
- EoC conditions (M. Margulis et al., ESFR-SMART deliverable D1.2.2)

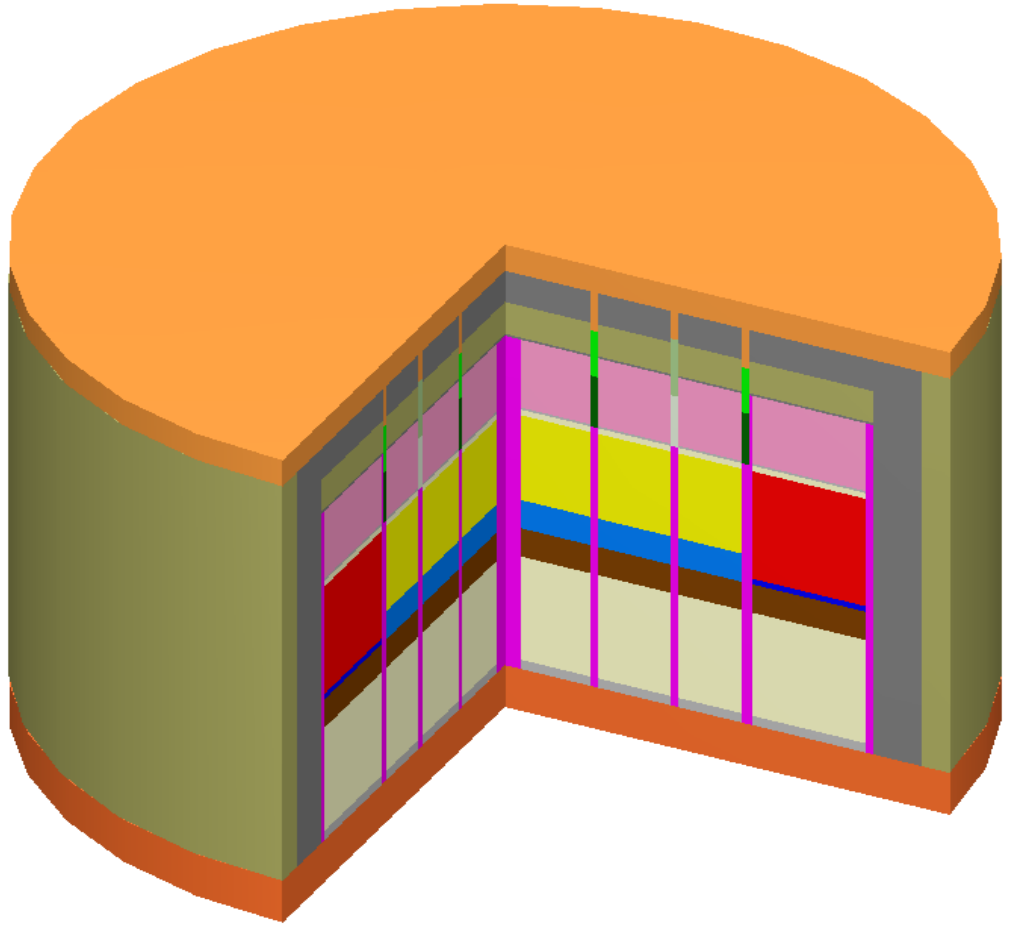




3. Models: simplified ESFR core

Homogeneous R-Z ESFR model

- R-Z model for systematic S/U analyses
- Volumes of zones adjusted to maintain masses
- Dimensions and materials collected in an Excel spreadsheet and sent to WPEC/SG46 (July 2020 after approval of the ESFR-SMART Governing Board)

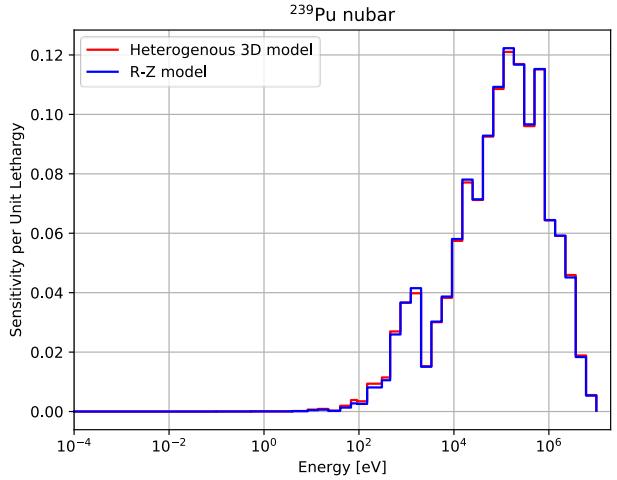


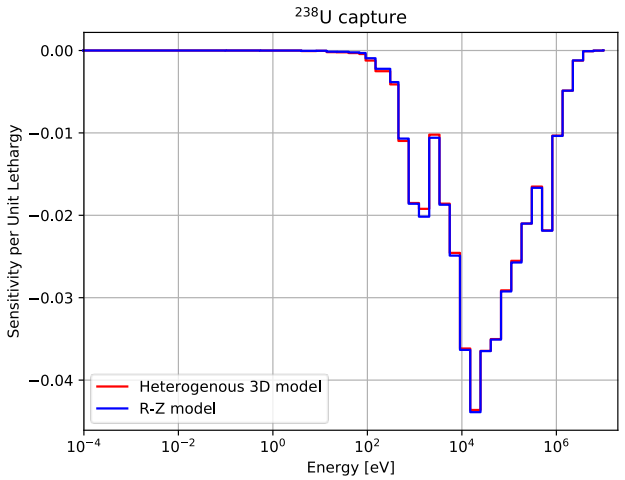
3. Models: impact of R-Z approximation

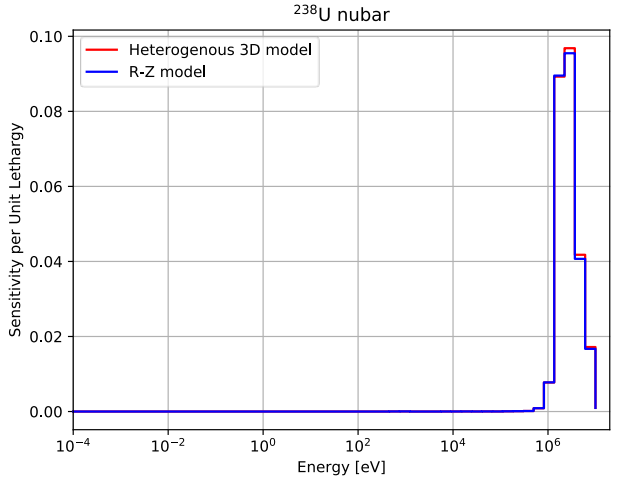
k_{eff} integrated sensitivity coefficients $\left(\frac{\Delta k/k}{\Delta \Sigma/\Sigma}\right)$ with TSUNAMI-3D CE and JEFF-3.1

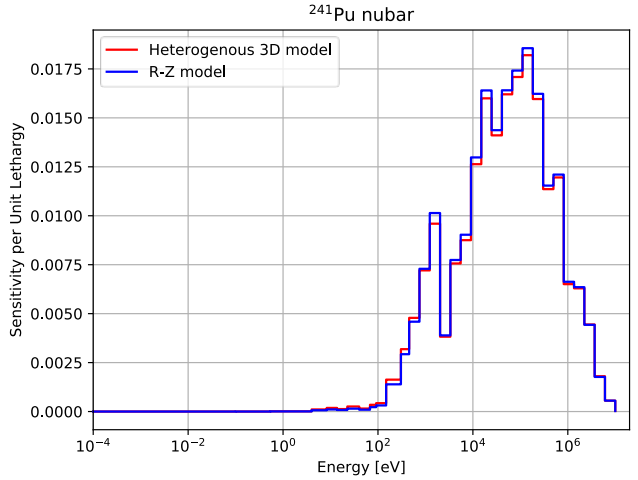
Quantity	Heterogeneous 3D (%/%)	R-Z (%/%)	Relative deviation (%)
Pu-239 nubar	$6.3496 \cdot 10^{-1} \pm 9.6 \cdot 10^{-5}$	$6.3444 \cdot 10^{-1} \pm 7.9 \cdot 10^{-5}$	0.08
Pu-239 fission	$4.7317 \cdot 10^{-1} \pm 9.8 \cdot 10^{-5}$	$4.7407 \cdot 10^{-1} \pm 8.0 \cdot 10^{-5}$	−0.19
U-238 (n,γ)	$-1.9655 \cdot 10^{-1} \pm 4.7 \cdot 10^{-5}$	$-1.9723 \cdot 10^{-1} \pm 3.7 \cdot 10^{-5}$	−0.45
U-238 nubar	$1.2774 \cdot 10^{-1} \pm 7.0 \cdot 10^{-5}$	$1.2643 \cdot 10^{-1} \pm 5.5 \cdot 10^{-5}$	1.04
Pu-241 nubar	$1.0068 \cdot 10^{-1} \pm 5.6 \cdot 10^{-5}$	$1.0190 \cdot 10^{-1} \pm 5.2 \cdot 10^{-5}$	−1.20
Pu-240 nubar	$8.1273 \cdot 10^{-2} \pm 5.4 \cdot 10^{-5}$	$8.1419 \cdot 10^{-2} \pm 4.4 \cdot 10^{-5}$	−0.18
U-238 fission	$7.6853 \cdot 10^{-2} \pm 7.1 \cdot 10^{-5}$	$7.6306 \cdot 10^{-2} \pm 5.6 \cdot 10^{-5}$	−0.64
Pu-241 fission	$7.6214 \cdot 10^{-2} \pm 5.7 \cdot 10^{-5}$	$7.7346 \cdot 10^{-2} \pm 5.2 \cdot 10^{-5}$	−0.12
U-238 (n,n')	$-7.5041 \cdot 10^{-2} \pm 1.8 \cdot 10^{-4}$	$-7.3781 \cdot 10^{-2} \pm 1.6 \cdot 10^{-4}$	1.71
O-16 elastic	$-6.1044 \cdot 10^{-2} \pm 1.1 \cdot 10^{-3}$	$-6.1258 \cdot 10^{-2} \pm 8.8 \cdot 10^{-4}$	−0.35
Pu-239 (n,γ)	$-4.1989 \cdot 10^{-2} \pm 1.5 \cdot 10^{-5}$	$-4.1352 \cdot 10^{-2} \pm 1.2 \cdot 10^{-5}$	1.54
Fe-56 (n,n')	$-2.0437 \cdot 10^{-2} \pm 6.9 \cdot 10^{-5}$	$-2.2033 \cdot 10^{-2} \pm 6.1 \cdot 10^{-5}$	**−7.24**
Fe-56 (n,γ)	$-1.0036 \cdot 10^{-2} \pm 7.3 \cdot 10^{-6}$	$-1.0255 \cdot 10^{-2} \pm 6.0 \cdot 10^{-6}$	**−2.14**
Na-23 (n,n')	$-7.2866 \cdot 10^{-3} \pm 4.9 \cdot 10^{-5}$	$-7.8449 \cdot 10^{-3} \pm 4.2 \cdot 10^{-5}$	**−7.12**

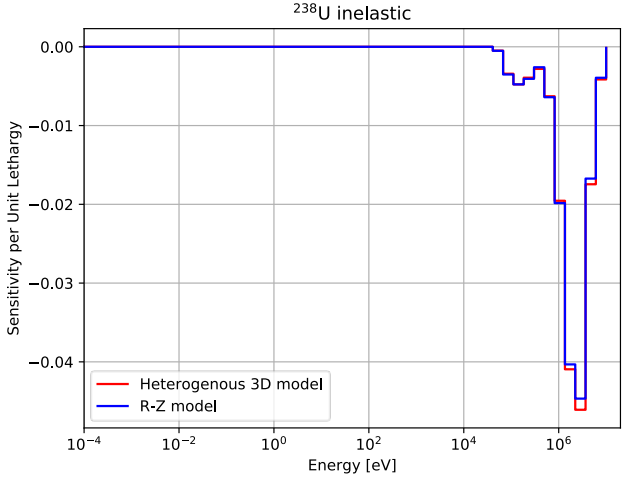
3. Models: impact of R-Z approximation

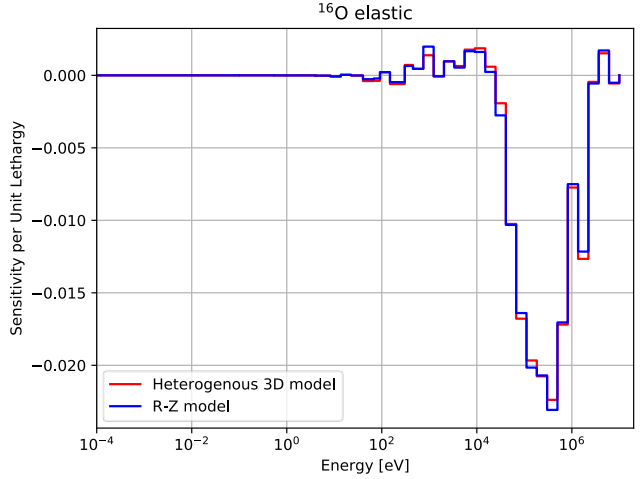


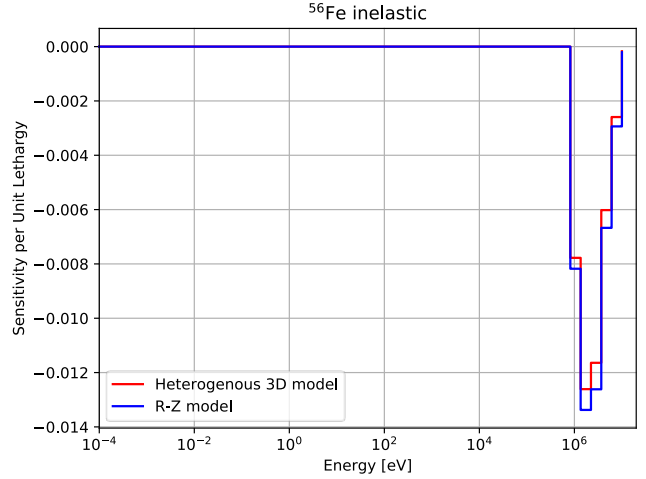


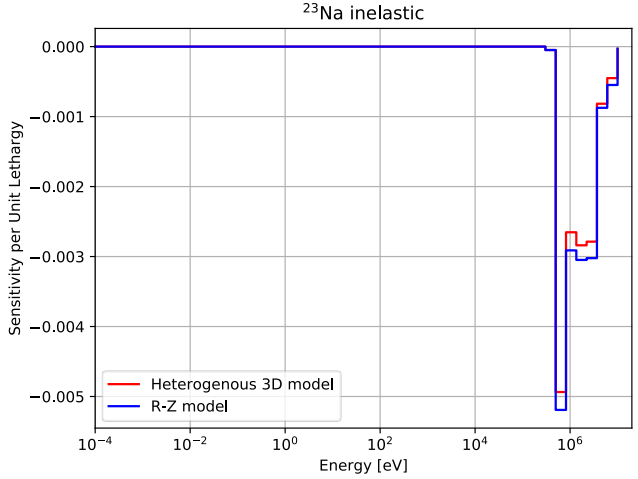








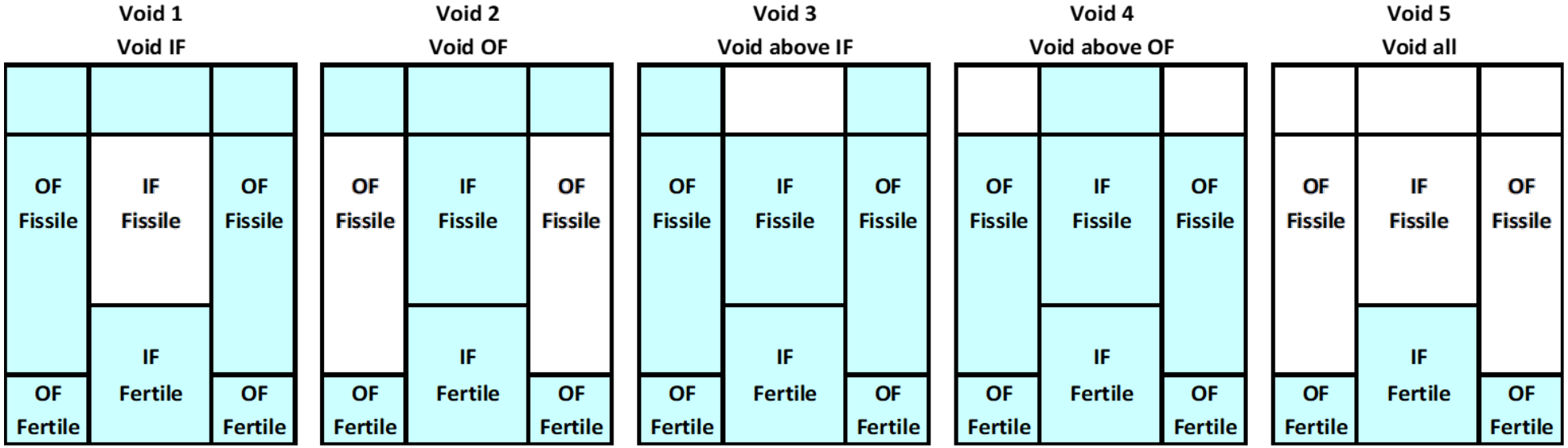




4. S/U analyses

S/U analyses for R-Z model with TSUNAMI-3D CE for the following integral parameters:

- k_{eff}
- Sodium void scenarios (see figure below)
- Doppler coefficient
- Control rod worth



4. S/U analyses: results

Parameter	TA (%)	Unc. (%) SCALE-6.2	Unc. (%) JEFF-3.3	Unc. (%) ENDF/B-VIII.0
k_{eff}	0.3	**1.35**	**1.05**	**0.80**
Sodium void worth	7	**11.5**	**8.5**	**11.2**
Doppler effect(+300 K)	7	**6.3**	**4.0**	**3.5**
Control rod worth	7	**2.4**	**1.9**	**1.3**

Target accuracies exceeded for k_{eff} and for SVR

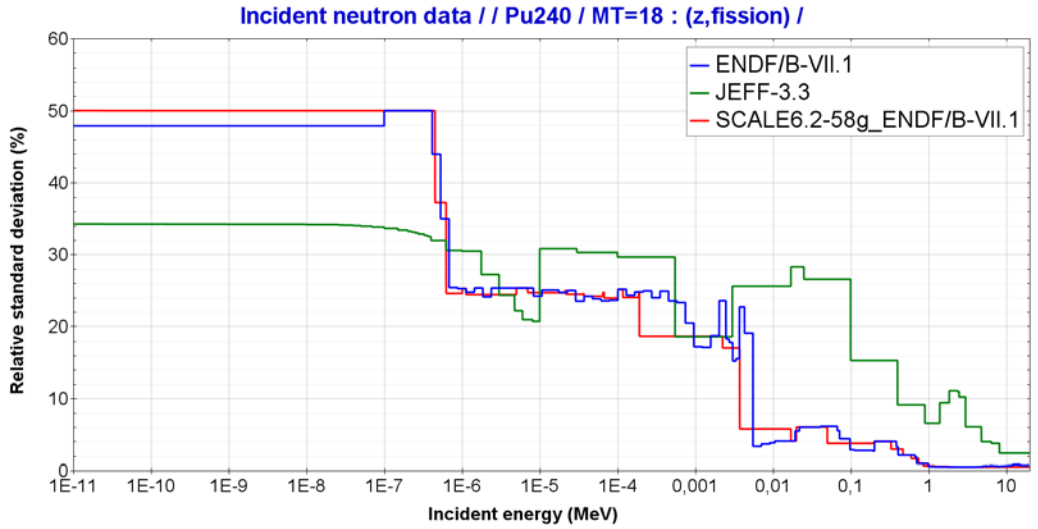
4. S/U analyses: k_{eff}

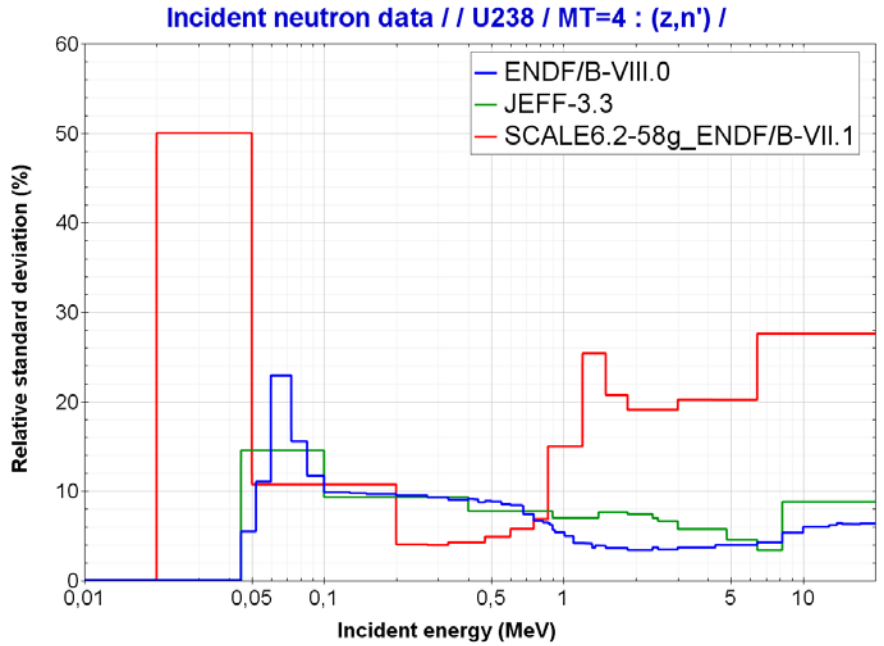
Quantity	$\Delta k_{eff}/k_{eff}$ (%)		
	SCALE6.2-56g	JEFF-3.3	ENDF/B-VIII.0
U-238 inelastic	1.1740	**0.4796**	0.2394
U-238 capture	0.2550	**0.3026**	0.2534
Pu-239 capture	0.2179	0.1193	0.2026
Pu-239 χ	0.2004	**0.4526**	0.2207
U-238 inelastic-elastic	0.1958	0.0927	0.0728
Pu-239 fission	0.1948	**0.3070**	0.5541
U-238 χ	0.1689	0.1059	0.0734
Pu-241 χ	0.1681	0.1853	-
U-238 nubar	0.1494	0.1218	0.1540
Fe-56 inelastic	0.1387	0.0608	0.0915
O-16 elastic	0.1219	0.1219	0.0198
Na-23 inelastic	0.0928	0.0198	0.0918
Pu-240 capture	0.0809	0.1794	0.0836
Pu-240 fission	0.0659	**0.5940**	0.0643
Pu-239 nubar	0.0555	**0.2935**	0.1730
Pu-241 fission	0.0519	0.0954	0.0538
U-238 fission	0.0399	0.2003	0.0933
Total uncertainty	**1.3457**	**1.0453**	**0.8027**

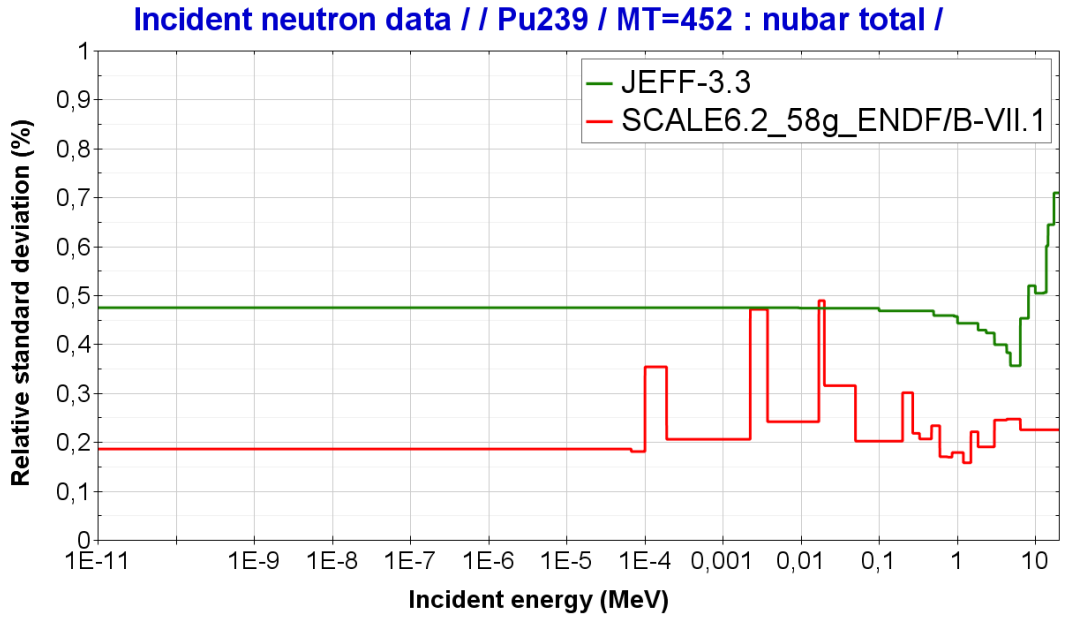
4. S/U analyses: k_{eff}

Uncertainties reported in different covariance evaluations:

- U-238 (n, n')
- Pu-240 fission
- Pu-239 ν

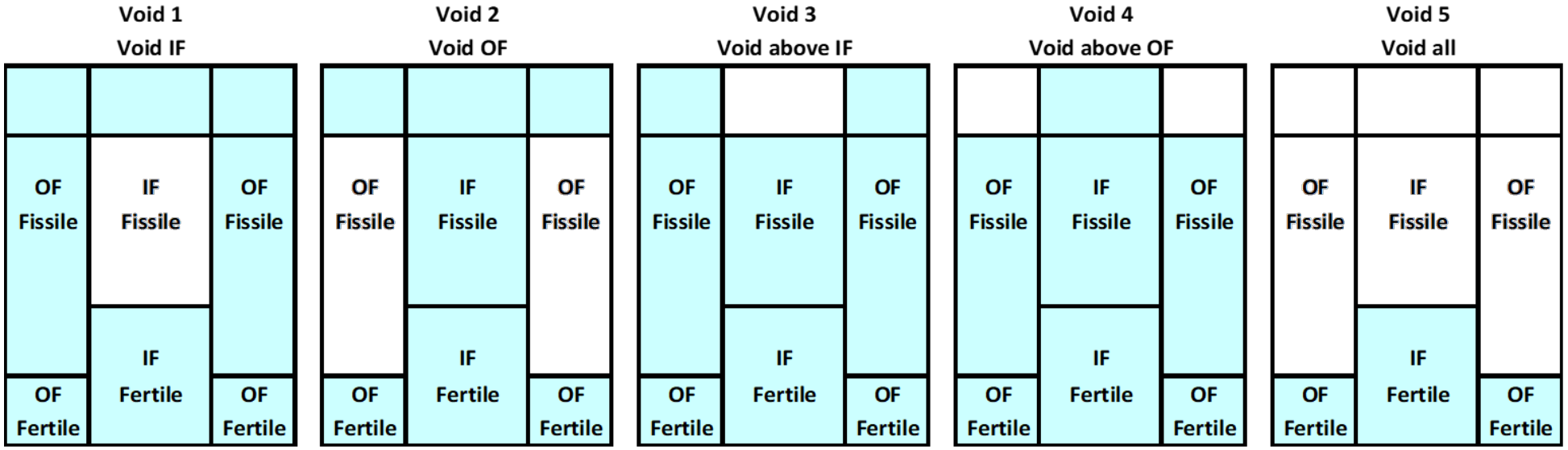




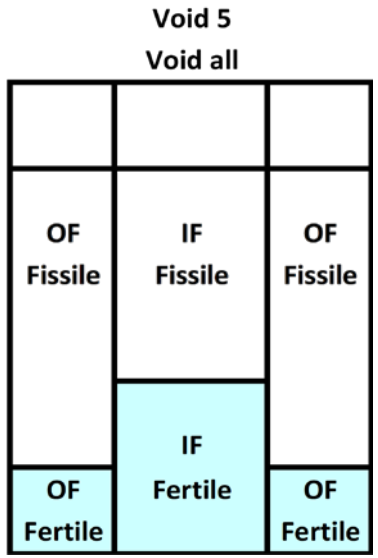


4. S/U analyses: sodium void scenarios

Scenario	Het. 3D void worth (pcm)	CE TSUNAMI-3D			
		RZ void worth (pcm)	Nuclear data uncertainty (pcm)		
			SCALE6.2-56g	JEFF-3.3	ENDF/B-VIII.0
1	954	1116 ± 12	57.7 ± 0.6 (5.2%)	43.7 (3.9%)	59.9 (5.4%)
2	755	1013 ± 12	69.1 ± 0.7 (6.8%)	50.7 (5.0%)	70.5 (7.0%)
3	-610	-445 ± 13	18.8 ± 1.0 (4.2%)	14.7 (3.3%)	11.5 (2.6%)
4	-466	-427 ± 12	17.4 ± 1.0 (4.1%)	14.5 (3.4%)	11.1 (2.6%)
5	269	989 ± 12	114 ± 0.6 (11.5%)	84.1 (8.5%)	110.5 (11.2%)



4. S/U analyses: sodium void scenario 5



Quantity	$\Delta\rho$ ISC (%/%)
Pu-239 nubar	$-1.26 \cdot 10^{0} \pm 1 \cdot 10^{-2}$
U-238 (n,γ)	$9.94 \cdot 10^{-1} \pm 5 \cdot 10^{-3}$
Na-23 elastic	$7.64 \cdot 10^{-1} \pm 8 \cdot 10^{-2}$
Na-23 (n,n')	$6.04 \cdot 10^{-1} \pm 5 \cdot 10^{-3}$

SCALE6.2		JEFF-3.3		ENDF/B-VIII.0	
Reaction	$\Delta\rho/\rho$ (%)	Reaction	$\Delta\rho/\rho$ (%)	Reaction	$\Delta\rho/\rho$ (%)
Na-23 inelastic	$\mathbf{6.96 \pm 0.01}$	Pu-239 fission	$\mathbf{6.26}$	Na-23 inelastic	$\mathbf{6.89}$
U-238 inelastic	$\mathbf{5.34 \pm 0.03}$	Pu-239 capture	2.77	Pu-239 fission	$\mathbf{6.35}$
Na-23 elastic	$\mathbf{4.87 \pm 0.04}$	U-238 inelastic	2.52	Na-23 elastic	$\mathbf{4.86}$
U-238 capture	2.59 ± 0.00	U-238 capture	2.33	Pu-239 capture	2.65
U-238 inel-elastic	2.58 ± 0.03	Na-23 elastic	2.28	U-238 capture	1.85
Fe-56 elastic	2.57 ± 0.02	Na-23 capture	1.69	U-238 inelastic	1.45

4. S/U analyses: Doppler coefficient

Inner core fissile fuel +300K

RZ temperature. reactivity (pcm)	Nuclear data uncertainty (pcm)		
	SCALE6.2	JEFF-3.3	ENDF/B-VIII.0
-148 ± 13	9.32 ± 1.1 (6.3%)	5.9 (4.0%)	5.1 (3.5%)

Quantity	R-Z - $\Delta\rho_{fuel}$ ISC (%/%)
Pu-239 fission	$6.91 \cdot 10^{-1} \pm 8 \cdot 10^{-2}$
U-238 nubar	$3.11 \cdot 10^{-1} \pm 5 \cdot 10^{-2}$
Pu-239 (n,γ)	$2.10 \cdot 10^{-1} \pm 1 \cdot 10^{-2}$
Pu-240 nubar	$1.94 \cdot 10^{-1} \pm 4 \cdot 10^{-2}$

SCALE6.2		JEFF-3.3		ENDF/B-VIII.0	
Reaction	$\Delta\rho/\rho$ (%)	Reaction	$\Delta\rho/\rho$ (%)	Reaction	$\Delta\rho/\rho$ (%)
Nd-150 elastic	3.06 ± 0.13	Fe-56 elastic	**1.99**	Fe-56 elastic	**1.36**
Fe-56 elastic	$\mathbf{2.65 \pm 0.47}$	Pu-240 fission	1.83	Cr-52 elastic	1.29
Nd-144 elastic	2.34 ± 0.27	Pu-239 χ	1.29	Pu-239 fission	1.23
U-238 elastic	2.25 ± 0.22	Nd-150 elastic	1.20	U-238 elastic	1.17
Cr-52 elastic	1.33 ± 0.06	Pu-239 capture	0.88	Pu-239 inelastic	1.16
Pu-239 inelastic	1.15 ± 0.04	Fe-54 elastic	0.79	Pu-239 capture	0.97

4. S/U analyses: Control rod worth

Het. 3D CR worth (pcm)	CE TSUNAMI-3D			
	RZ CR worth (pcm)	Nuclear data uncertainty (pcm)		
		SCALE6.2	JEFF-3.3	ENDF/B-VIII.0
-4988	-5418.5 ± 13	127.8 ± 1.0	101.3	71.6

Quantity	R-Z - $\Delta\rho_{CR}$ ISC (%/%)
Pu-239 fission	$4.38 \cdot 10^{-1} \pm 2 \cdot 10^{-3}$
O-16 elastic	$2.56 \cdot 10^{-1} \pm 2 \cdot 10^{-2}$
U-238 nubar	$2.48 \cdot 10^{-1} \pm 2 \cdot 10^{-3}$
B-10 (n,γ)	$-2.40 \cdot 10^{-1} \pm 3 \cdot 10^{-4}$

SCALE6.2		JEFF-3.3		ENDF/B-VIII.0	
Reaction	$\Delta\rho/\rho$ (%)	Reaction	$\Delta\rho/\rho$ (%)	Reaction	$\Delta\rho/\rho$ (%)
U-238 inelastic	1.46 ± 0.01	Pu-240 fission	1.16	Pu-239 fission	0.73
Fe-56 elastic	1.04 ± 0.01	Pu-239 χ	0.71	Na-23 elastic	0.69
Na-23 elastic	0.67 ± 0.00	Fe-56 elastic	0.56	Pu-239 χ	0.35
U-238 inel-elastic	0.64 ± 0.01	U-238 fission	0.53	Pu-240 χ	0.33
U-238 χ	0.50 ± 0.00	O-16 elastic	0.50	U-238 nubar	0.30
O-16 elastic	0.50 ± 0.00	Pu-239 fission	0.41	U-238 inel-elastic	0.27

4. S/U analyses: conclusions

- **Nuclear data needs for ESFR in JEFF-3.3**:
  - Reduction of uncertainty ^{238}U (n,n'), (n,γ)
  - Reduction of uncertainty ^{240}Pu (n,f)
  - Reduction of uncertainty ^{239}Pu ν, χ, (n,f), (n,γ)
  - Reduction of uncertainty ^{23}Na (n,n)
  - Reduction of uncertainty ^{56}Fe (n,n)

5. Data assimilation

- **Revision of experiments from**:
  - Critical experiments from ICSBEP (DICE)
  - Reactor experiments from IRPhE
- **For the following integral parameters:**
  - k-eff
  - Sodium void worth

5. Data assimilation

- **Useful experiments for k-eff**:

Source	Experiment	DICE or IDAT (Sensitivity ranking)	c_k	E	Experimental value
DICE	MIX-COMP-FAST-006-001	0,967	0,91	0,97	0,9889 ± 0,0021
	MIX-COMP-FAST-005-001	0,964	0,96	0,97	0,9913 ± 0,0023
	MIX-COMP-FAST-001-001	0,970	0,93	0,97	0,9866 ± 0,0023
	MIX-MISC-FAST-002-001	0,942	0,94	0,95	1,0005 ± 0,0021
IDAT	ZPR-FUND-EXP-014-001	0,962	0,96	0,97	0,9913 ± 0,0023
	BFS1-FUND-EXP-004-001	0,942	0,94	0,95	1,0005 ± 0,0021
	FFTF-LMFR-RESR-001-001	0,933	0,73	0,95	0,9993 ± 0,0021
	SNEAK-LMFR-EXP-001-001	0,929	0,87	0,95	1,001 ± 0,0035
WPEC-SG33 (ANL)	ZPPR9_Keff_Sens_Coef.ANL	-	0,96	0,79	1,0008 ± 0,00154
	ZPR6-7_Keff_Sens_Coef.ANL	-	0,92	0,78	0,9866 ± 0,0023
	ZPR6-7_PU240_Keff_Sens_Coef.ANL	-	0,92	0,79	0,9874 ± 0,0022

5. Data assimilation

- **Useful experiments for sodium void worth**:

Source	Experiment	c_k	E	Experimental value (pcm)
WPEC-SG33 (ANL)	ZPPR9_VOID_Step3	0,855	0,939	29,18 ± 1,7 %
	ZPPR9_VOID_Step5	0,840	0,944	31,3 ± 1,7 %
IRPhE (UPM - CIEMAT)	ZPPR-LMFR-EXP-011-VOID_case09	0,584	0,918	195,42 ± 5,1 %

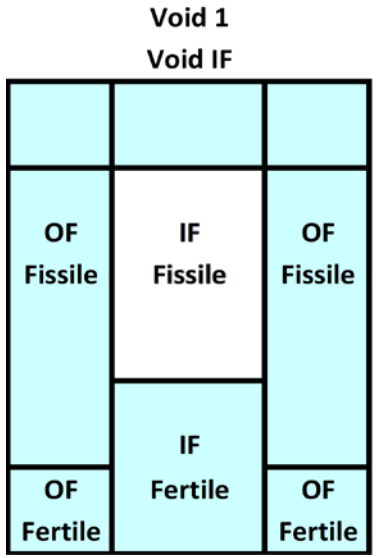
6. Outlook

- ESFR R-Z model has been developed
- S/U for ESFR using TSUNAMI-3D CE approach for main integral parameters (comparison of methodologies ongoing in the EU SANDA project)
- Uncertainty quantification with different covariance evaluations
- Identification of nuclear data needs in JEFF-3.3 via major contributors to the uncertainty
- Revision of experiments useful for DA in k_{eff} and sodium void worth from different sources
- Data assimilation for ESFR currently ongoing

Thank you for your attention!

Backup slides

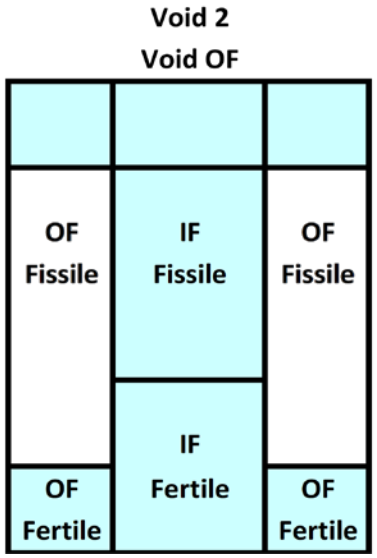
4. S/U analyses: sodium void scenario 1



Quantity	R-Z - $\Delta\rho$ ISC (%/%)
Pu-239 nubar	$-7.59 \cdot 10^{-1} \pm 1 \cdot 10^{-2}$
Na-23 elastic	$5.23 \cdot 10^{-1} \pm 8 \cdot 10^{-2}$
U-238 (n,γ)	$4.04 \cdot 10^{-1} \pm 5 \cdot 10^{-3}$
Na-23 inelastic	$2.76 \cdot 10^{-1} \pm 5 \cdot 10^{-3}$

SCALE6.2		JEFF-3.3		ENDF/B-VIII.0	
Reaction	$\Delta\rho/\rho$ (%)	Reaction	$\Delta\rho/\rho$ (%)	Reaction	$\Delta\rho/\rho$ (%)
Na-23 inelastic	3.09 ± 0.01	Pu-239 fission	2.63	Na-23 elastic	3.08
Na-23 elastic	3.02 ± 0.05	Na-23 elastic	1.49	Na-23 inelastic	3.06
U-238 inelastic	1.77 ± 0.02	U-238 inelastic	1.18	Pu-239 fission	2.64
U-238 capture	1.05 ± 0.00	Pu-239 capture	1.14	Pu-239 capture	1.12
Pu-239 fission	0.93 ± 0.00	U-238 capture	0.93	U-238 inelastic	0.89
U-238 inel-elastic	0.86 ± 0.02	U-238 capt-inelastic	0.72	U-238 capture	0.76

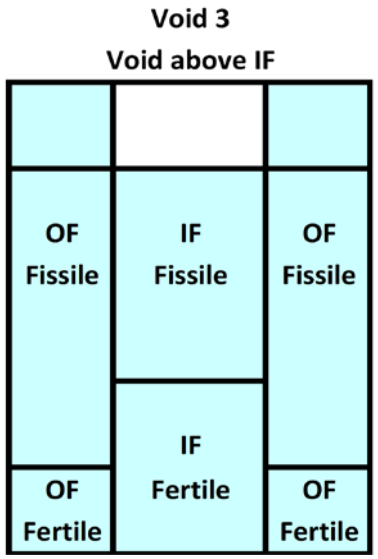
4. S/U analyses: sodium void scenario 2



Quantity	R-Z - $\Delta\rho$ ISC (%/%)
Pu-239 nubar	$-1.06 \cdot 10^{0} \pm 1 \cdot 10^{-2}$
U-238 (n,γ)	$6.88 \cdot 10^{-1} \pm 5 \cdot 10^{-3}$
Na-23 elastic	$5.29 \cdot 10^{-1} \pm 9 \cdot 10^{-2}$
Na-23 inelastic	$3.86 \cdot 10^{-1} \pm 5 \cdot 10^{-3}$

SCALE6.2		JEFF-3.3		ENDF/B-VIII.0	
Reaction	$\Delta\rho/\rho$ (%)	Reaction	$\Delta\rho/\rho$ (%)	Reaction	$\Delta\rho/\rho$ (%)
Na-23 inelastic	4.39 ± 0.01	Pu-239 fission	3.58	Na-23 inelastic	4.34
Na-23 elastic	3.48 ± 0.05	Pu-239 capture	1.53	Pu-239 fission	3.57
U-238 inelastic	2.58 ± 0.03	Na-23 elastic	1.51	Na-23 elastic	3.50
U-238 capture	1.64 ± 0.00	U-238 capture	1.43	Pu-239 capture	1.48
Pu-239 fission	1.29 ± 0.00	U-238 inelastic	1.26	U-238 capture	1.15
U-238 inel-elastic	1.06 ± 0.03	Fe-56 elastic	0.98	Pu-239 capt-fission	0.79

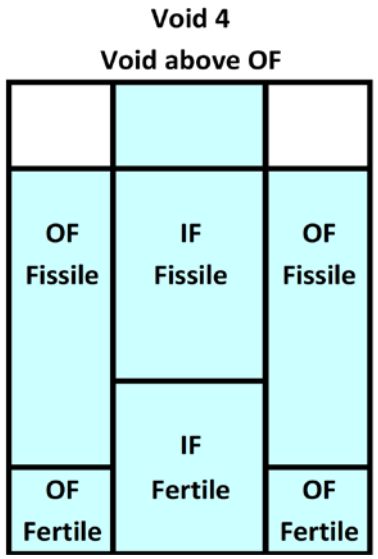
4. S/U analyses: sodium void scenario 3



Quantity	R-Z - $\Delta\rho$ ISC (%/%)
O-16 elastic	$6.92 \cdot 10^{-1} \pm 3 \cdot 10^{-1}$
Fe-56 elastic	$4.76 \cdot 10^{-1} \pm 3 \cdot 10^{-1}$
Pu-239 nubar	$3.79 \cdot 10^{-1} \pm 3 \cdot 10^{-2}$
U-238 nubar	$2.86 \cdot 10^{-1} \pm 2 \cdot 10^{-2}$

SCALE6.2		JEFF-3.3		ENDF/B-VIII.0	
Reaction	$\Delta\rho/\rho$ (%)	Reaction	$\Delta\rho/\rho$ (%)	Reaction	$\Delta\rho/\rho$ (%)
Fe-56 elastic	3.15 ± 0.20	Fe-56 elastic	1.53	Cr-52 elastic	1.14
O-16 elastic	1.35 ± 0.02	Pu-240 fission	1.36	Na-23 elastic	1.01
Cr-52 elastic	1.11 ± 0.02	O-16 elastic	1.34	Fe-56 elastic	0.93
Na-23 elastic	1.01 ± 0.04	Fe-54 elastic	0.86	Pu-239 fission	0.86
U-238 elastic	0.81 ± 0.03	Fe-57 elastic	0.75	U-238 elastic	0.86
Fe-57 elastic	0.66 ± 0.01	Na-23 elastic	0.60	U-238 inelastic	0.72

4. S/U analyses: sodium void scenario 4



Quantity	R-Z - $\Delta\rho$ ISC (%/%)
O-16 elastic	$6.34 \cdot 10^{-1} \pm 3 \cdot 10^{-1}$
Pu-239 fission	$5.97 \cdot 10^{-1} \pm 3 \cdot 10^{-2}$
Fe-56 elastic	$5.05 \cdot 10^{-1} \pm 3 \cdot 10^{-1}$
U-238 elastic	$4.14 \cdot 10^{-1} \pm 3 \cdot 10^{-2}$

SCALE6.2		JEFF-3.3		ENDF/B-VIII.0	
Reaction	$\Delta\rho/\rho$ (%)	Reaction	$\Delta\rho/\rho$ (%)	Reaction	$\Delta\rho/\rho$ (%)
Fe-56 elastic	3.04 ± 0.21	Fe-56 elastic	1.45	Na-23 elastic	1.54
Na-23 elastic	1.46 ± 0.07	Pu-240 fission	1.27	Pu-239 fission	1.10
O-16 elastic	1.25 ± 0.03	O-16 elastic	1.25	U-238 elastic	0.83
U-238 elastic	0.74 ± 0.04	Pu-239 χ	0.98	Fe-56 elastic	0.76
Cr-52 elastic	0.59 ± 0.01	U-238 elastic	0.92	Cr-52 elastic	0.62
Nd-144 elastic	0.57 ± 0.04	Na-23 elastic	0.75	Pu-239 χ	0.58