Nuclear data sensitivity and uncertainty assessment of sodium voiding reactivity coefficients of an ASTRID-like Sodium Fast Reactor

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Outline

Motivation and goals

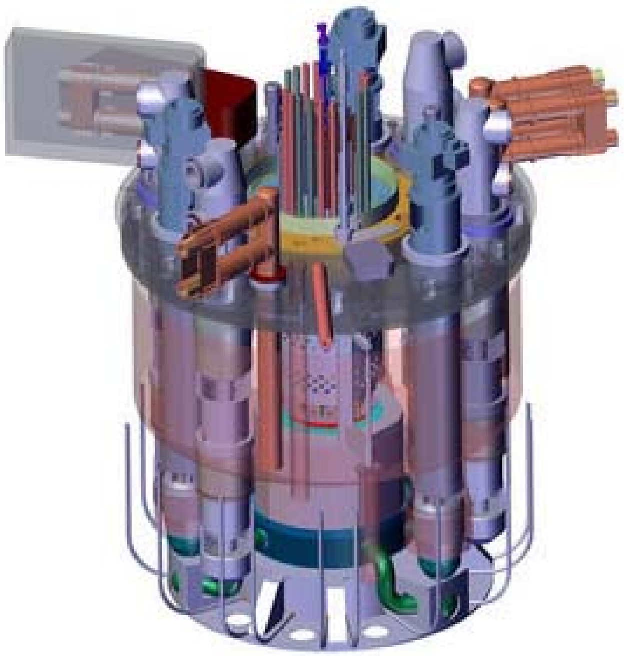
ASTRID-like core configuration

Applied methodologies

S/U results

Conclusions

Motivation



2010 EC creates the European Industrial Initiative on Nuclear Energy (ESNII) to promote the development of advanced Gen IV reactor technologies for a sustainable implementation of nuclear energy

2013 FP7 EURATOM ESNII+ project launched to establish the roadmap for the development of fast reactors

The prototype for the sodium cooled fast reactor (SFR) technology is ASTRID (**A**dvanced **S**odium **T**echnological **R**eactor for **I**ndustrial **D**emonstration)

2019 Designer: CEA. Detailed design phase is foreseen to be initiated

Motivation

- Sodium as a coolant:

Advantages:
- relatively high neutron transparency
- high thermal conductivity, …

Disadvantages:
- chemical reactivity with air and water
- inherent positive feedback in case of sodium voiding: main neutronics challenge of SFR

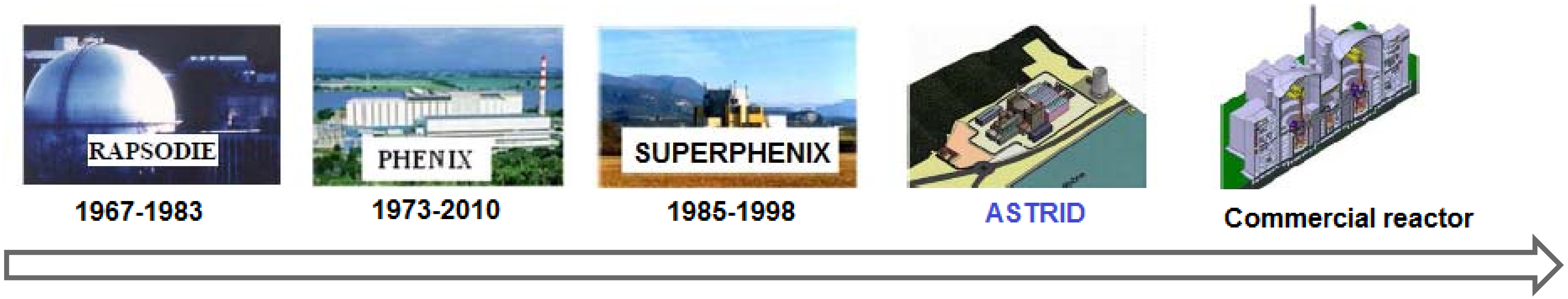
- Main effects associated to the sodium removal (reduction of scattering reactions):
  - Increase of neutron leakage → reactivity reduction, negative contribution
  - Spectral hardening → reactivity increase, positive contribution

- ASTRID particular design: high axial heterogeneity aiming increase neutron leakage rate in sodium voiding scenarios → overall negative reactivity feedback (CFV: low-void core concept) resulting from compensation of effects at the different core zones

- Neutronics characterization requires computing SV contributions at the different zones and associated uncertainties, which are translated into safety margins. High level of accuracy in simulation tools

Goal

- Nuclear data S/U assessment of the spatial-dependent sodium void reactivity effects of an ASTRID-like reactor
  - Get a more complete picture of the actual safety margins of this innovative design
  - Compare different methodologies pointing out any methodological shortcomings



The ASTRID reactor, the last born of the French Sodium Fast Reactor family

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ASTRID-like configuration

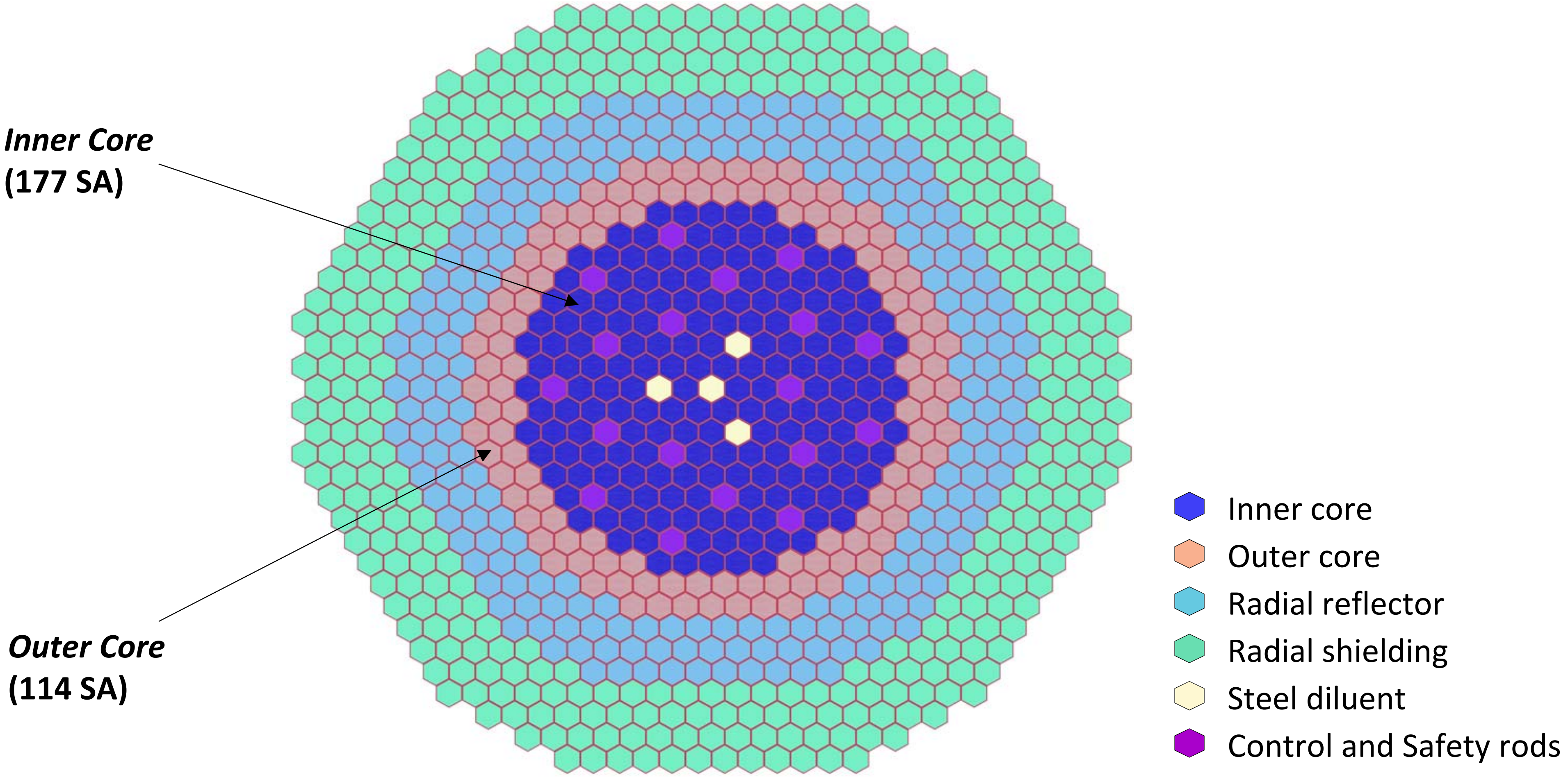


Figure 1. Radial view at the core mid-plane

ASTRID-like configuration

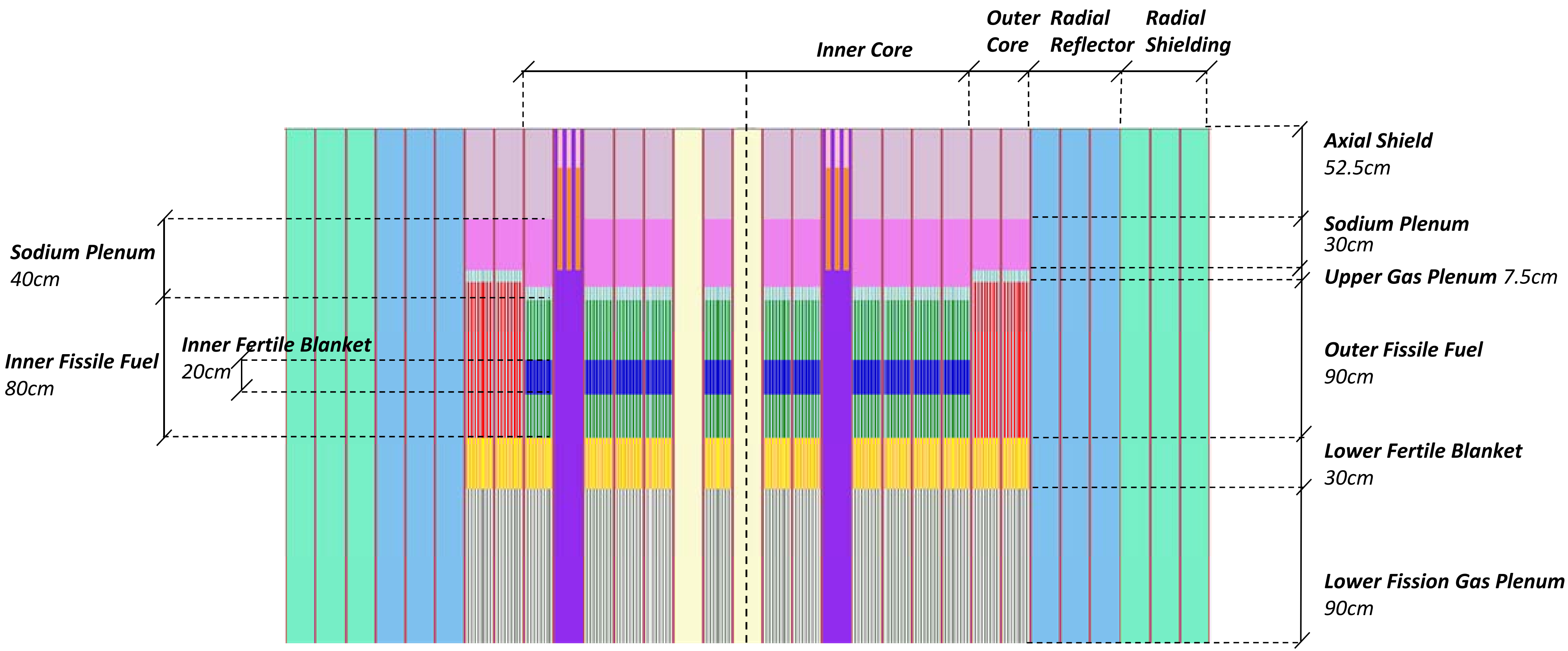


Figure 2. Axial view

ASTRID-like configuration

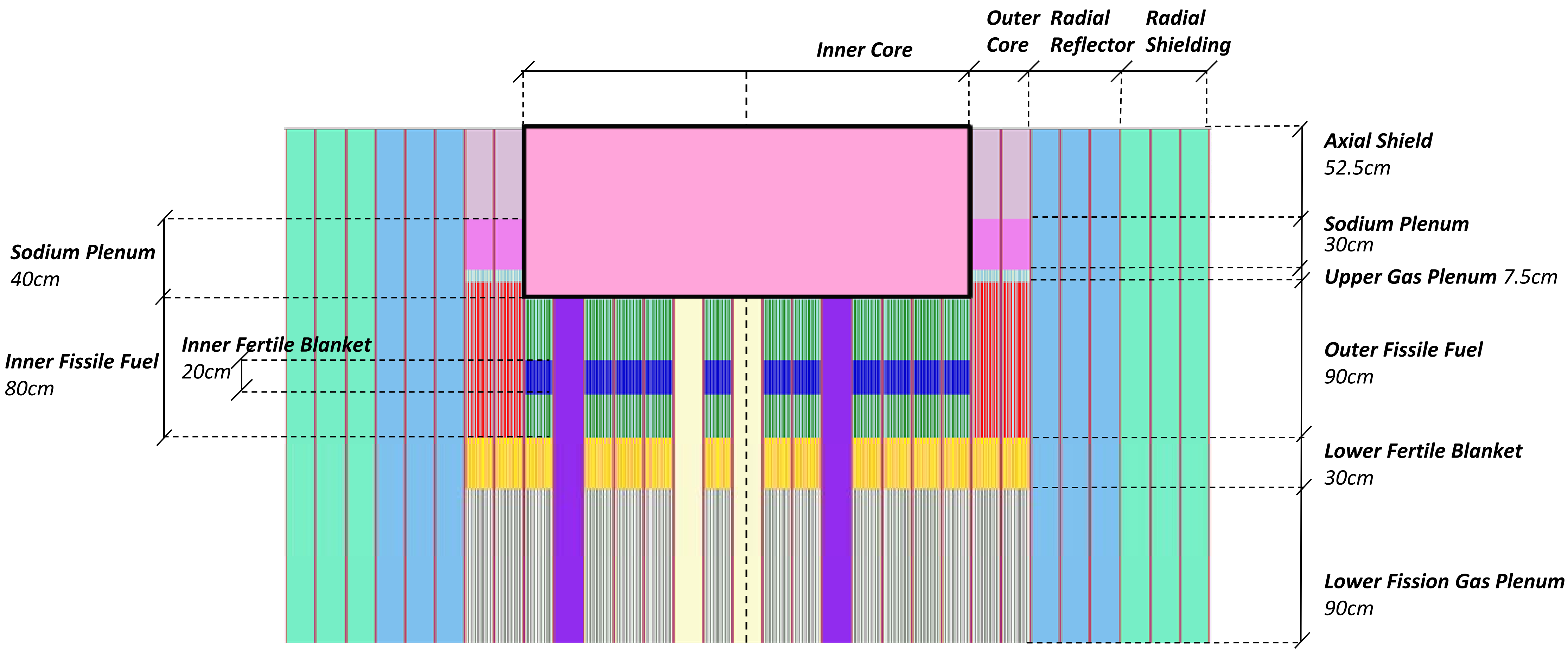


Figure 2. Axial view

ASTRID-like configuration

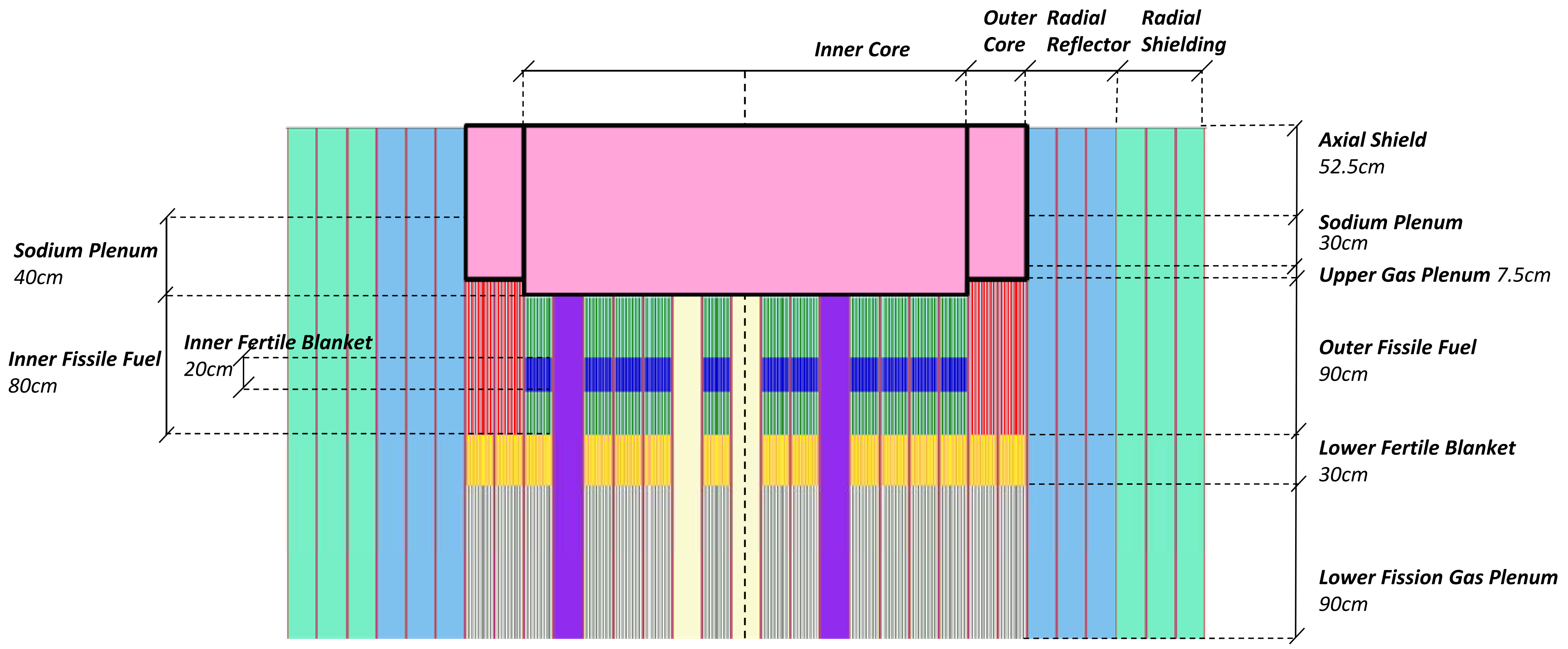


Figure 2. Axial view

ASTRID-like configuration

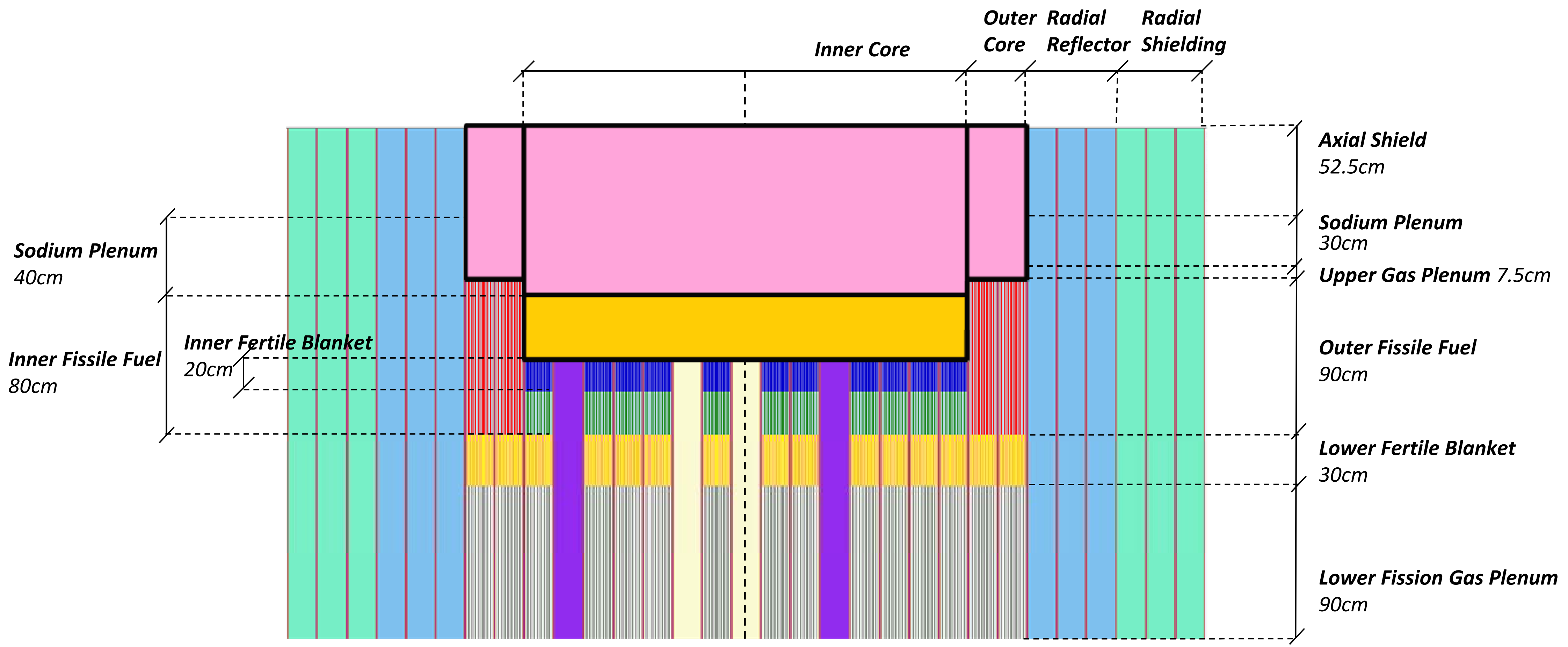
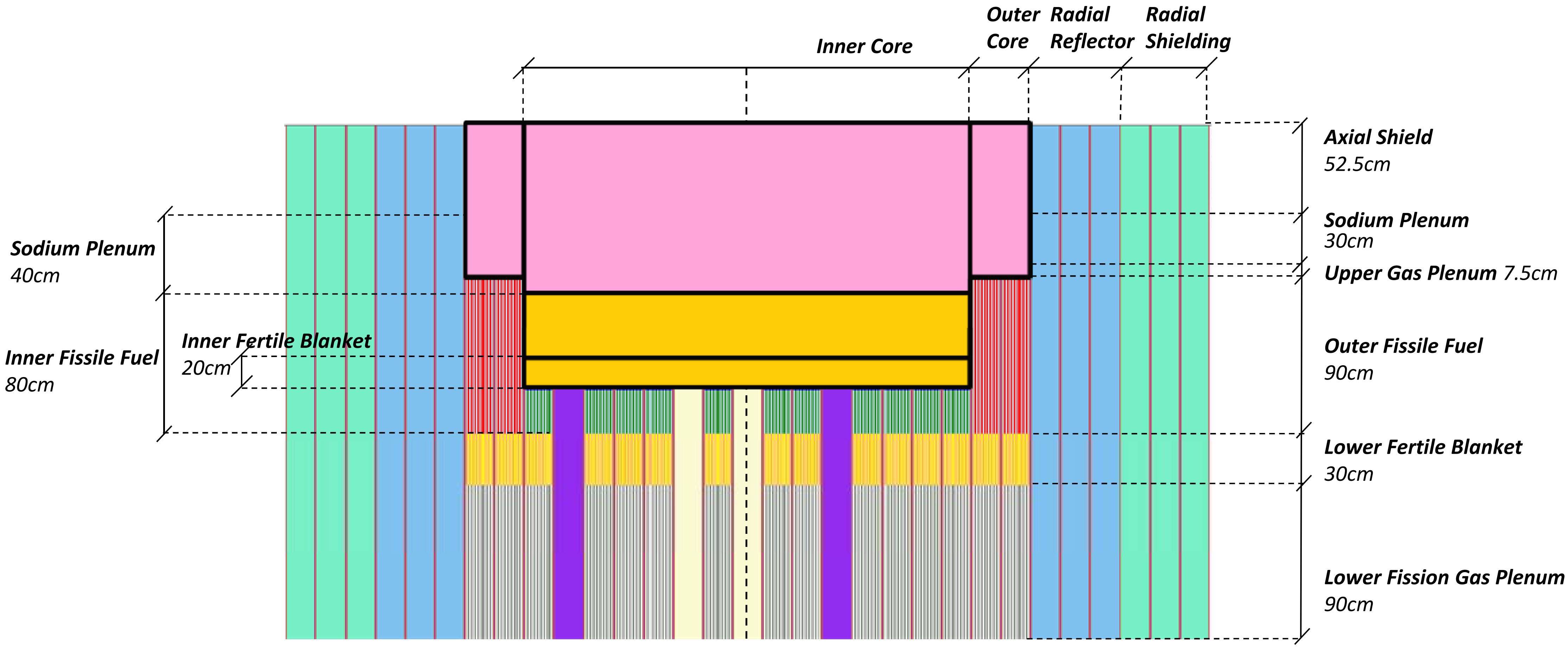


Figure 2. Axial view

ASTRID-like configuration



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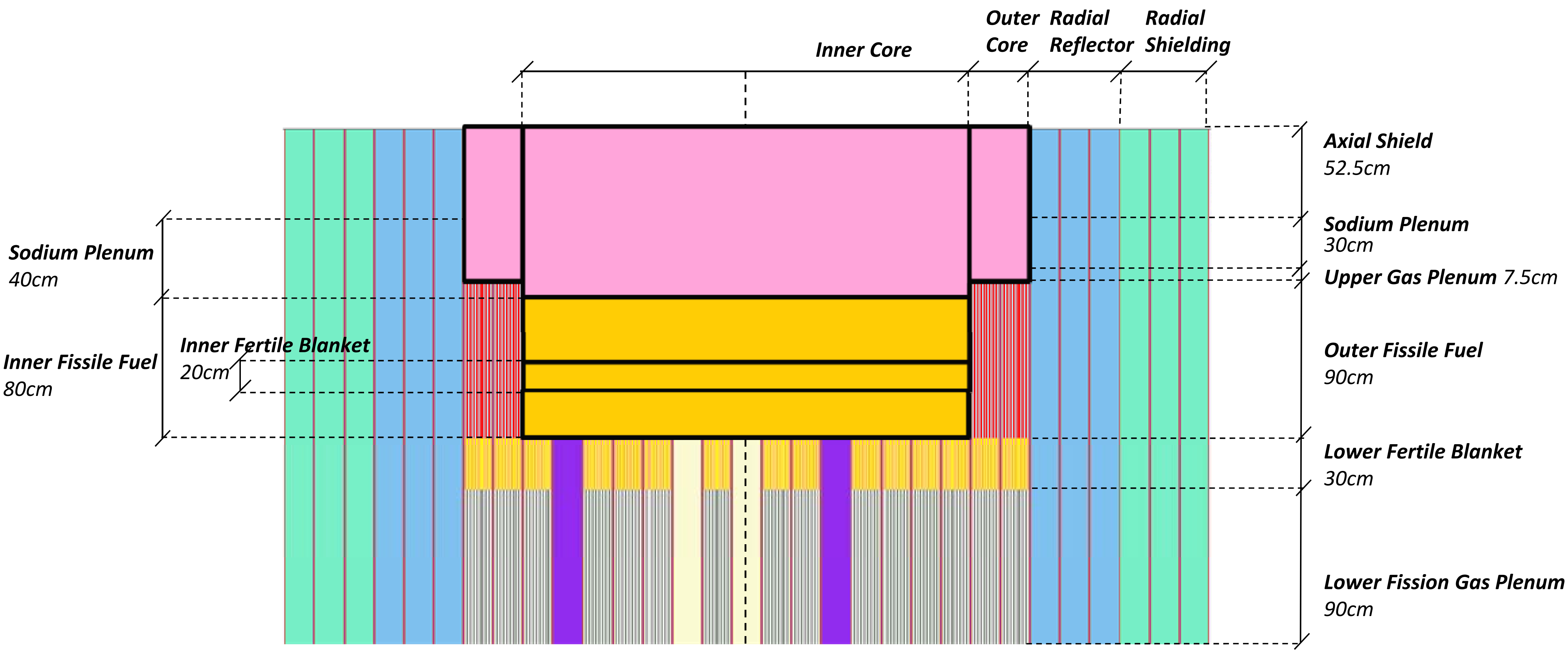
ASTRID-like configuration



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ASTRID-like configuration

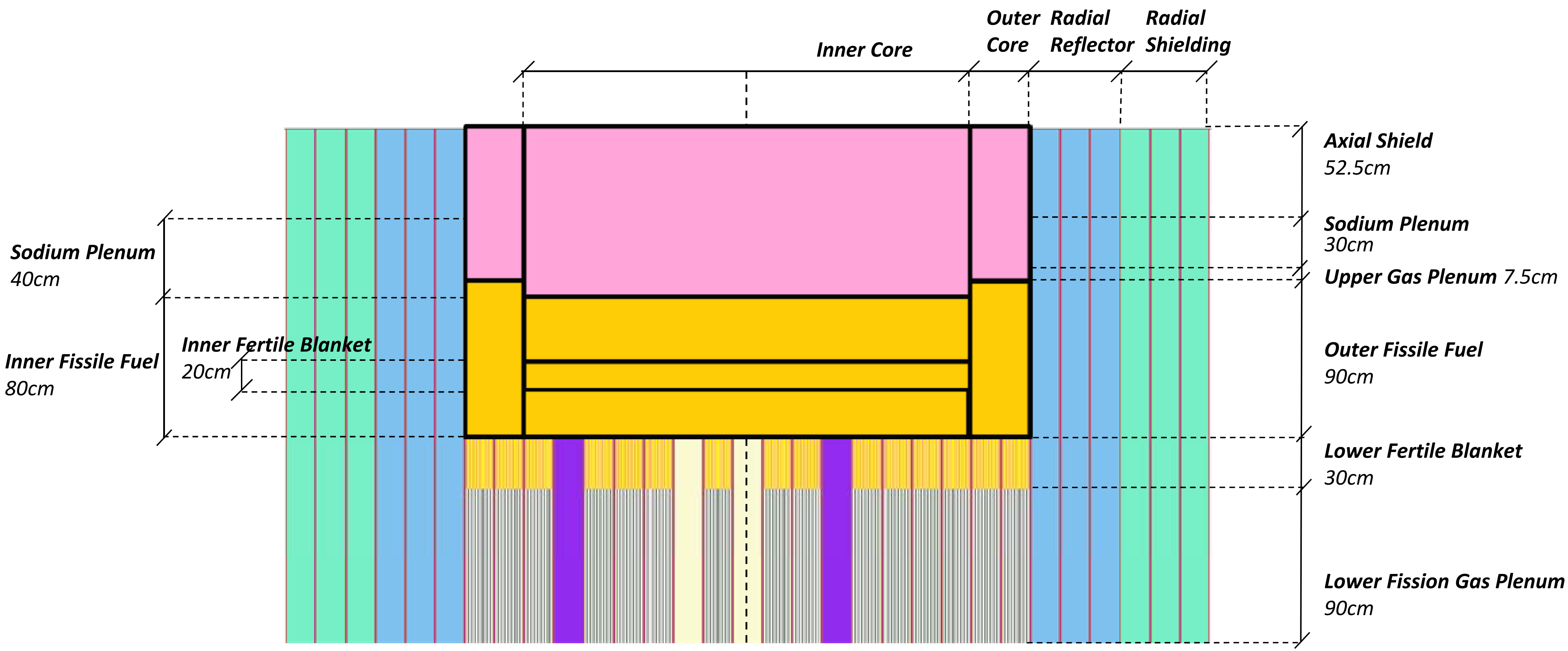
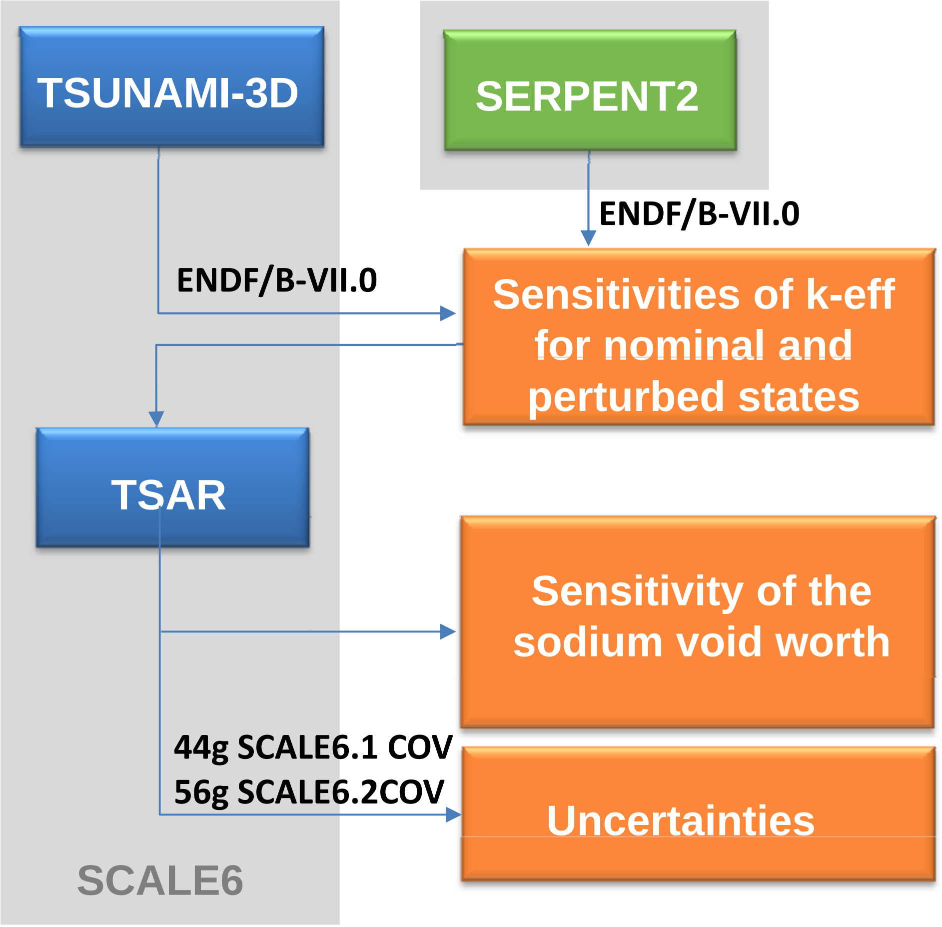


Figure 2. Axial view

Applied methodologies

Sodium void worth

$$\Delta\rho = \left(1 - \frac{1}{k_p}\right) - \left(1 - \frac{1}{k}\right) = \frac{k_p - k}{k_p \cdot k}$$



$$S_{k,\alpha} = \frac{\delta k / k}{\delta \alpha / \alpha} \qquad S_{k_p,\alpha} = \frac{\delta k_p / k_p}{\delta \alpha / \alpha}$$

$$S_{\Delta\rho,\alpha} = \frac{\delta(\Delta\rho)/|\Delta\rho|}{\delta \alpha / \alpha} = \frac{\frac{S_{k_p,\alpha}}{k_p} - \frac{S_{k,\alpha}}{k}}{|\Delta\rho|}$$

$$\varepsilon_{\Delta\rho} = \sqrt{\mathbf{S}^{T}_{\Delta\rho,\alpha} \boldsymbol{COV}_{\alpha\alpha} \mathbf{S}_{\Delta\rho,\alpha}}$$

Applied methodologies

SCALE MG TSUNAMI-3D module

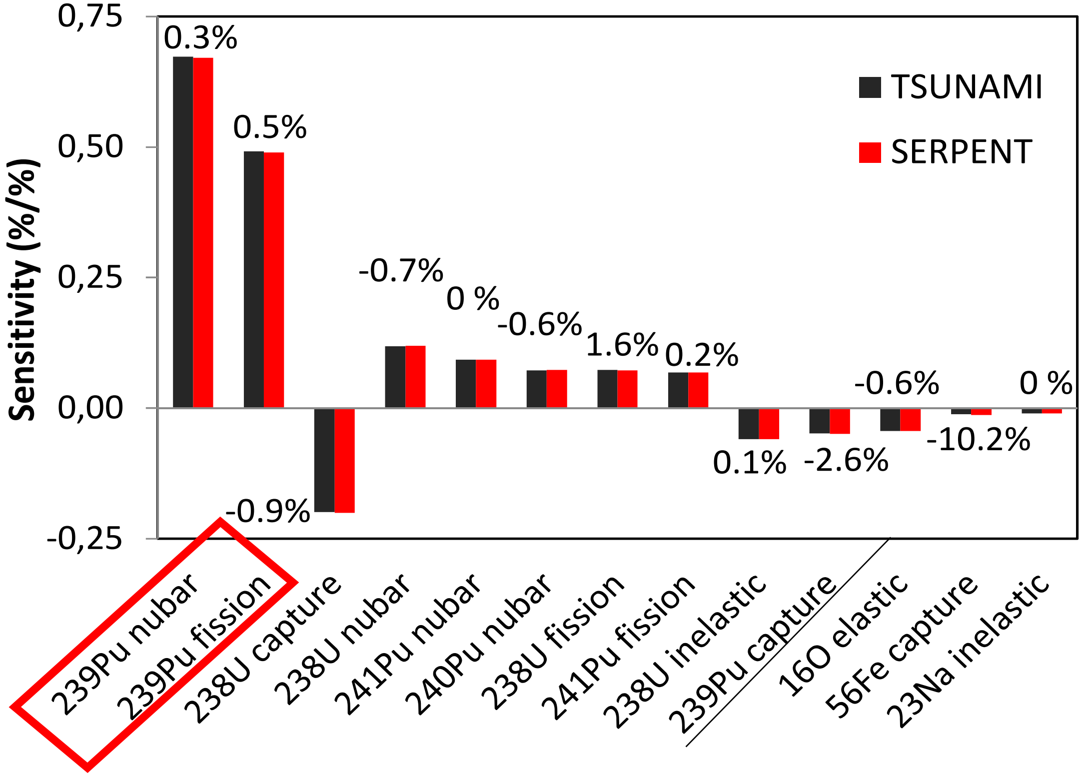
- Forward and Adjoint Monte Carlo neutron transport calculations with KENO-VI code
- Sensitivity coefficients to nuclear data via 1st order linear Perturbation Theory
- Advantage: sensitivities for all reactions are calculated
- Critical aspect: Relevant energy, spatial and directional dependences of the fluxes must be captured for accurate sensitivities
  - Energy → 238g SCALE
  - Spatial → fluxes computed in a cubic mesh of 10 cm, refined in the sodium plenum up to 5 cm
  - Angular → 3rd order flux moments

SERPENT2 GPT module

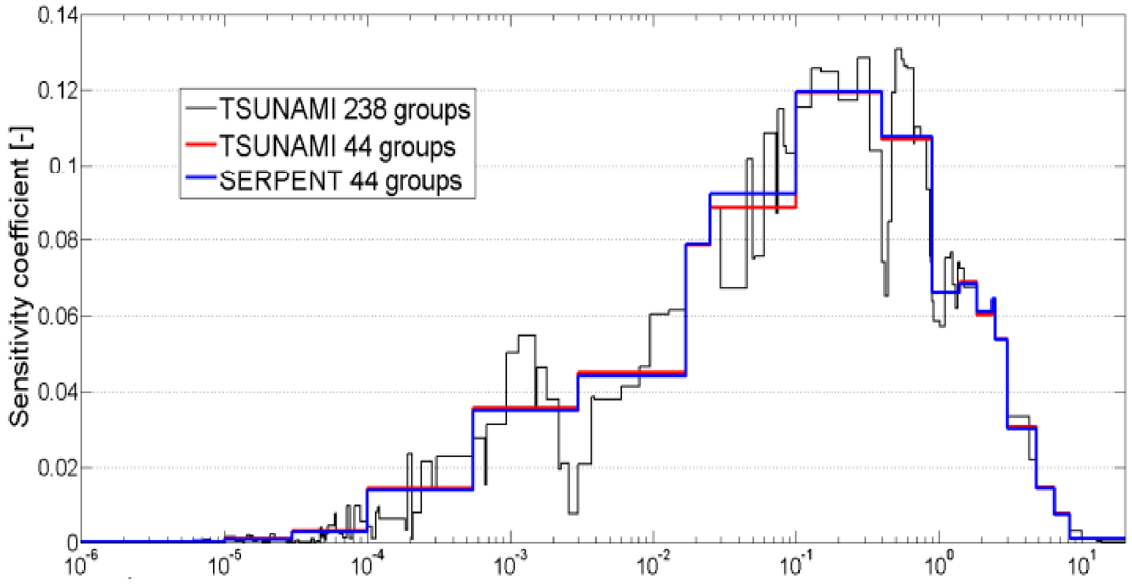
- Single forward MC transport calculation
- Collision-based approach to sensitivity-perturbation calculations
- Advantage: CE calculation scheme
- Critical aspect: isotopes have to be defined prior to simulations; computation time depends on the number of isotopes considered, energy groups and spatial zones (high statistics to obtain reasonable convergence in each energy / spatial zone)
  - Energy grid → 44g SCALE for its reasonable number of bins and compatibility
  - 10 isotopes considered
  - Simulation of the perturbation of χ still under development

S/U analysis of nominal k-eff

Highest Integrated Sensitivity Coefficients (ISC) of k-eff (energy, region and mixture integrated)



Sensitivity profile for Pu-239 nubar (quantity with the highest sentitivity)



Good agreement TSUNAMI-SERPENT. Differences < 3% except for Fe-56 capture

S/U analysis of nominal k-eff

k-eff uncertainty and main contributors using 44-group SCALE6.1 covariance

Quantity	$\Delta k/k$ (%) SCALE	$\Delta k/k$ (%) SERPENT
^{238}U inelastic	0.92	0.91
^{239}Pu nubar	0.66	0.67
^{239}Pu χ	0.29	Not computed
^{238}U capture	0.27	0.27
^{239}Pu capture	0.25	0.25
^{240}Pu nubar	0.21	0.21
^{238}U elastic-inelastic	0.21	0.21
^{239}Pu fission	0.19	0.20
^{238}U nubar	0.14	0.14
^{238}Pu fission	0.14	0.13
OVERALL	**1.318**	**1.280**

k-eff uncertainty and main contributors using 56-group SCALE6.2 covariance

Quantity	$\Delta k/k$ (%) SCALE	$\Delta k/k$ (%) SERPENT
^{238}U inelastic	0.93	0.91
^{238}U capture	0.27	0.26
^{239}Pu capture	0.24	0.25
^{238}U elastic-inelastic	0.21	0.21
^{239}Pu fission	0.20	0.20
^{239}Pu χ	0.19	Not computed
^{238}U χ	0.15	Not computed
^{238}U nubar	0.14	0.14
^{241}Pu χ	0.14	Not computed
^{56}Fe inelastic	0.13	0.12
OVERALL	**1.131**	**1.078**

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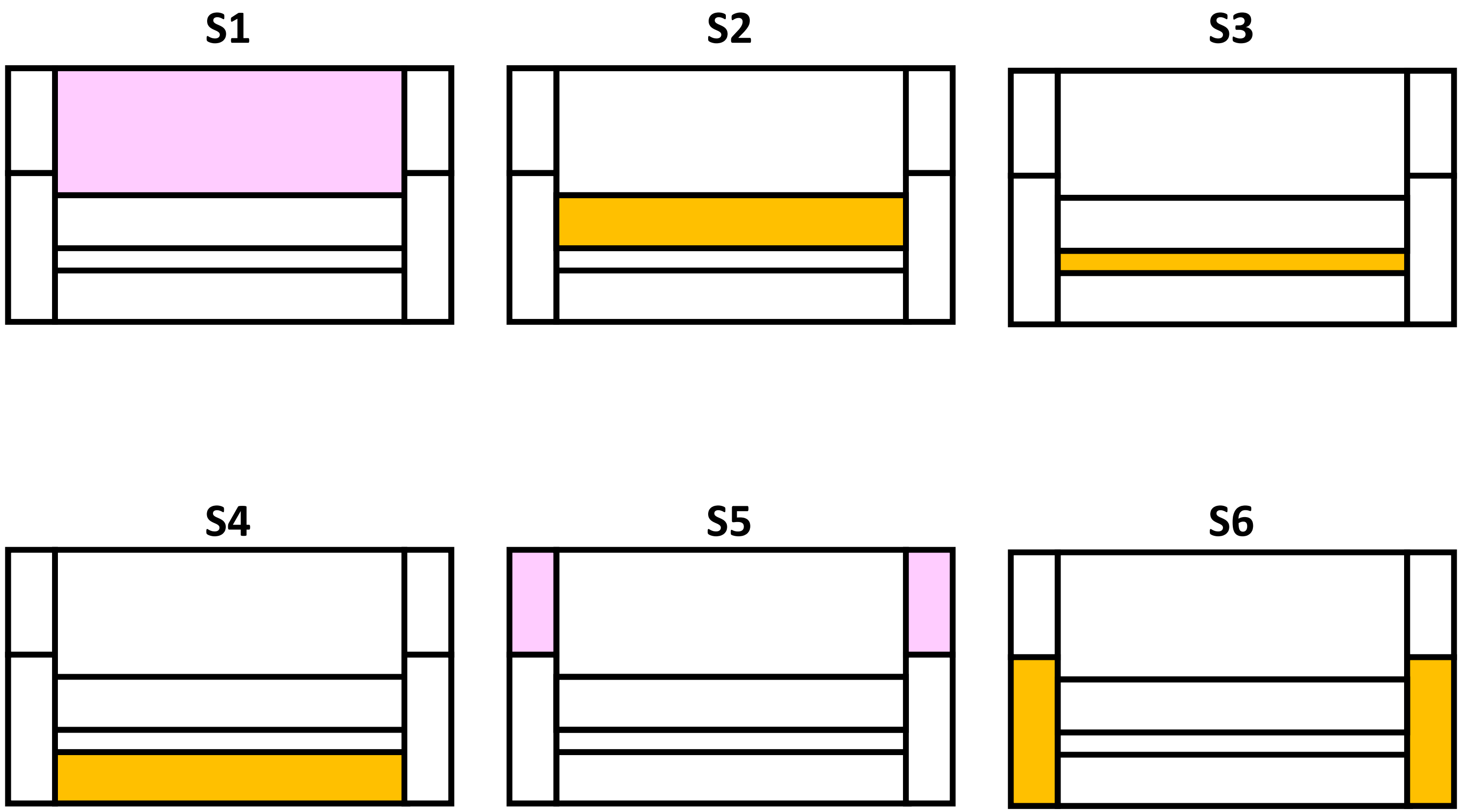
S/U analysis of sodium void

Voiding scenarios



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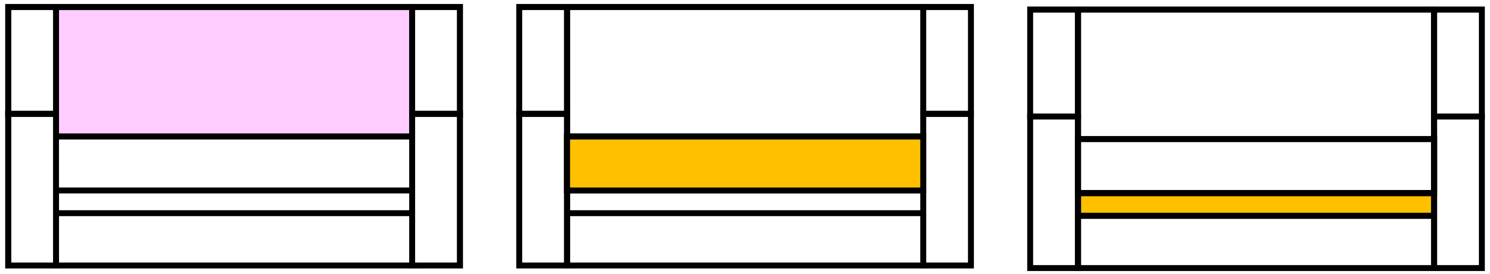
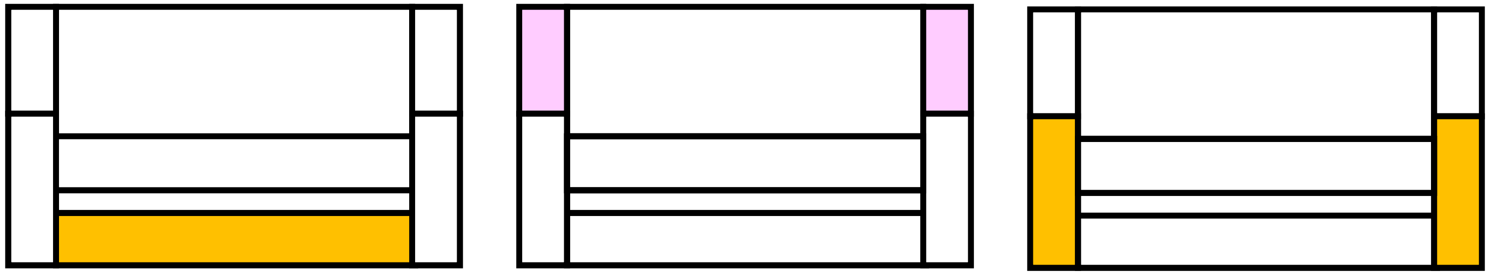
S/U analysis of sodium void

Voiding scenarios and Na void worth values



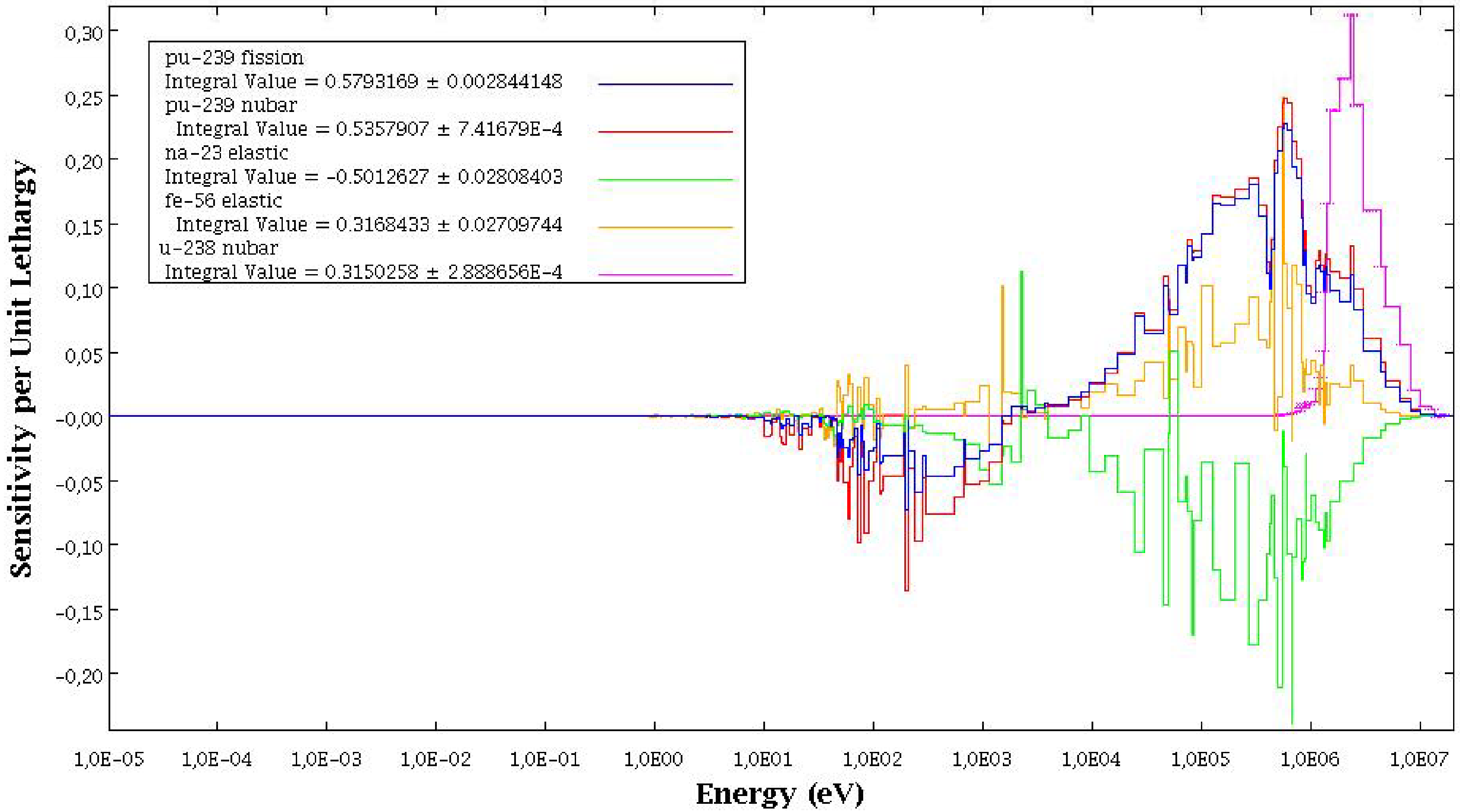
	S1	S2	S3
SCALE	-1413 ± 13	439 ± 13	326 ± 12
SERPENT	-1451 ± 5	460 ± 5	354 ± 5



	S4	S5	S6
SCALE	219 ± 12	-264 ± 11	203 ± 12
SERPENT	241 ± 5	-268 ± 5	202 ± 5

S/U analysis of sodium void

Na void worth sensitivities for Scenario 1



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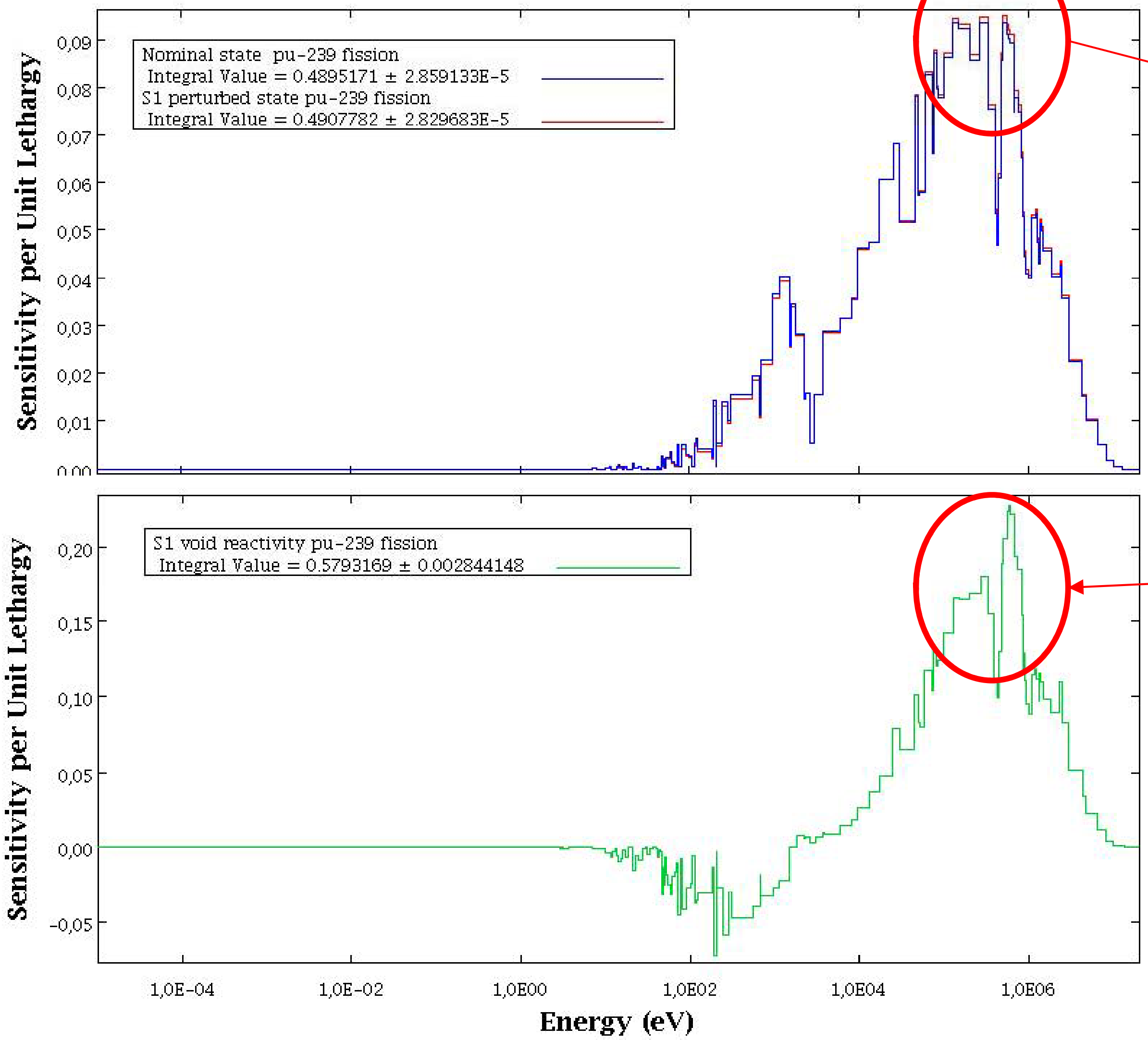
S/U analysis of sodium void

Na void worth sensitivities for Scenario 1 (to ^{239}Pu fission)



Perturbed state more sensitive than nominal state for a 1% increase in Pu-239 fission

Sensitivity in the Na void worth magnifies processes that can lead to biases in the reactivity response

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S/U analysis of sodium void

Highest integrated sensitivity coefficients for the Na void worth (%/%)

Scenario S1		
Quantity	SCALE	SERPENT
^{239}Pu fission	0,58	0,58
^{239}Pu nubar	0,54	0,55
^{23}Na elastic	-0,50	-0,47
^{23}Fe elastic	0,32	0,27
^{238}U nubar	0,32	0,30

Scenario S2		
Quantity	SCALE	SERPENT
^{239}Pu nubar	-1,11	-1,07
^{238}U capture	0,84	0,69
^{239}Pu fission	-0,82	-0,82
^{23}Na elastic	0,66	0,57
^{23}Na inelastic	0,46	0,40

Scenario S3		
Quantity	SCALE	SERPENT
^{239}Pu nubar	-0,85	-0,82
^{239}Pu fission	-0,64	-0,61
^{23}Na elastic	0,60	0,55
^{16}O elastic	-0,48	-0,62
^{238}U capture	0,45	0,37

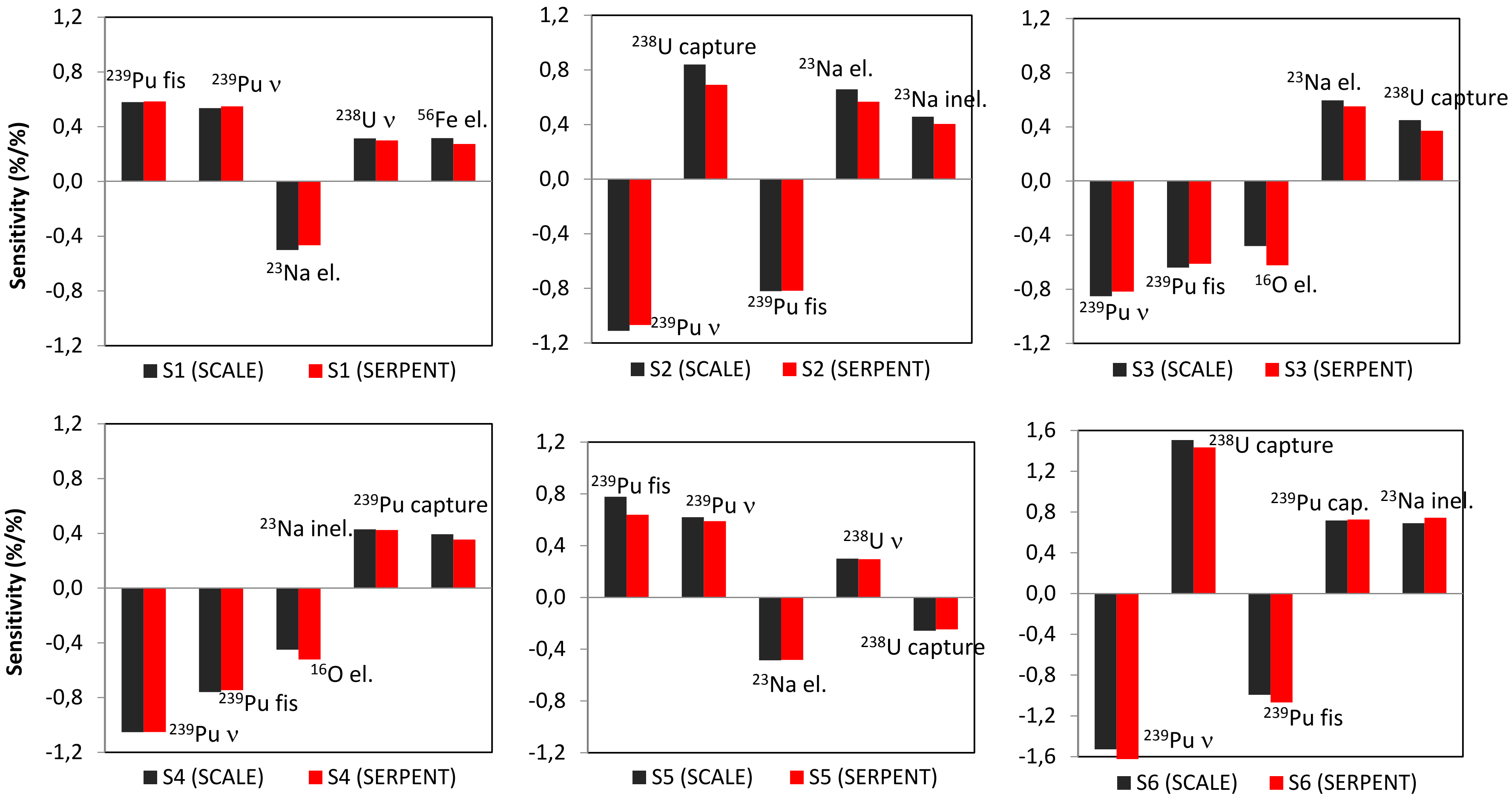
Scenario S4		
Quantity	SCALE	SERPENT
^{239}Pu nubar	-1,05	-1,05
^{239}Pu fission	-0,76	-0,75
^{16}O elastic	-0,45	-0,52
^{23}Na inelastic	0,43	0,42
^{239}Pu capture	0,39	0,35

Scenario S5		
Quantity	SCALE	SERPENT
^{239}Pu fission	0,78	0,64
^{239}Pu nubar	0,62	0,59
^{23}Na elastic	-0,49	-0,48
^{238}U nubar	0,30	0,30
^{238}U capture	-0,26	-0,25

Scenario S6		
Quantity	SCALE	SERPENT
^{239}Pu nubar	-1,53	-1,62
^{238}U capture	1,51	1,43
^{239}Pu fission	-0,99	-1,07
^{239}Pu capture	0,72	0,73
^{23}Na inelastic	0,69	0,74

S/U analysis of sodium void

Highest integrated sensitivity coefficients for the Na void worth (%/%)



Voiding of sodium plenum:

- Relevant sensitivities to ^{23}Na elastic but inconsequential effects of inelastic
- ^{56}Fe elastic also significant, showing that for void patterns located near the reflector or shielding, nuclear data of iron is concerned

Voiding of fuel regions:

- ^{23}Na inelastic scattering becomes important
- Capture of ^{238}U and ^{239}Pu
- ^{16}O elastic

Largest discrepancies SCALE-SERPENT are for sensitivities to ^{238}U capture and elastic cross sections, indicating that an accurate modelling of the anisotropic elastic scattering is a key point to get accurate Na void worth estimations

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S/U analysis of sodium void

Spatial distribution of the Na void worth uncertainties

	SCALE			SERPENT		
Na voiding Scenario	Void worth (pcm)	Uncertainties (pcm)		Void worth (pcm)	Uncertainties (pcm)	
		SCALE6.1COV	SCALE6.2COV		SCALE6.1COV	SCALE6.2COV
S1	-1413 ± 13	43 ± 0.8	58± 0.9	-1451 ± 5	38 ± 0.7	50 ± 0.7
S2	439 ± 13	29 ± 0.5	33 ± 0.7	460 ± 5	26 ± 0.5	29 ± 0.5
S3	326 ± 12	16 ± 0.7	19 ± 1.0	354 ± 5	17 ± 0.7	20 ± 0.7
S4	219 ± 12	15 ± 0.6	17 ± 0.9	241 ± 5	15 ± 0.6	17 ± 0.6
S5	-264 ± 11	8 ± 0.9	10 ± 1.3	-268 ± 5	7 ± 1.0	11 ± 0.9
S6	203 ± 12	23 ± 0.5	24 ± 0.8	202 ± 5	24 ± 0.6	24 ± 0.7
All[a]	-536 ± 12	112 ± 0.6	116 ± 0.8	-	-	-

S/U analysis of sodium void

Spatial distribution of the Na void worth uncertainties

	SCALE			SERPENT		
Na voiding Scenario	Void worth (pcm)	Uncertainties (%)		Void worth (pcm)	Uncertainties (%)	
		SCALE6.1COV	SCALE6.2COV		SCALE6.1COV	SCALE6.2COV
S1	-1413 ± 13	3%	4%	-1451 ± 5	3%	3%
S2	439 ± 13	7%	8%	460 ± 5	6%	6%
S3	326 ± 12	5%	6%	354 ± 5	5%	6%
S4	219 ± 12	7%	8%	241 ± 5	6%	7%
S5	-264 ± 11	3%	3%	-268 ± 5	3%	4%
S6	203 ± 12	11%	12%	202 ± 5	12%	12%
All[a]	-536 ± 12	21%	22%	-	-	-

Good agreement SCALE vs. SERPENT values

S/U analysis of sodium void

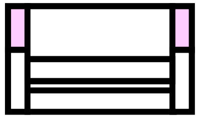
Spatial distribution of the Na void worth uncertainties

	SCALE			SERPENT		
Na voiding Scenario	Void worth (pcm)	Uncertainties (%)		Void worth (pcm)	Uncertainties (%)	
		SCALE6.1COV	SCALE6.2COV		SCALE6.1COV	SCALE6.2COV
S1	-1413 ± 13	3%	4%	-1451 ± 5	3%	3%
S2	439 ± 13	7%	8%	460 ± 5	6%	6%
S3	326 ± 12	5%	6%	354 ± 5	5%	6%
S4	219 ± 12	7%	8%	241 ± 5	6%	7%
S5	-264 ± 11	3%	3%	-268 ± 5	3%	4%
S6	203 ± 12	11%	12%	202 ± 5	12%	12%
All[a]	-536 ± 12	21%	22%	-	-	-

SCALE6.2 covariance matrix increases slightly sodium void uncertainties, unlike k-eff uncertainties

S/U analysis of sodium void

Spatial distribution of the Na void worth uncertainties

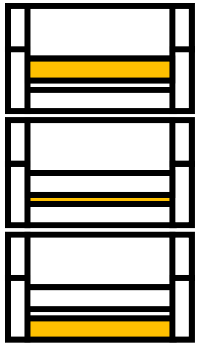


Na voiding Scenario	SCALE Void worth (pcm)	SCALE Uncertainties (%) SCALE6.1COV	SCALE Uncertainties (%) SCALE6.2COV	SERPENT Void worth (pcm)	SERPENT Uncertainties (%) SCALE6.1COV	SERPENT Uncertainties (%) SCALE6.2COV
S1	-1413 ± 13	3%	4%	-1451 ± 5	3%	3%
S2	439 ± 13	7%	8%	460 ± 5	6%	6%
S3	326 ± 12	5%	6%	354 ± 5	5%	6%
S4	219 ± 12	7%	8%	241 ± 5	6%	7%
S5	-264 ± 11	3%	3%	-268 ± 5	3%	4%
S6	203 ± 12	11%	12%	202 ± 5	12%	12%
All[a]	-536 ± 12	21%	22%	-	-	-

The smallest relative uncertainties correspond to Scenarios 1 and 5 where the sodium is voided from the plenum region. Leakage component is dominant, showing that this component is not very sensitivity to nuclear data uncertainties

S/U analysis of sodium void

Spatial distribution of the Na void worth uncertainties



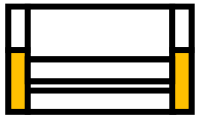
	SCALE			SERPENT		
Na voiding Scenario	Void worth (pcm)	Uncertainties (%)		Void worth (pcm)	Uncertainties (%)	
		SCALE6.1COV	SCALE6.2COV		SCALE6.1COV	SCALE6.2COV
S1	-1413 ± 13	3%	4%	-1451 ± 5	3%	3%
S2	439 ± 13	7%	8%	460 ± 5	6%	6%
S3	326 ± 12	5%	6%	354 ± 5	5%	6%
S4	219 ± 12	7%	8%	241 ± 5	6%	7%
S5	-264 ± 11	3%	3%	-268 ± 5	3%	4%
S6	203 ± 12	11%	12%	202 ± 5	12%	12%
All[a]	-536 ± 12	21%	22%	-	-	-

Scenarios 2, 3, and 4, where the sodium is voided from the inner fuel zones, exhibit uncertainties up to 7-8 %

S/U analysis of sodium void

Spatial distribution of the Na void worth uncertainties

	SCALE			SERPENT		
Na voiding Scenario	Void worth (pcm)	Uncertainties (%)		Void worth (pcm)	Uncertainties (%)	
		SCALE6.1COV	SCALE6.2COV		SCALE6.1COV	SCALE6.2COV
S1	-1413 ± 13	3%	4%	-1451 ± 5	3%	3%
S2	439 ± 13	7%	8%	460 ± 5	6%	6%
S3	326 ± 12	5%	6%	354 ± 5	5%	6%
S4	219 ± 12	7%	8%	241 ± 5	6%	7%
S5	-264 ± 11	3%	3%	-268 ± 5	3%	4%
S6	203 ± 12	11%	12%	202 ± 5	12%	12%
All[a]	-536 ± 12	21%	22%	-	-	-

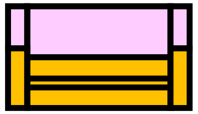


The largest uncertainty occurs for Scenario 6 corresponding to the voiding of the outer fuel

S/U analysis of sodium void

Spatial distribution of the Na void worth uncertainties

Na voiding Scenario	SCALE			SERPENT		
	Void worth (pcm)	Uncertainties (%)		Void worth (pcm)	Uncertainties (%)	
		SCALE6.1COV	SCALE6.2COV		SCALE6.1COV	SCALE6.2COV
S1	-1413 ± 13	3%	4%	-1451 ± 5	3%	3%
S2	439 ± 13	7%	8%	460 ± 5	6%	6%
S3	326 ± 12	5%	6%	354 ± 5	5%	6%
S4	219 ± 12	7%	8%	241 ± 5	6%	7%
S5	-264 ± 11	3%	3%	-268 ± 5	3%	4%
S6	203 ± 12	11%	12%	202 ± 5	12%	12%
All[a]	-536 ± 12	21%	22%	-	-	-



Additivity of effects when voiding all regions simultaneously can be considered but with a large uncertainty since positive spatial correlations among the zones of the core increase the uncertainty in the sum of reactivities. No correlation would lead to underestimate the overall uncertainty during transient uncertainty propagation

Uncertainty breakdown (up to 95%) for the spatial distribution of sodium void worth using 44g SCALE6.1 covariance

Quantity	S1		S2		S3		S4		S5		S6	
	SCALE	SERPENT	SCALE	SERPENT	SCALE	SERPENT	SCALE	SERPENT	SCALE	SERPENT	SCALE	SERPENT
^{238}U elastic										0.93		
^{238}U inelastic	2.14	1.90	2.75	2.32	2.70	3.26	4.30	3.65	2.18	1.86	5.36	6.76
^{238}U elastic-inelastic	0.84	0.37		-1.26			1.24	-1.78	0.83	-1.30	2.58	
^{238}U capture			1.92	1.56	1.46	1.20	1.37	1.26	0.36		3.37	3.27
^{238}U nubar	0.37									0.35		
^{238}Pu fission											2.09	
^{239}Pu elastic										0.36		
^{239}Pu elastic-inelastic										0.44		
^{239}Pu capture			1.23	1.01							2.12	
^{239}Pu fission			1.24	1.10	0.95		1.21	1.11		0.37		2.21
^{239}Pu nubar	0.79	0.81	2.32	2.09	1.36	1.22	1.96	1.85	0.80	0.86	3.95	4.21
^{239}Pu χ	0.65								0.52			
^{240}Pu nubar												
^{16}O elastic					0.98	1.18				0.47		
^{23}Na elastic	1.30	1.21	2.67	2.30	2.28	1.98	2.22	2.33	1.33	1.39	3.35	3.20
^{23}Na inelastic			3.99	3.55	2.26	2.25	3.73	3.77			6.18	6.60
^{23}Na capture			1.07					1.09			1.81	
^{23}Na elastic-inelastic			-1.68	-1.55	-0.90	-1.04		-1.59		-0.37	-1.38	
^{56}Fe elastic	0.58	0.47							0.37	0.72		
OVERALL	**3.06**	**2.59**	**6.69**	**5.58**	**4.94**	**4.67**	**7.04**	**5.84**	**3.03**	**2.63**	**11.50**	**11.20**

Summary and Conclusions

- SCALE MG TSUNAMI-3D and GPT SERPENT2 modules were assessed for a S/U analysis of the sodium void in an ASTRID-like core using SCALE6.1 and 6.2 covariance libraries
- They predict very similar sensitivities to nuclear data for nominal k-eff. Larger differences for Na void worth, mainly with respect to elastic cross sections
- Sensitivity coefficients to nuclear data:

  → ^{239}Pu nubar and ^{239}Pu fission involve high sensitivities of k-eff and Na void worth for all void patterns

  → ^{23}Na elastic and ^{56}Fe elastic important for voiding of sodium plenum

  → ^{23}Na elastic and inelastic and ^{16}O elastic important for voiding of fuel zones

Summary and Conclusions

- Uncertainties (using SCALE covariances):
  - → Uncertainties in the Na void worth depend on the voided region, being lower in the plenum regions (~3%) than in fuel regions (up to 12%)
  - → No additivity of local uncertainties when voiding all regions (~20%) because of positive spatial correlations among the local zones
  - → Using SCALE6.2COV reduces k-eff uncertainty ~200 pcm but slightly increase Na void uncertainties
  - → ^{238}U inelastic and ^{239}Pu cross sections main responsible of k-eff uncertainty
  - → Na void uncertainties are mainly due to uncertainties in:
    - → ^{238}U inelastic for all void patterns
    - → ^{23}Na elastic for voiding of sodium plenums
    - → ^{23}Na elastic and ^{23}Na inelastic for voiding of fuel zones
  - → Dependencies of reactivity coefficients on nuclear data can be notably different from dependencies of the nominal k-eff

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