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Spatial interdependence of safety related effects in ESFR-SMART core

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Introduction

- ESFR-SMART core belongs to the low void SFR concepts relying:
  1) on upper sodium plenum with neutron absorber above it and
  2) on flux importance shift towards this plenum
     by means of bottom axial blanket.

- System behavior analysis of this concepts should be accomplished at best with spatial neutron kinetics coupled to thermal-hydraulics solver.

- However, often only point kinetics is applied.

- This simplification rely on so called temperature reactivity coefficients and its application to the transients with sodium boiling could be inaccurate.

- This study focuses on spatial dependence of these coefficients.

Issue with reactivity coefficients

- Spatial kinetics rely on parametrized multi-group cross-sections.
- They are not perfect, but they capture well the local conditions and address possible **changes in flux shape and spectrum**.
- **Point kinetics** assumes that

  1) flux can be separated into amplitude and shape function,
  2) the **shape function is constant during transient,**
  3) and that the coefficients are independent and additive.

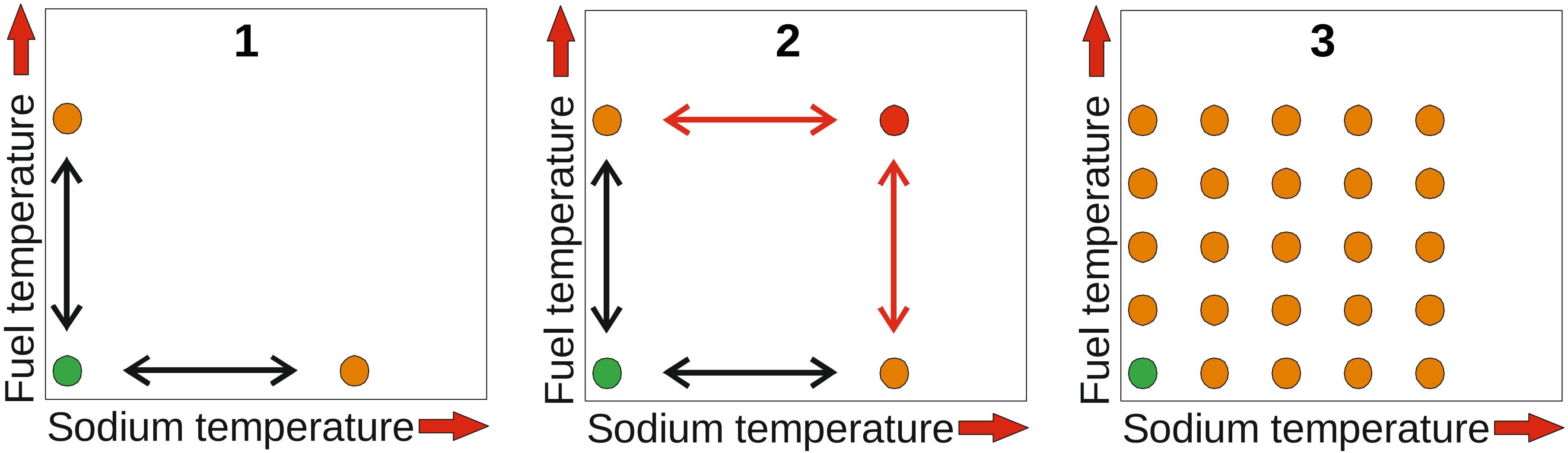
- During the **unprotected loss of flow** sodium boiling can occur in SFR core. This strong effect can result in:

  – **Shape function change** and
  – interdependency and non-additivity of the partial coefficients.

Coefficients derivation

The major coefficients are **fairly independent** (especially for mild transients).

1. Accordingly, coefficient are usually based on **nominal value** and **derivatives**. Actual coefficient is obtained by linear and logarithmic interpolations.
2. More precise would be **bi-interpolation** based on four values (needs 1 more point).
3. Sometimes also tabulated coefficients and interpolation could be used.



Four analyzed coefficients

1. Sodium void effect
   (sodium removal from the respective zone,
   keeping it between the wrappers)

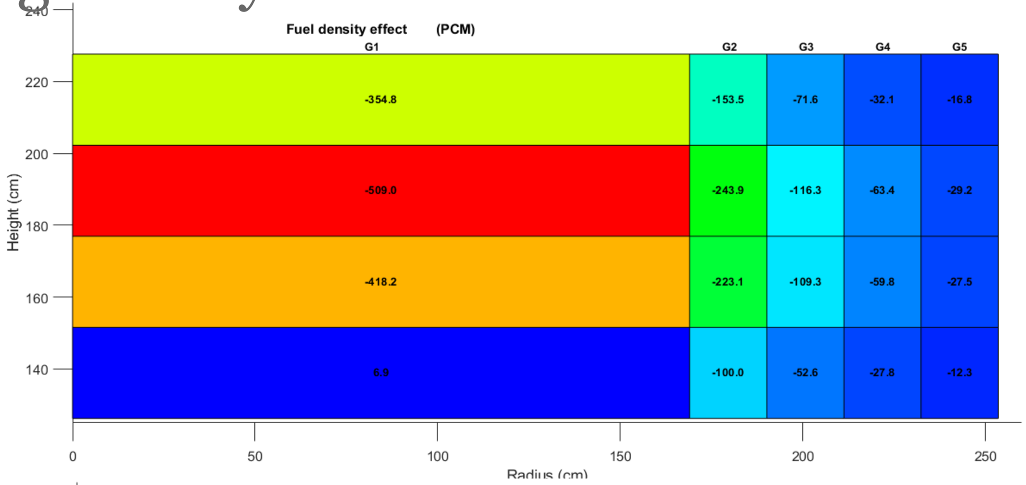
2. Doppler effect
   (fuel temperature increase by 1000K)

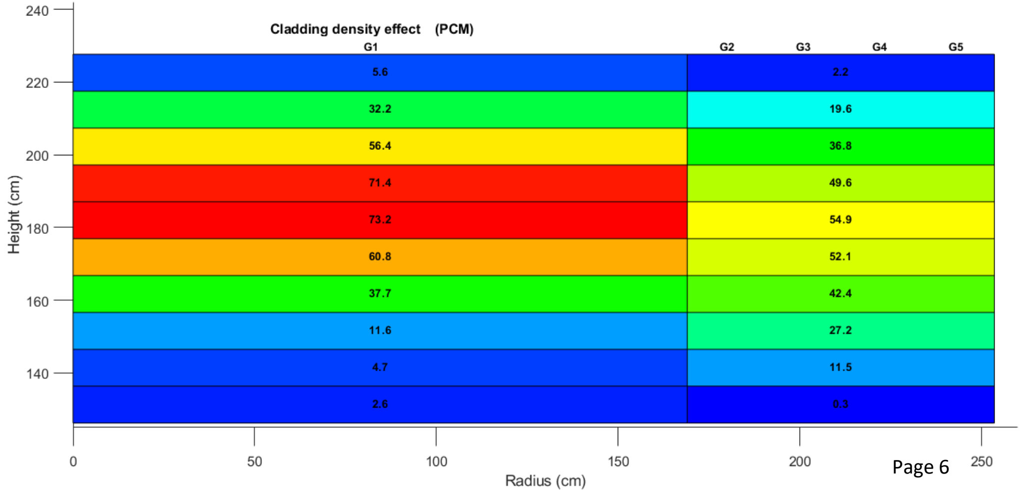
3. Fuel density effect
   (fuel density reduction by 10%, not preserving the total mass)

4. Cladding density effect
   (cladding density decrease by 10%, not preserving the total mass)

Fuel and cladding density effects

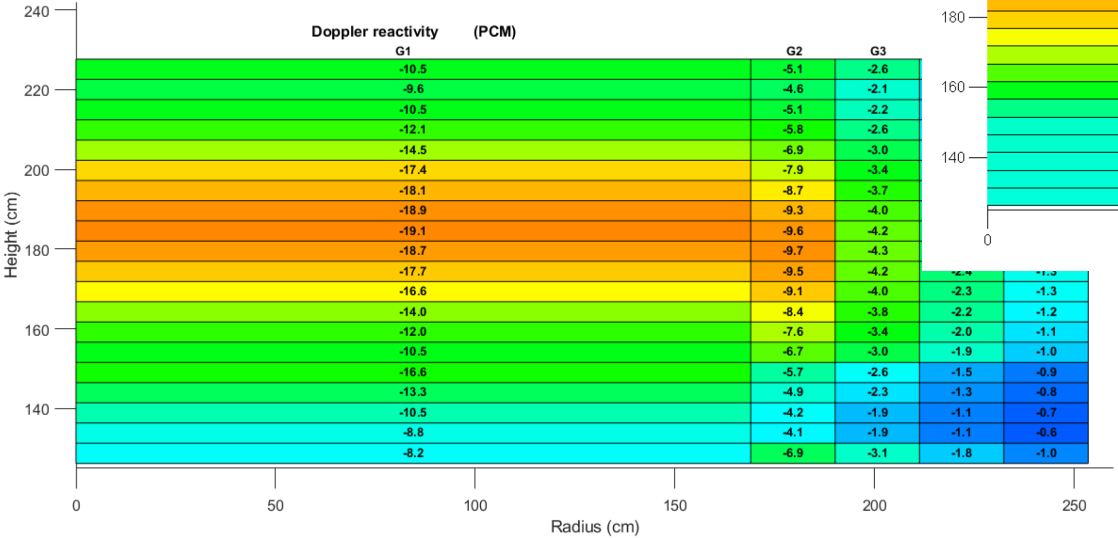
- Generally the effects distribution follows the flux importance.
- The effects have also three components:
  1. Direct, caused by XS change
  2. Spectral, cause by spectra change
  3. Leakage, caused by increased or decreased neutron leakage.

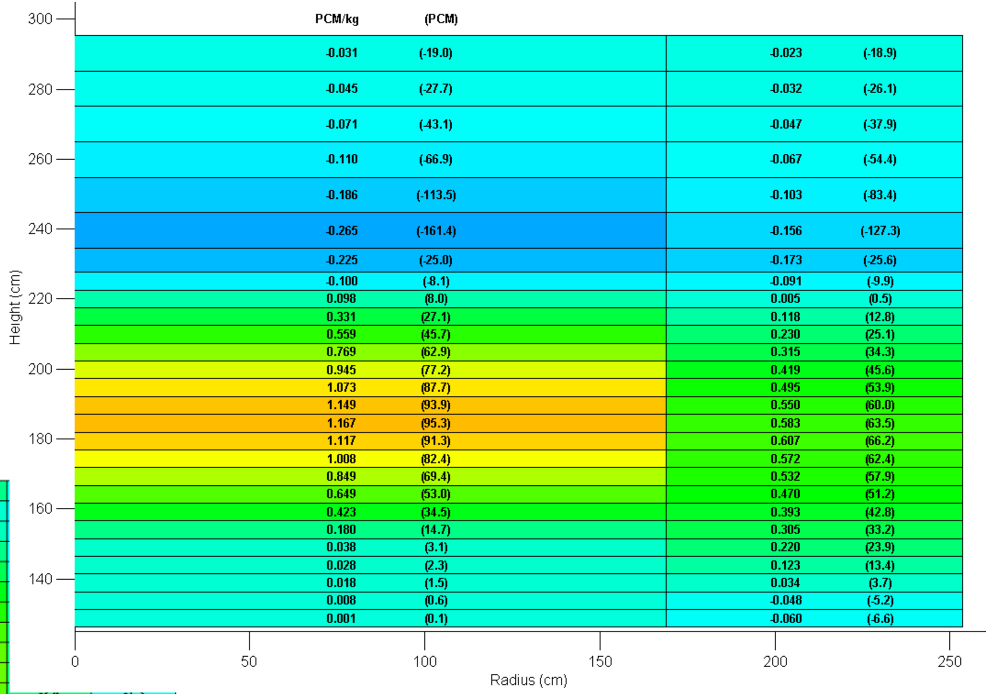




Doppler and void effect

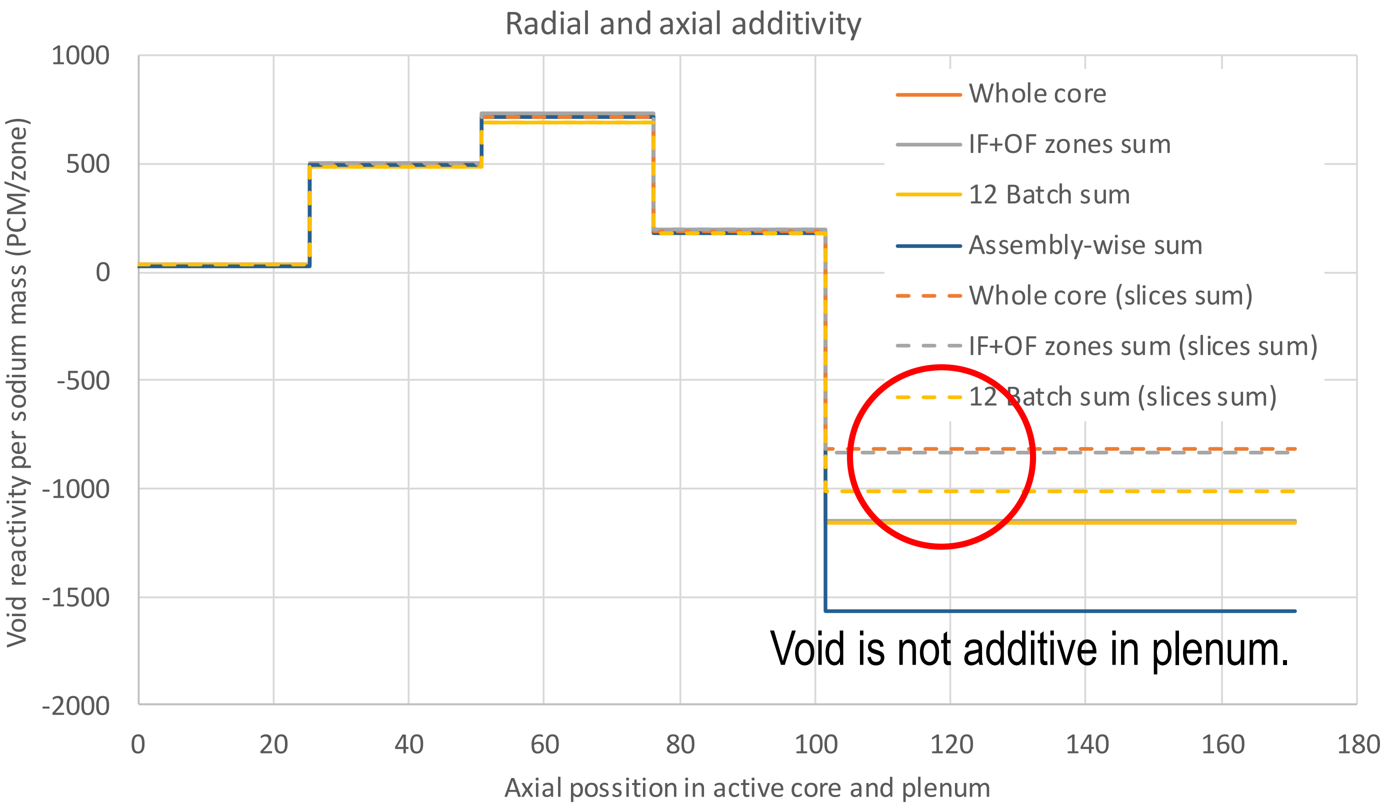
- On peripheries the spectral component can strongly influence the resulting effect.
- Plenum voiding, in case of void effect introduce negative reactivity.





Void effect additivity

- Void effect is not additive in the sodium plenum.



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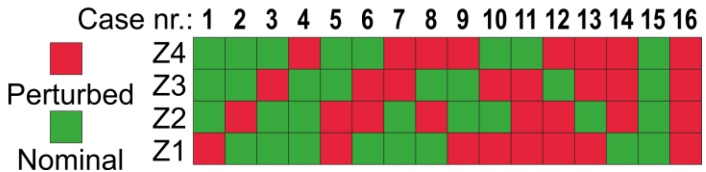
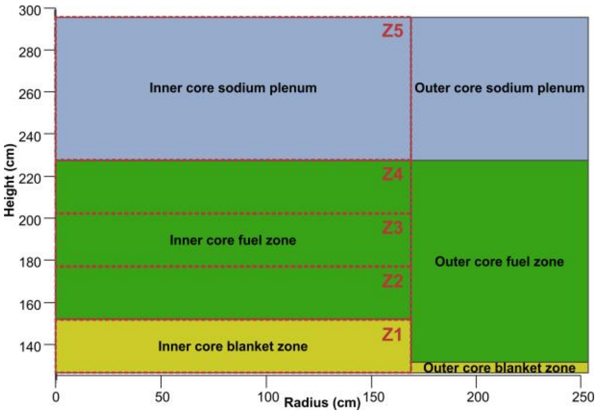
Mutual inter dependence: perturbation of the zones

- For sodium void effect all 5 zones were used.
- There are 32 possible voiding option.

- For other effect: **Fuel temperature, Fuel density, and Cladding density** only the 4 core zones have been used, resulting in 16 combinations.





Void mutual inter dependence

- The void effect is positive in the core and negative in the sodium plenum.
- **strongest** mutual inter **dependence** was identified for **upper core part Z4 and plenum Z5**.

Void effect	**Impact of other zones on the main zone effect in %**														
Main Zone	**2 zones** (e.g. Z1+Z2)				**3 zones** (e.g. Z1+Z2+Z3)						**4 zones**				**5 zones**
Z1	Z2	Z3	Z4	Z5	Z2,Z3	Z2,Z4	Z2,Z5	Z3,Z4	Z3,Z5	Z4,Z5	Z2,Z3,Z4	Z2,Z3,Z5	Z2,Z4,Z5	Z3,Z4,Z5	Z2,Z3,Z4,Z5
7.4 (PCM)	-2	-24	-13	6	4	-5	22	-29	4	5	-19	15	21	3	14
Z2	Z1	Z3	Z4	Z5	Z1,Z3	Z1,Z4	Z1,Z5	Z3,Z4	Z3,Z5	Z4,Z5	Z1,Z3,Z4	Z1,Z3,Z5	Z1,Z4,Z5	Z3,Z4,Z5	Z1,Z3,Z4,Z5
266.0 (PCM)	0	9	1	5	9	1	6	10	-1	7	10	-1	8	-1	-1
Z3	Z1	Z2	Z4	Z5	Z1,Z2	Z1,Z4	Z1,Z5	Z2,Z4	Z2,Z5	Z4,Z5	Z1,Z2,Z4	Z1,Z2,Z5	Z1,Z4,Z5	Z2,Z4,Z5	Z1,Z2,Z4,Z5
470.6 (PCM)	0	5	3	-9	5	3	-9	8	-13	-8	8	-13	-8	-12	-12
Z4	Z1	Z2	Z3	Z5	Z1,Z2	Z1,Z3	Z1,Z5	Z2,Z3	Z2,Z5	Z3,Z5	Z1,Z2,Z3	Z1,Z2,Z5	Z1,Z3,Z5	Z2,Z3,Z5	Z1 Z2,Z3,Z5
137.9 (PCM)	-1	2	12	-68	2	11	-68	14	-65	-62	13	-65	-62	-62	-62
Z5	Z1	Z2	Z3	Z4	Z1,Z2	Z1,Z3	Z1,Z4	Z2,Z3	Z2,Z4	Z3,Z4	Z1,Z2,Z3	Z1,Z2,Z4	Z1,Z3,Z4	Z2,Z3,Z4	Z1 Z2,Z3,Z4
-669.4 (PCM)	0	-2	7	14	-2	6	14	10	12	22	10	11	21	26	26

Krepel, J., et al., 2021, SPATIAL INTERDEPENDENCE OF SAFETY RELATED EFFECTS IN ESFR-SMART CORE, FR21 (FR22) proceedings.

Doppler effect mutual inter dependence

- The Doppler effect (+1000K) is generally negative.
- Mutual inter dependence is much weaker (smaller flux shape changes).

Doppler effect	**Impact of other zones on the main zone effect in %**						
Main Zone	**2 zones** (e.g. Z1+Z2)			**3 zones**			**4 zones**
Z1	Z2	Z3	Z4	Z2,Z3	Z2,Z4	Z3,Z4	Z2,Z3,Z4
-55.3 (PCM)	-16	4	10	0	1	3	0
Z2	Z1	Z3	Z4	Z1,Z3	Z1,Z4	Z3,Z4	Z1,Z3,Z4
-75.9 (PCM)	-12	-7	-1	-10	-8	-8	-10
Z3	Z1	Z2	Z4	Z1,Z2	Z1,Z4	Z2,Z4	Z1,Z2,Z4
-91.7 (PCM)	2	-6	2	4	-2	-4	-4
Z4	Z1	Z2	Z3	Z1,Z2	Z1,Z3	Z2,Z3	Z1,Z2,Z3
-57.3 (PCM)	10	-2	3	14	3	1	2

Krepel, J., et al., 2021, SPATIAL INTERDEPENDENCE OF SAFETY RELATED EFFECTS IN ESFR-SMART CORE, FR21 (FR22) proceedings.

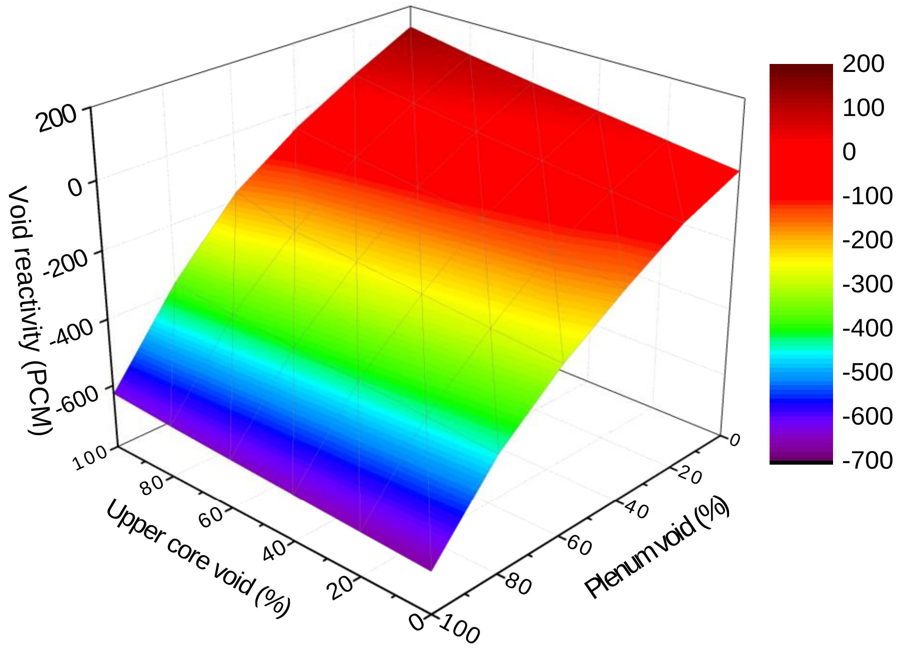
Additivity of the effect in active core

- Sodium void effect, Fuel temperature, Fuel density, and Cladding density are **all reasonable additive in the active core**

Additivity in the core	Z1234	Z1+Z234	Z2+Z134	Z3+Z124	Z4+Z123	Z12+Z34	Z13+Z24	Z14+Z23	Z1+2+3+4
Sodium void effect	**923.2**	924.6	895.9	884.7	904.7	898.0	883.2	904.5	881.9
Difference in %	reference	0.2	-3.0	-4.2	-2.0	-2.7	-4.3	-2.0	-4.5
Fuel temperature effect	**-275.9**	-275.7	-283.7	-279.6	-274.9	-273.4	-281.1	-280.4	-280.3
Difference in %	reference	-0.1	2.9	1.3	-0.3	-0.9	1.9	1.7	1.6
Fuel density effect	**-1166.0**	-1166.4	-1237.6	-1256.6	-1236.7	-1238.1	-1256.3	-1236.4	-1275.1
Difference in %	reference	0.0	6.1	7.8	6.1	6.2	7.7	6.0	9.4
Cladding density effect	**366.1**	365.1	362.0	360.5	363.2	362.5	360.6	362.2	359.3
Difference in %	reference	-0.3	-1.1	-1.5	-0.8	-1.0	-1.5	-1.1	-1.9

Void in upper part

- Sodium void effect is **not really additive for upper fuel Z4 and sodium plenum Z5 zones.**
- Sodium plenum void increases neutron leakage and is not linear =>
- However summation of two effects in Z4 and Z5 is more conservative than bi-linear interpolation between 4 points. *(only because of compensating effects)*



Additivity with plenum	Z2345	Z2+Z345	Z3+Z245	Z4+Z235	Z5+Z234	Z23+Z45	Z24+Z35	Z25+Z34	Z2+3+4+5
Sodium void effect	73.5	76.1	130.5	159.3	247.8	135.1	164.6	235.8	205.123
Difference in %	reference	3.5	77.5	116.7	237.1	83.8	123.9	220.7	179.0

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Summary

- Coupled neutronics & TH simulation are important for conceptual studies as well as for safety assessment.
- Accuracy of the simulation tool should be selected according to the importance of the results.
- Standard solution uses multi-group XS as the coupling between TH & neutronics solver.
  (the solver uses prepared XS to calculate flux shape)
- Transients without sodium boiling, can be well addressed by TH & point kinetics.
- In transients with sodium boiling, which are CPU demanding from TH perspective, point kinetics is less precise and the related CPU savings are less important.

Wir schaffen Wissen – heute für morgen

Thank you for your attention.