SPATIAL INTERDEPENDENCE OF SAFETY RELATED EFFECTS IN ESFR-SMART CORE

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Abstract

ESFR-SMART belongs to the family of Gen-IV sodium cooled reactors. For the demonstration of its safety performance the detailed knowledge of selected safety related parameters is required. It is very important to know not only their spatial distribution and amplitude but also their mutual interdependence. In this paper the sodium void effect, the Doppler effect, and the density effects of fuel and cladding were analyzed. Impact of these effects on reactivity was enumerated by the ERANOS 2 code. It was applied for detail mapping of these effects and analysis of the mutual influence between the local effects. For each of the effect and for each of the interdependence many direct calculation were accomplished. It was found that all studied effects are spatially additive in the active zone. However, in case of sodium void, the effect is not additive in the upper core and sodium plenum above the core. Especially the top fuel zone is strongly influenced by sodium plenum and vice versa. Furthermore, there is a difference between radial and axial additivity of the void effect. Few approaches for simplified calculation of the local void effect in the upper core part was assessed. It was found that for instance the 4 points interpolation, is not necessarily conservative from safety perspective. Accordingly, the sum of local coefficient as the simplest solution or more complex interpolation should be preferred; or more sophisticated mapping applied.

1. INTRODUCTION

The reactor analysed in this study is the reference design of the H2020 ESFR-SMART project with the identical name ESFR-SMART [1]. The core was analysed at the equilibrium End Of Cycle (EOC) state [2]. The EOC state and all other simulations were accomplished by the ERANOS 2 code [3] coupled with the EQL3D procedure [4] using JEFF 3.1 nuclear data library. The EQL3D procedure simulates the reactor batch burnup by assembly shuffling or refuelling at a given position. It has also the capability to simulate reactivity effects for the respective EOC state. The effects considered in this study were:

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)

The mapping of these effects was accomplished at different resolutions. In the most detailed maps, the perturbation of one local node caused a reactivity change of a less than one PCM (Per Cent Mille). This is beyond the accuracy even for deterministic code like ERANOS, hence the methodology from [5] was adopted, where the nominal and perturbed calculations were launched, using a restart option, from the same flux distribution and reactivity value obtained after fixed number, e.g. 25, of iterations was adopted. For both calculations the absolute reactivity value is not converged, however their difference is already stabilized.

The four selected effects in this paper were calculated for different locations in the active core. In case of sodium void effect also the sodium plenum was accounted for. The interdependency between the two major effects (sodium void and Doppler effects) was already shown in [5]. The major zones selected in this study are illustrated by FIG. 1, where internal blanket represents zone Z1, internal fuel is divided into 3 zones Z2, Z3 and Z4, and

internal sodium plenum is zone Z5. In the outer part of the core the respective zones labels include “o” at the end. The zone Z1o consist of outer blanket and outer bottom fuel part.

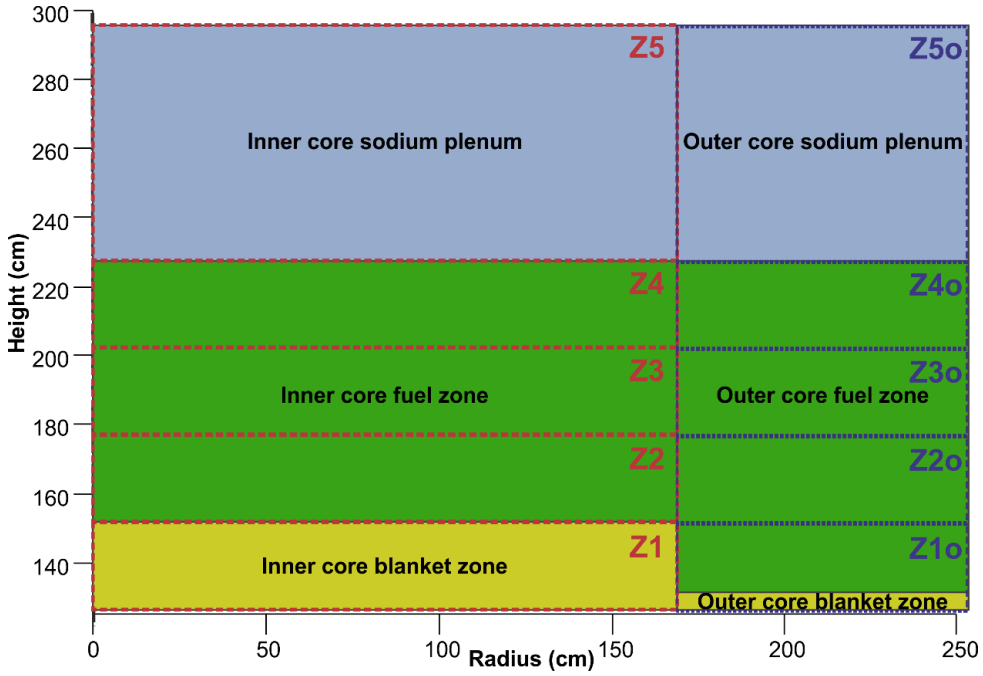


FIG. 1. Axial cut of the ESFR-SMART inner and outer core with highlighted 4 fuel zones and 1 sodium plenum zone.

2. EFFECTS MAPPING

For many calculations of the four selected effects more detailed axial or radial distributions than in FIG. 1 were applied. The respective mapping is graphically presented together with the results. The map resolutions in radial direction were: whole core, separated inner and outer core, separation by fuel group (IF1-5, OF1-5), separation by cooling groups (G1-5) and ultimately separation into individual assemblies. In axial direction, the map was divided into: whole core, core and plenum, 5 zones (FIG. 1), 10 or 20 zones in fuel and 4 or 7 zones in sodium plenum. Following four figures illustrate the resulting maps. These maps can be applied in a system code simulation in case that it relies on point kinetics approximation. Application of these maps can provide better results that one integral coefficient. At the same time, the correctness and conservatives of this approach should be confirmed from safety perspective. It depends on additivity and mutual interdependence of the values presented in each map, which is analysed in this paper.

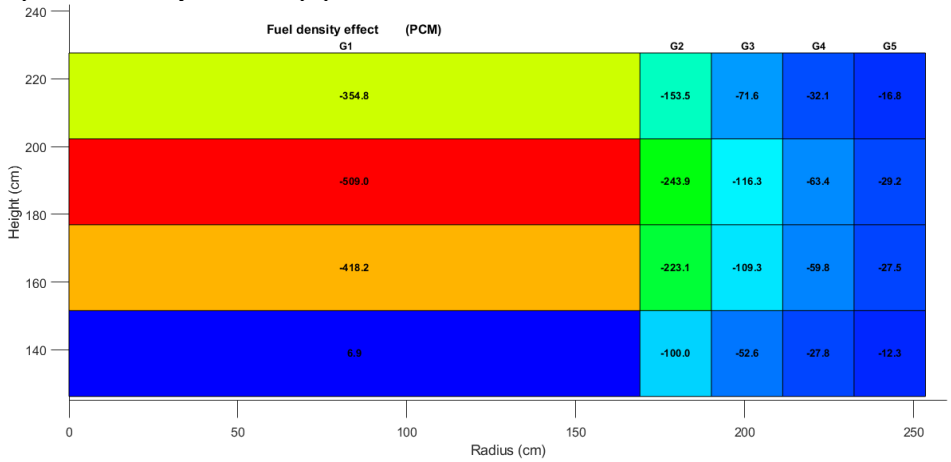


FIG. 2. Fuel density effect mapping for 4 axial layers and 5 radial nodes according to cooling groups G1-5.

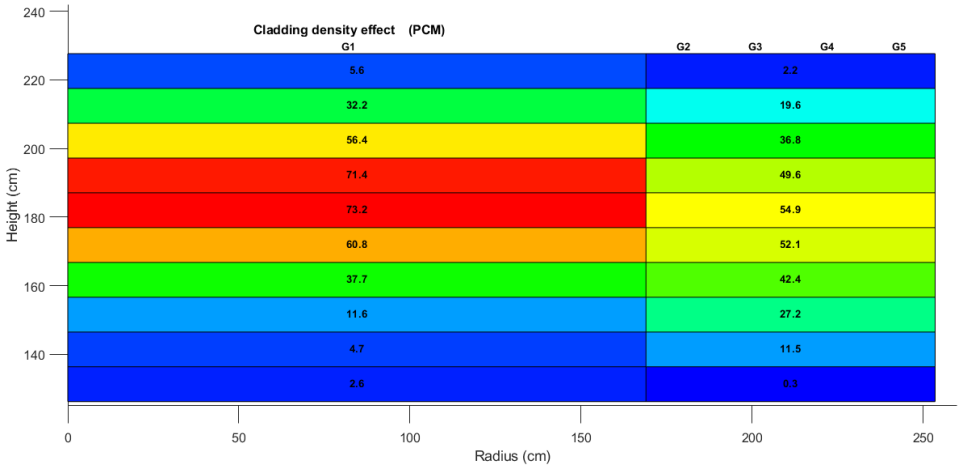


FIG. 3. Cladding density effect mapping for 10 axial layers and 2 radial nodes according to cooling groups G1-5.

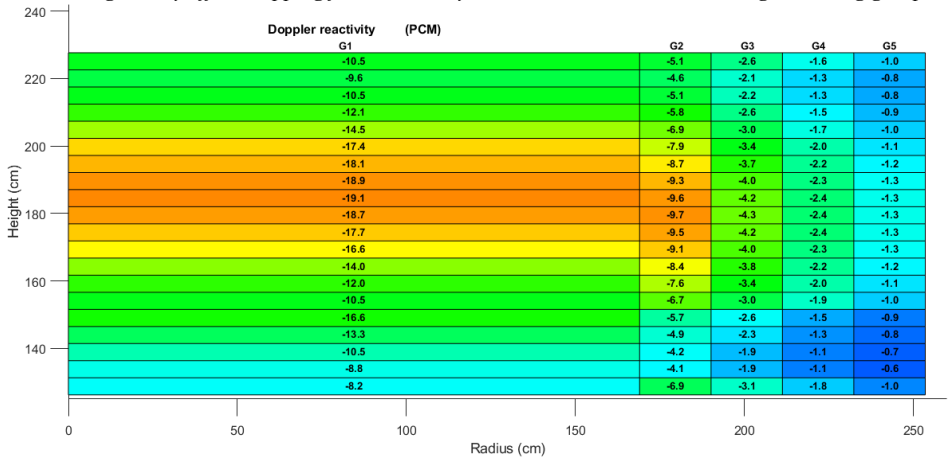


FIG. 4. Doppler reactivity mapping for 20 axial layers and 5 radial nodes according to cooling groups G1-5. The colour scheme follows Dopper effect reactivity normalized per zone size.

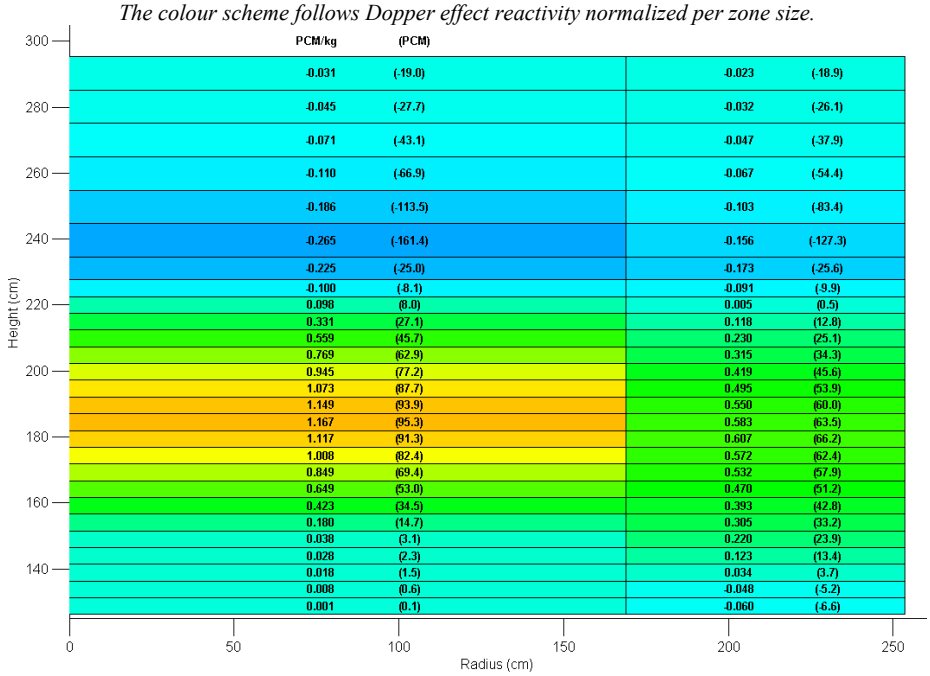


FIG. 5. Void reactivity mapping for 27 axial layers and 2 radial nodes. The colour scheme follows the void reactivity normalized per kg of voided sodium.

3. MUTUAL INFLUENCE OF COARSE AXIAL ZONES

To analyse the mutual influence of the zone-wise effects the 5 zones of the inner active core were selected (see FIG. 1). The sodium plenum above the inner core as fifth zone was considered only for the void effect. The division into 4 or 5 zones results in respective 16 or 32 possible combinations. These combinations are illustrated in FIG. 6 and FIG. 7. Set of these results can be used for multi-linear interpolation to provide reactivity effect for any void distribution within these 5 zones. However, the required formula for penta-linear interpolation is beyond the scope of this paper. Since the strongest mutual influence was identified for the void effect between zones Z4 and Z5 (top fuel quarter and sodium plenum) the bi-linear interpolation will be used later as an illustration.

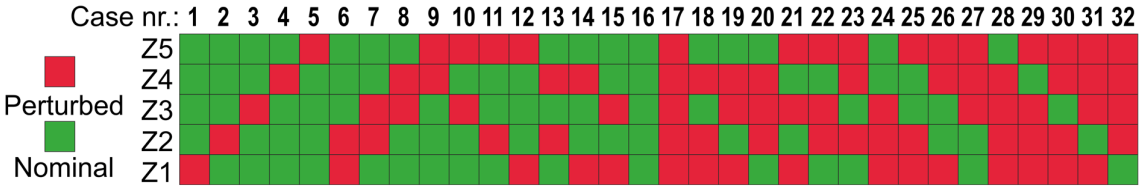


FIG. 6. Overview of 32 possible combinations for perturbing (voiding) inner core and sodium plenum.

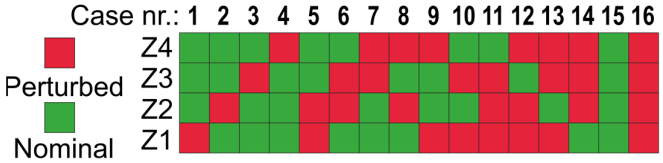


FIG. 7. Overview of 16 possible combinations for inner core perturbation for the other effects (exclusive void).

3.1. Void effect interdependence

The void effect in each of the 5 defined zones was obtained, as for the above mapping cases, by several direct simulations. The resulting void effects are presented in the first column of Table 1. Obviously, the void effect is most positive in the centre of the core Z3, where the flux importance is the highest and where the voiding causes predominantly spectral changes. In the sodium plenum Z5 it is negative, because the plenum voiding mainly increases the neutron leakage from the core. In the bottom Z1 and top Z4 fuel zone the void effects consist of spectral component and leakage component. The ESFR-SMART core belongs to the low void cores [6], [7] and as such it uses bottom fertile blanket to increase the flux importance in the upper fuel part and in the sodium plenum (see FIG. 5). Accordingly, the void effect in Z1 is much lower than in Z4 and it is the highest in Z3. For more detailed void effect distribution and interdependence analysis refer to [8], [9], [10], [11].

TABLE 1. Void effect reactivity in fuel and plenum zones (in PCM) and the influence of other zones perturbation (in %).

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

Mutual impact of the void effects in the 4 fuel zones is driven by the shift of respective flux importance. Voided zone is more reactive, because the local neutron capture is reduced [12]. Accordingly, the void effect in

bottom blanket Z1 becomes weaker when also Z2, Z3 or Z4 is voided (see top line of Table 1.). Voiding of sodium plenum Z5 decreases locally the reactivity. Thus it slightly increases the void effect in the bottom fuel part (Z1 +6% and Z2 +5%). However, in the central fuel zone (Z3) the plenum void causes already 9% reduction of the effect and especially in the upper core zone Z4 it has tremendous impact. The local void effect is reduced by 68% when sodium plenum is voided.

The void effect in sodium plenum Z5 is not really influenced by Z1 and Z2 voiding. The Z3 voiding results in 7% increase of the negative plenum void effect and Z4 even in 14% increase. In absolute reactivity the mutual impact of Z4 and Z5 is comparable and the strongest from all analysed mutual effects. From the cases where 3 or more zones are voided it can be seen that the negative plenum void get stronger with every additionally voided fuel zone. Zones Z3 and Z4 alone cause increase by 7% and 14% respectively. Simultaneous void of Z3 and Z4 results in 22% increase and when Z2, Z3, and Z4 are all voided the plenum void effect get stronger by 26%. The impact of Z1 is negligible. On the other hand the impact of plenum void on Z4 gets weaker when also Z3 and/or Z2 is voided.

3.2. Partial void effect and interpolation between Z4 and Z5 zones

The strong mutual dependence of Z4 and Z5 was further studied by introducing intermediate steps of voiding. The fully flooded case (0% void) and fully voided case (100% void) was accompanied by 20%, 40%, 60% and 80% void level. It resulted in 25 calculations, which covered all possible combinations of Z4 and Z5 partial voids. The results can be seen in right FIG. 8 or in [8]. It is obvious that plenum void behaves non-linearly. The negative effect becomes stronger with increased plenum void level. In system codes, which are relying on point kinetics, often the void effect maps are applied, where local sodium concentration and local void effect are calculated and summed up to the integral effect. It assumes additivity of the local void effects and corresponds to sum of interpolations between one nominal and set of individual perturbed cases. In case of Z4 and Z5 zones it requires two perturbed points illustrated by left FIG. 9. The respective sum of two interpolated values is shown in left FIG. 10. Such an interpolation rely on independent Z4 and Z5 results and provide highest error when both zones are voided simultaneously. This simple model can be replaced by the bi-linear interpolation illustrated by middle FIG. 9, where fourth double-perturbation point is needed. The bi-linear interpolation is described by following equation:

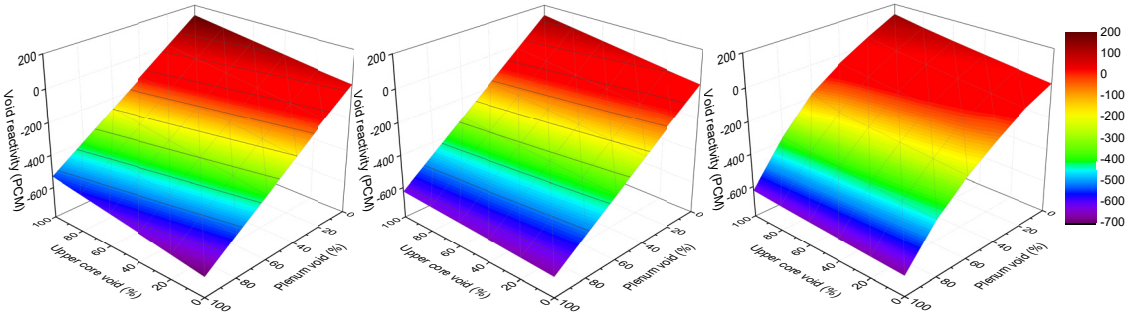
$$V\left(z_4, z_5\right) = w_{0,0}V\left(0,0\right) + w_{0,1}V\left(0,1\right) + w_{1,0}V\left(1,0\right) + w_{1,1}V\left(1,1\right), \tag{1}$$

where the coefficients w are obtained from relative void level z_4 and z_5 (value between 0 = no void and 1 = full void in Z4 and Z5 zones) and V represents the interpolated reactivity for relative void level z_4 and z_5 or the simulated void reactivities in corner points: (0,0), (0,1), (1,0) and (1,1):

$$\begin{aligned} w_{0,0} &= \left(1-z_4\right)\left(1-z_5\right) & V\left(0,0\right) &= 0 \\ w_{0,1} &= \left(1-z_4\right)\left(z_5\right) & V\left(0,1\right) &= -669.4 \\ \text{and} & & & \\ w_{1,0} &= \left(z_4\right)\left(1-z_5\right) & V\left(1,0\right) &= 137.9 \\ w_{1,1} &= \left(z_4\right)\left(z_5\right) & V\left(1,1\right) &= -625.1 \end{aligned} \quad . \tag{2}$$

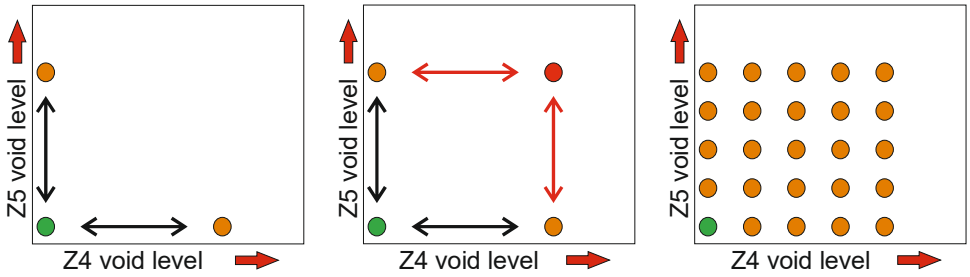
The results of bi-linear interpolation are shown in middle FIG. 8. However, it does not fully resolve the accuracy issue. The differences between nominal 25 points calculation and 3 or 4 points interpolation is shown in FIG. 10. Four points interpolation improves the error for the combined void V(1,1). This can be seen from the difference between left and right FIG. 10 at top right corner. At the same time, the bi-linear interpolation cannot address the non-linearity of the plenum void. Accordingly, it introduces strong overestimation of the negative plenum void effect, when it is voided only by 40-80% (see the middle area of right FIG. 10). This overestimation is absent or weaker for the 3 point interpolation (see right FIG. 10). Accordingly, 3 points interpolation or actually simple map summing seems more conservative option.

The conservativeness of simple sum (left FIG. 10) is caused by compensating errors. The under prediction of bi-linear interpolation between 4 points is caused by the effect non-linearity (right FIG. 8). Accordingly, it can improved either by other than linear interpolation between 4 points or by application to more than 4 point (see right FIG. 9).



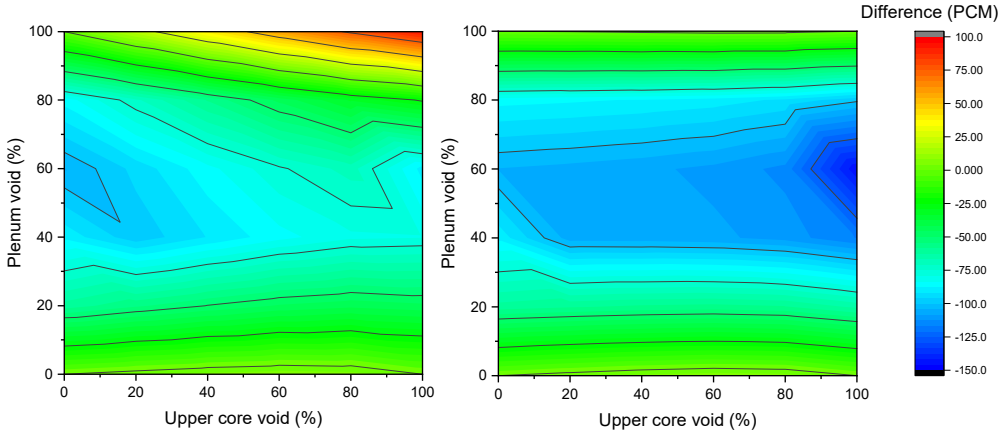
A) B) C)

FIG. 8. Mutual interdependence of void effect in upper fuel part Z4 and sodium plenum Z5: A) interpolation between 3 corner points, B) interpolation between 4 corner points, and 3) direct simulation of 25 points.



A) B) C)

FIG. 9. Possible options how to calculate total void effect in Z4 and Z5 by means of: A) 3 simulated points, B) 4 simulated points and C) 25 simulated points.



A) B)

FIG. 10. Error introduced by: A) interpolation between 3 corner points, B) interpolation between 4 corner points.

3.3. Interdependence of other effects

The Doppler effect caused by 1000K fuel temperature increase is negative everywhere in the active core (see FIG. 4). Since it introduces negative reactivity, it is shaping the flux in opposite direction than the void effect. Accordingly, the fuel temperature increase in Z2 reduces flux importance and so the Doppler effect in Z1 by 16% and, vice-versa (see Table 2.). Similarly, temperature increase in Z4 amplify Doppler effect in Z1 by 10%. The mutual influence of Z2 and Z3 is weaker and around 7%.

In the fuel zone, the interdependence is similar for the local Doppler and void effects. Since these are predominantly spectral effects, they are not really cumulative in the sense that perturbation of more zones does not have the stronger impact on the observed zone than sum of partial perturbation. For instance Z2 Doppler effect is decreased by -12% or -7% when Z1 or Z3 is perturbed, respectively, but the common influence of Z1 and Z3 is -10%. Similar behaviour can be seen for the void effect in the fuel zones, but not in the plenum zone.

TABLE 2. Doppler effect in fuel zones (in PCM) and the influence of other zones perturbation (in %).

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

The fuel density effect is simulated by 10% fuel density reduction and the fuel mass is not preserved. It thus introduces a negative effect in the fissile zones Z2, Z3, and Z4 and a positive effect in the blanket zone Z1. It is not really a spectral effect. The reduced fuel density results in higher parasitic neutron absorption by non-fuel materials and to higher neutron leakage when perturbing peripheral zones. Since the zones are mutually interdependent mainly through varying flux importance, cumulative behaviour can be seen in Table 3. For instance Z4 effect is by -5% and -10% influenced by Z2 and Z3; however, the common influence of Z2 and Z3 is -20%.

TABLE 3. Fuel density effect in fuel zones (in PCM) and the influence of other zones perturbation (in %).

Fuel density 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
6.9 (PCM)	-3	5	6	2	0	5	5
Z2	Z1	Z3	Z4	Z1,Z3	Z1,Z4	Z3,Z4	Z1,Z3,Z4
-418.2 (PCM)	0	-9	-4	-9	-4	-17	-17
Z3	Z1	Z2	Z4	Z1,Z2	Z1,Z4	Z2,Z4	Z1,Z2,Z4
-509.0 (PCM)	0	-8	-7	-8	-7	-18	-18
Z4	Z1	Z2	Z3	Z1,Z2	Z1,Z3	Z2,Z3	Z1,Z2,Z3
-354.8 (PCM)	0	-5	-10	-5	-10	-20	-20

The cladding density effect is simulated by 10% cladding density reduction. It is positive in all fuel zones and roughly 3 to 4 times weaker than the fuel density effect. Since the effect is weaker, also the mutual interdependence is generally weaker (see Table 4.). Here it can be pointed out that 1000K heat up of fuel in Doppler effect case or sodium removal from big zone in void effect case are rather maximal than realistic perturbations. Even though, in void effect case the sodium boiling can in deed cause strong local void.

TABLE 4. Cladding density effect in fuel zones (in PCM) and the influence of other zones perturbation (in %).

Cladding density 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
11.2 (PCM)	6	8	4	12	7	1	8
Z2	Z1	Z3	Z4	Z1,Z3	Z1,Z4	Z3,Z4	Z1,Z3,Z4
107.5 (PCM)	1	2	0	3	1	3	4
Z3	Z1	Z2	Z4	Z1,Z2	Z1,Z4	Z2,Z4	Z1,Z2,Z4
176.8 (PCM)	0	1	1	2	1	3	3
Z4	Z1	Z2	Z3	Z1,Z2	Z1,Z3	Z2,Z3	Z1,Z2,Z3
63.9 (PCM)	1	1	4	1	3	5	5

4. ADDITIVITY OF THE REACTIVITY EFFECTS

4.4. Axial additivity

As already mentioned, many codes for system behaviour analysis rely on point kinetics and use maps of reactivity coefficients to calculate the integral effect. This approach assumes that flux importance is not changing dramatically and that the respective effects are thus additive. The additivity can be checked for any map resolution simply by summation of partial values. To roughly check the additivity in the core the four previously used core zones can be summed up. In Table 5 the total reactivity effects in the active core are compared with different zone-wise sums. The differences ranges from -5% in case of sodium void to +10% in case of fuel density effect. It seems that the amplitude of the difference is proportional to the absolute value of the effect. Hence, the very strong fuel density effect shows the highest difference in the map sum. Obviously, the selected 10% density reduction is not realistic, at least for nominal operation cases. Generally, it can be concluded that all effects are well additive in the active core. This is confirmed also by summation of more refined maps presented earlier.

However, the additivity assumption is not valid for the void effect if also the sodium plenum is included. In this case the relative difference can be more than 200% (see TABLE 6.). The reason for such a relative error is that the overall reactivity for Z2345 voiding is small, only 74 PCM. However, it composes from strong positive Z234 and negative Z5 components, which are much stronger. As a result the total effect is smaller that the deviation caused by zone-wise sum. Fortunately, the zone-wise sum is at least conservative and provide higher positive reactivity than the direct simulation.

TABLE 5. Total reactivity effects in the active core and their comparison with different zone-wise sums.

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

TABLE 6. Total void reactivity effect in the upper 4 zones and its comparison with different zone-wise sums.

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

4.5. Radial additivity

The radial additivity can be analysed by summing of the available maps in radial direction. The ultimate radial resolution in this study is based on assemble-wise values presented in FIG. 11. This map represent one third of the ESFR-SMART core. The sums of void and Dopper effects are -181 PCM and -497 PCM, respectively. The corresponding values are 74 PCM for void effect (TABLE 6) and -276 PCM for Doppler (Table 5). Hence, both radial sums are not conservative and predict stronger negative effect than direct calculation. In case of other more coarse radial resolutions the sum is more accurate. Especially in the case of void effects it can be also caused by selected approximation and deterministic nature of the simulation.

4.6. Combined axial and radial additivity

The combined axial and radial additivity is illustrated by FIG. 12, where the void effect in entire core (inner and outer zone) is divided into 5 axial nodes. For each node several values are presented, which originate from different maps. The respective summation is axial and radial simultaneously. As it can be seen, both axial and

radial additivity is acceptable in the fuel zones. However, there are strong differences in the sodium plenum zone. The whole core (1 radial group) value in sodium plenum is overlapped by inner and outer fuel zone sum (2 radial groups) and assembly groups sum (12 radial groups). Hence, radial nodalizations based on big zones provide similar value. However, the sum of radially refined maps (assembly-wise or cooling group sum) over predict the strength of negative void effect in sodium plenum.

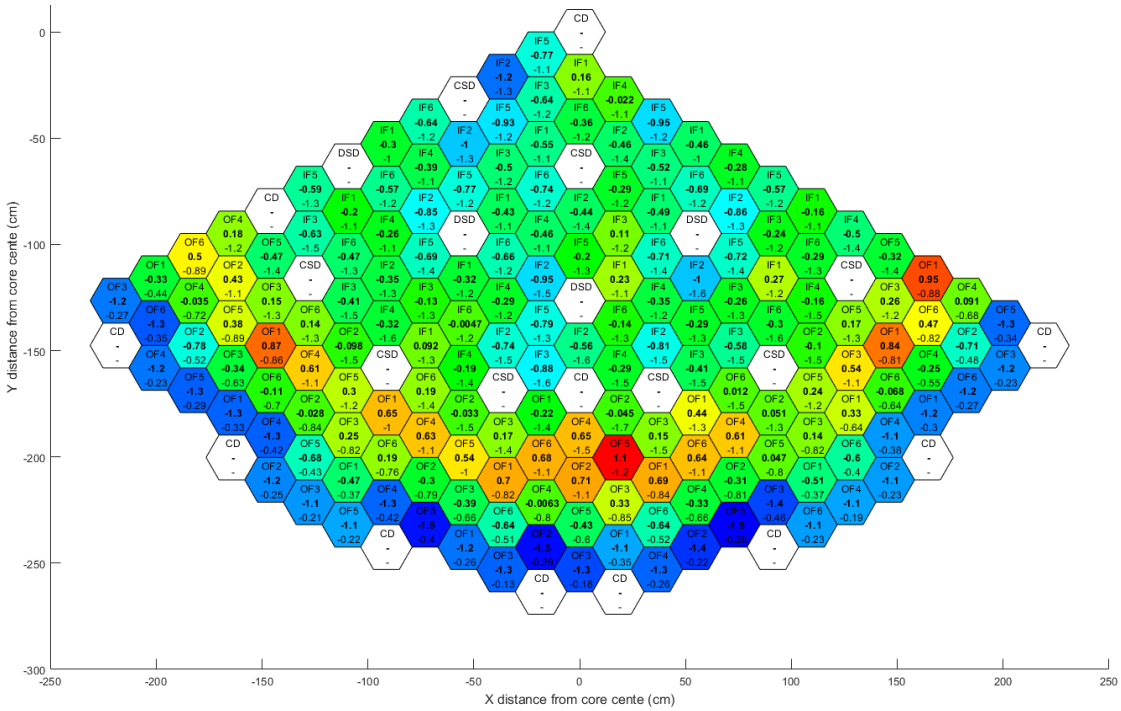


FIG. 11. Assembly-wise reactivity effect in PCM for void in the core and plenum (middle number) and Dopper in the core. The void effect is used for the colour scheme normalization.

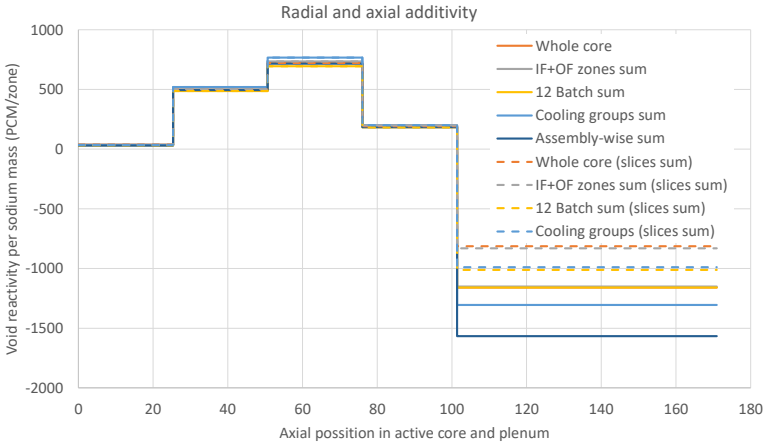


FIG. 12. Zone-wise values of the void effect originated as radial and axial sums in the entire core.

The FIG. 12 also shows that the same radial nodalizations provide different values, when axial slices are summed at the same time. The respective results are represented by dashed lines and obviously under predict the negative sodium plenum reactivity effect. Accordingly, radial refinement leads to over prediction and axial refinement to under prediction of the total void effect in the sodium plenum. Nonetheless, it is questionable, how realistic it is to completely void the sodium plenum. The nature of sodium boiling shows that it starts in upper fuel part and propagates axially upwards to the sodium plenum and downwards to the fuel within one assembly. Firstly later there may be radial propagation of the effect. So complete sodium plenum void is probably not the most realistic case and neither the mentioned over prediction nor the under prediction can be understood as an error. At

best more sophisticated “mapping” of the effect should be used, which follows the nature of the boiling. For instance for each assembly there could be a reactivity function of a sodium void level.

5. SUMMARY

In this paper four selected reactivity effects: sodium void, Doppler effect, fuel and cladding density effects have been analysed. Their global and local values in the ESFR-SAMRT core were calculated by ERANOS 2 code for EOC state obtained by EQL3D routine. For each effect several maps with different axial and radial resolutions have been created. The mutual interdependence of the local effects as well as the additivity of these effects was checked. As expected, it was shown, that the additivity is better and the interdependence weaker for effect with smaller absolute amplitude. Generally, it is also better in the active core. Mutual interdependence between the different effects was not discussed. However, the major effects, sodium void and Doppler effect, both result in spectrum hardening and Doppler effect is weaker in voided core and vice versa as shown in previous study [5].

The only identified strongly non-additive and non-linear effect is the sodium void in the upper fuel part and plenum. At this location, the effect includes very strong neutron leakage component. The simple map summation in this area represented by 3-points interpolation was compared with 4-points bi-linear interpolation and 25-points direct results. The conclusion is that due to the compensating errors, the simple 3-points interpolation is more conservative than 4-points bi-linear interpolation. The bi-linear interpolation option can improved either by other than linear interpolation between 4 points or by application to more than 4 point. Furthermore, the additivity of the void effect is problematic, because different radial and axial resolutions can lead either to over prediction or under prediction. However, the chosen reference, full sodium plenum void, is not really realistic and more sophisticated mapping, which follows the nature of the boiling, could possibly provide better balance between accuracy and conservativeness. Generally, since sodium boiling simulation is itself demanding, neutronic solution based on point kinetics should be avoided.

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