DETERMINATION OF WEIGHTING FACTORS AND FUNCTIONS FOR VVER-440 EX-CORE NEUTRON DETECTORS USING MCNP5

Gabriel Farkas[1], Vladimír Kršjak[2], Vladimír Slugeň[1], Ján Haščík[1]

[1]SUT in Bratislava, FEEIT
Ilkovičova 3, 81219 Bratislava

[2]IE JRC Petten, The Netherlands

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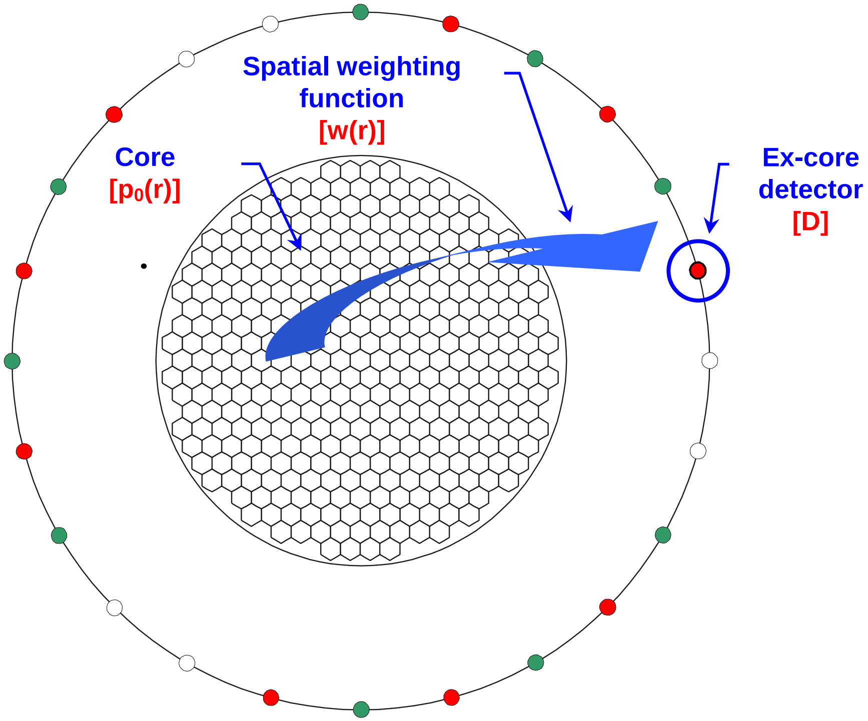
Theoretical background

- It is known, that the contribution of fuel assemblies to the ex-core detector response depends not only on the power, but also on the position of the given assembly in the core.
- The spatial weighting function gives a relationship between the spatial power distribution in the core and the ex-core detector response.



- **Ex-core detector response:**

$$D = C \cdot P \cdot \int_V p_0(r)w(r)dV$$

Numerical solution

$$D \cong C \cdot P \cdot \sum_i P_i W_i$$

SCORPIO, BIPR,... → P_i

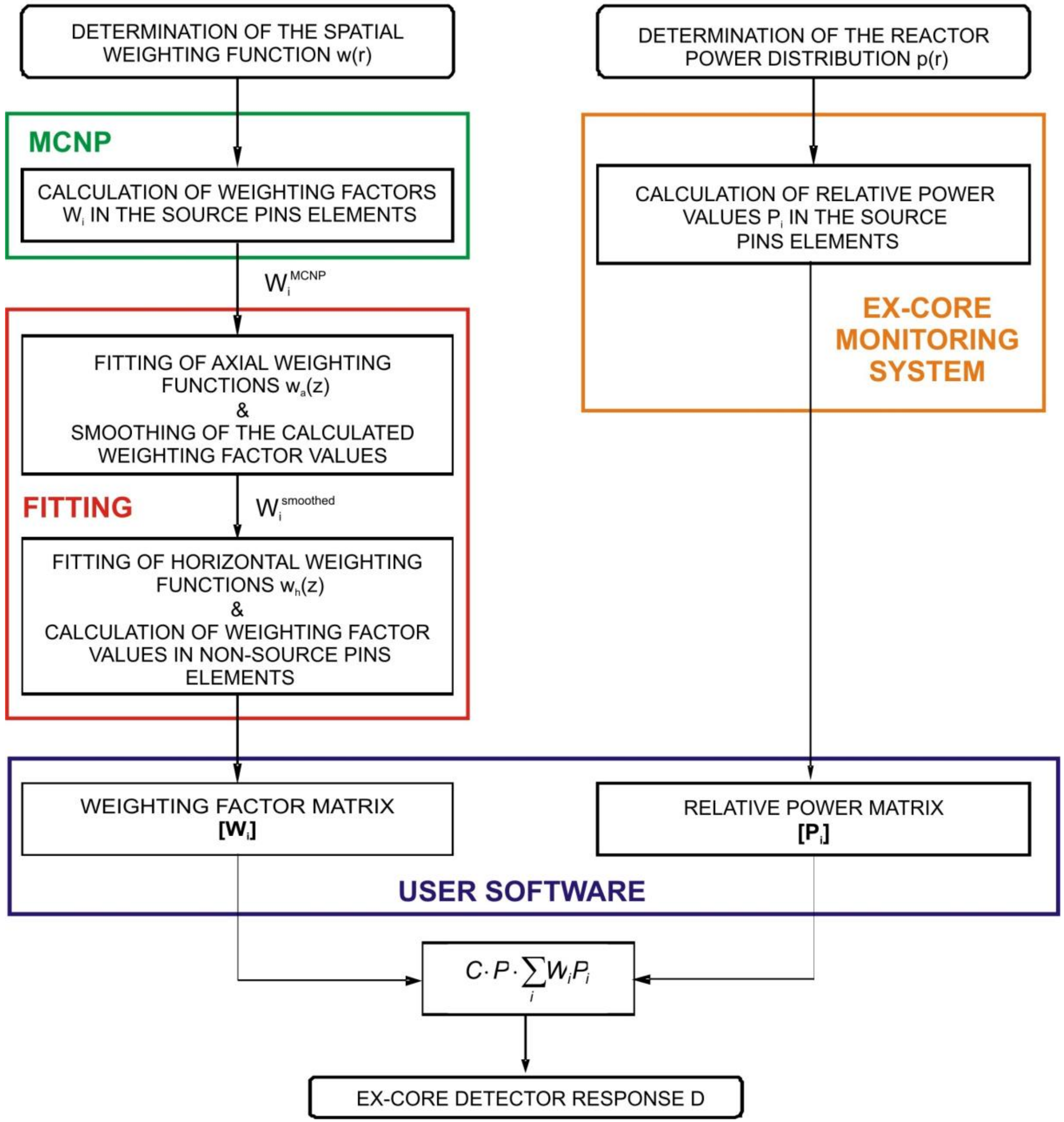
MCNP → W_i

W_i – weighting factor of *i*-th volume element

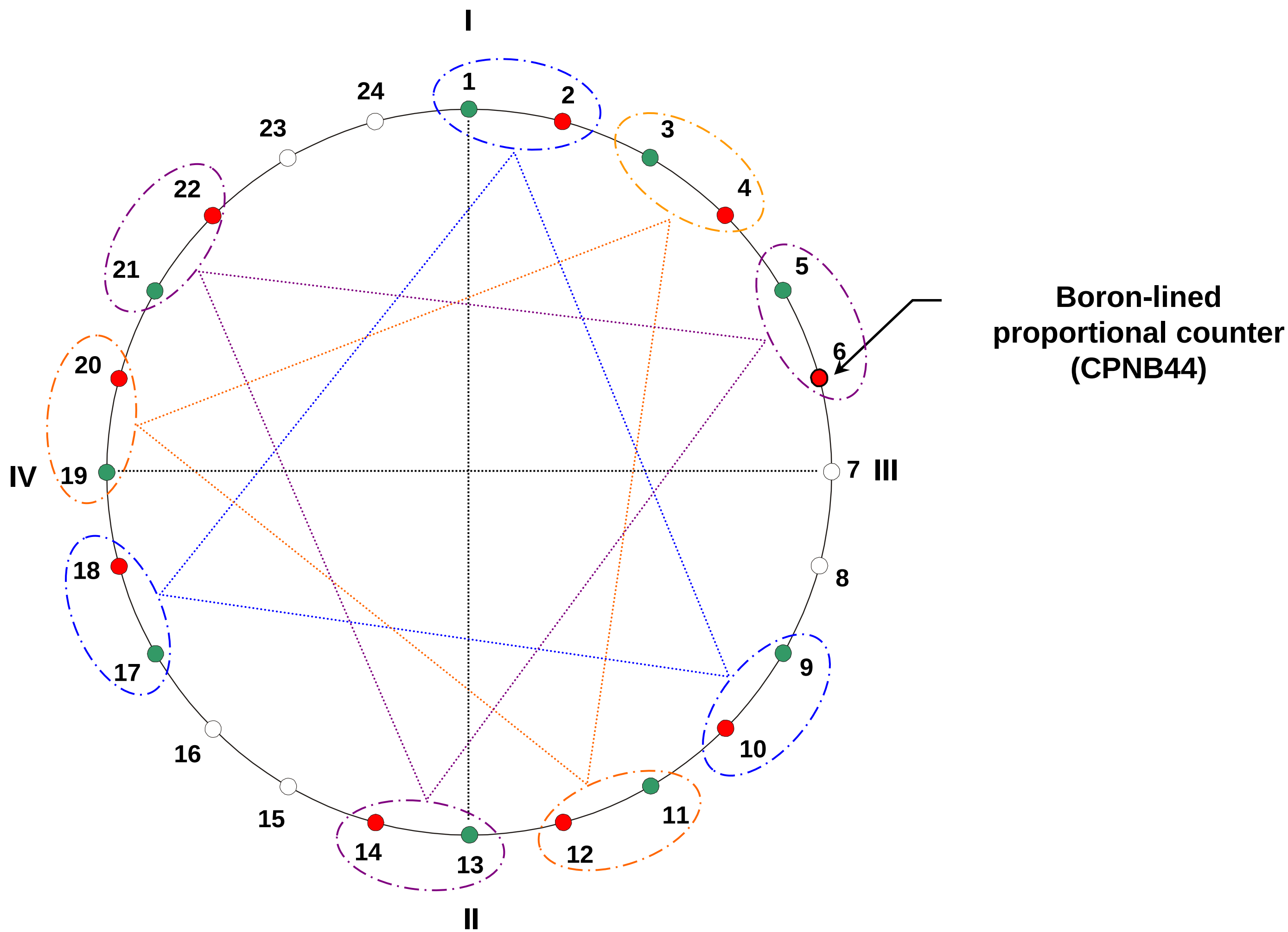
P_i - corresponding relative power

Volume element – the twentieth of fuel pin height

Problem-solving flowchart



Conditions

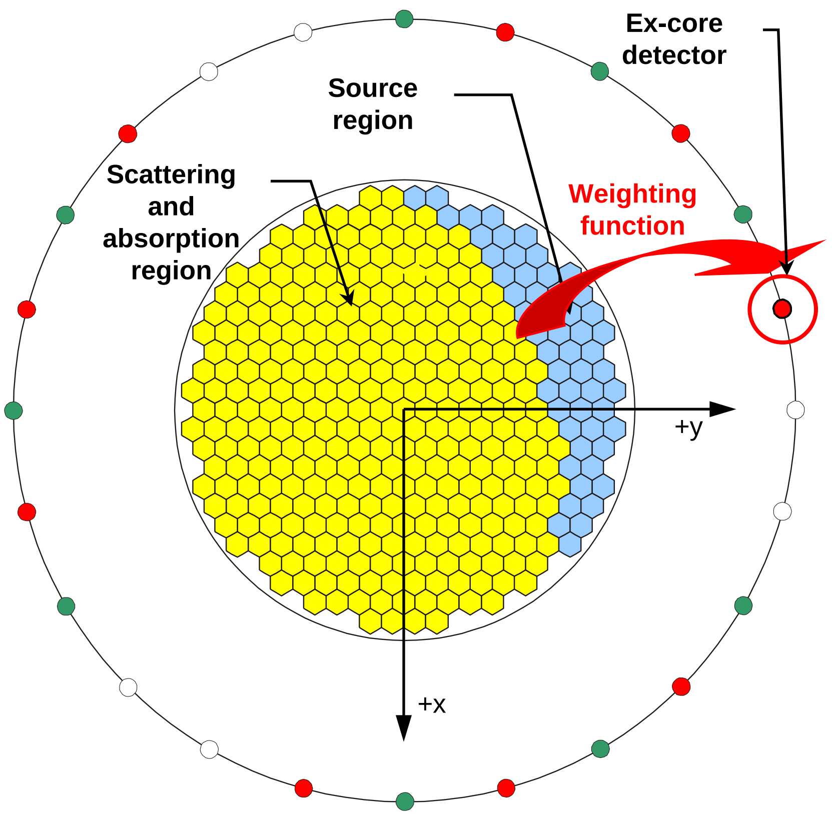


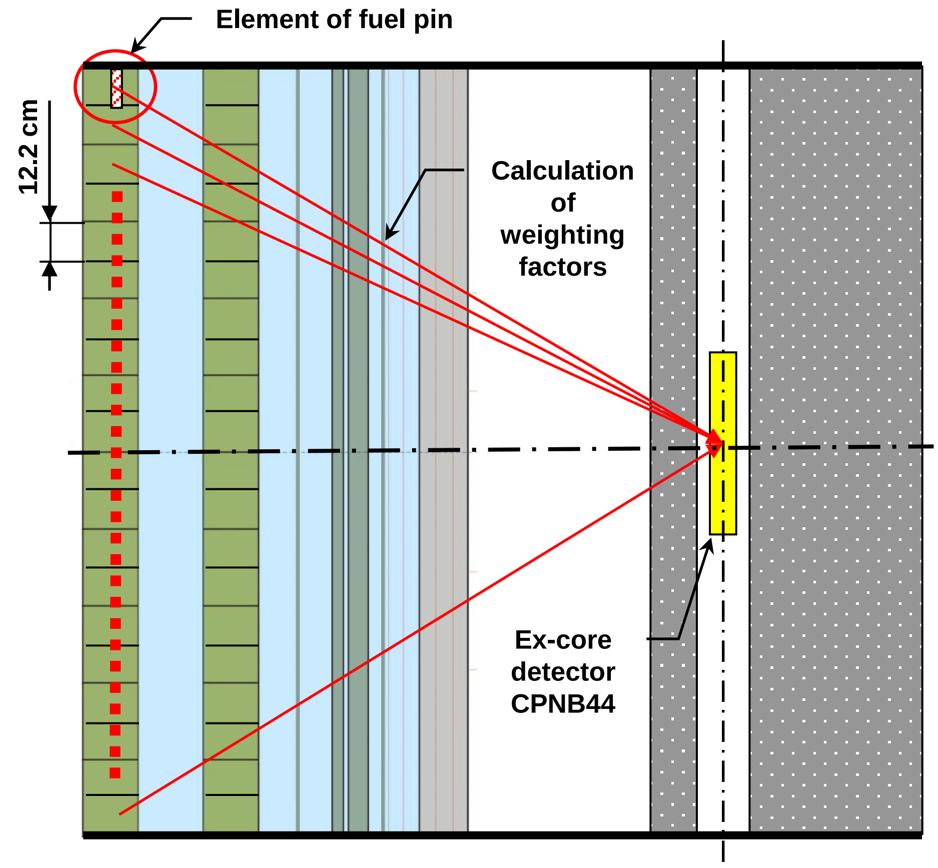
Placement of the ex-core detectors - NPP Jaslovské Bohunice, the 3rd unit

● **Source range** ● **Intermediate + Power range**

Method of calculation

- Forward transport Monte Carlo – code MCNP5
- Calculation performed by the so named Fix Source method
- Source region boundaries → cover all of the fuel pin elements with $W_i > 0.5\% \ W_{i,max}$
- Calculation of W_i only in the source fuel pins → quasi-regular grid
- Required uncertainty of the MC calculation < 3,5 % (for peripheral pins < 1,0 %)





Approximation of weighting functions

- Approximation of analytical function in two steps:
  - Vertical (1D) approximation → $w_a(z)$
  - Horizontal (2D) approximation → $w_h(x,y)$ or Volume (3D) approximation
- Vertical approximation:
  - Finding an analytical function which properly describes W_i distribution in vertical direction (that is along the source fuel pins).
  - Smoothing the calculated (MCNP) W_i values for a horizontal approximation.
- Horizontal approximation:
  - Fitting of two-dimensional function for layers of the twentieth of fuel pin height.
  - Calculation of W_i values in non-source fuel pins.

Approximation methods

- **Vertical approximation** ⇒ weighted least square method

  - Minimization can be expressed by the formula:

$$\chi^2 = \sum_{i=1}^{N} \left[\frac{W_i - \sum_{k=0}^{M} a_k Z_k(z_i)}{\sigma_i} \right]^2 \rightarrow min$$

  - Quantitative measure for the goodness-of-fit ⇒ probability Q computed as

$$Q = gammq(0,5\nu;\ 0,5\chi^2)$$

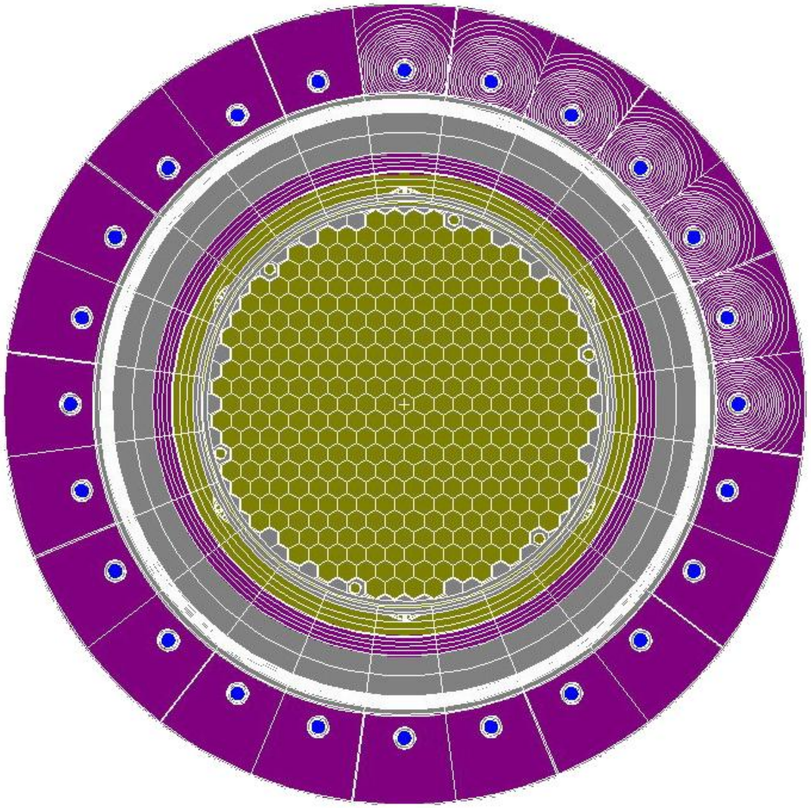
  - Acceptance: Q $>$ 10^{-3} (truly wrong approximations: Q << 10^{-18})

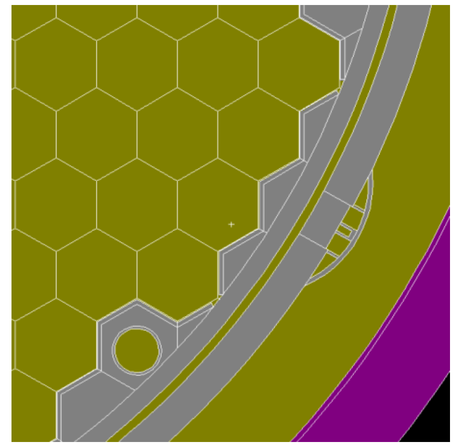
- **Horizontal approximation** ⇒ the polyhedral approximation of closed Jordan surfaces

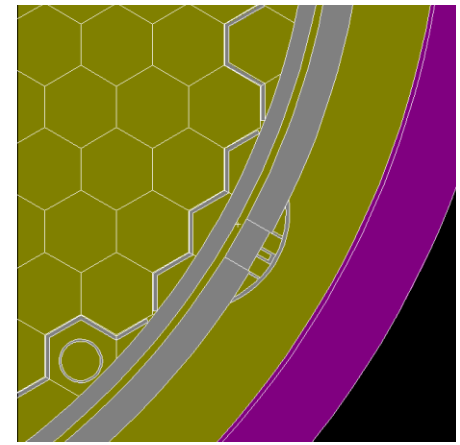
Results – universal model of VVER-440 in MCNP5

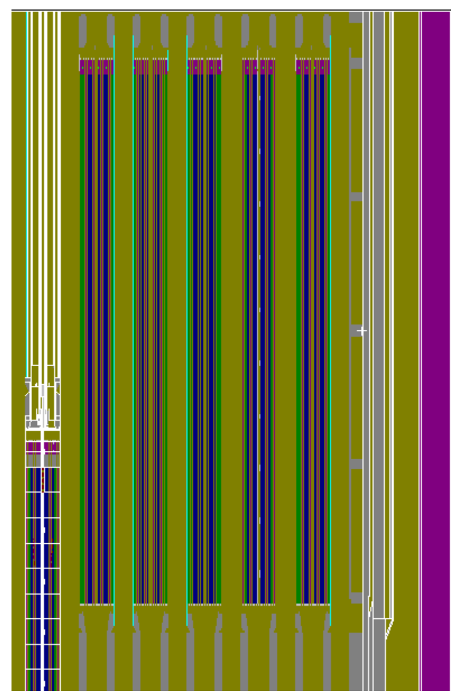
- Precise 3D whole-core model of the VVER-440 was developed in MCNP5
- The model enables:
  - to define any core loading pattern and various reactor operational parameters
  - to define axial and radial burnup profile as well as coolant (moderator) density profile in the core,
  - to specify temperature profile of the in-vessel and ex-vessel reactor components,
  - to fill the ionization chamber channels with given detectors.

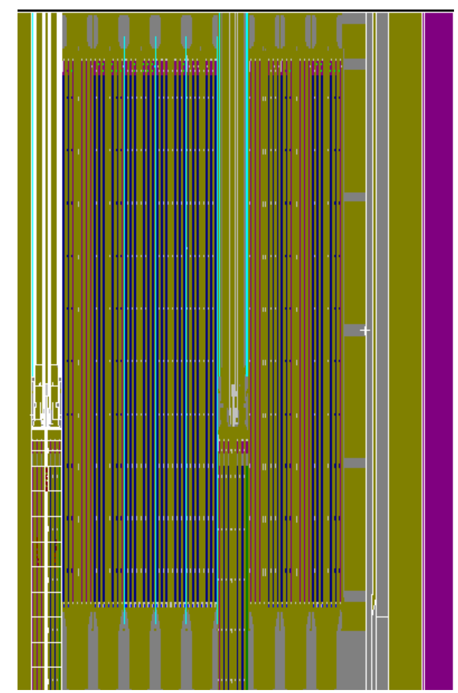
Model of the VVER-440 in MCNP5

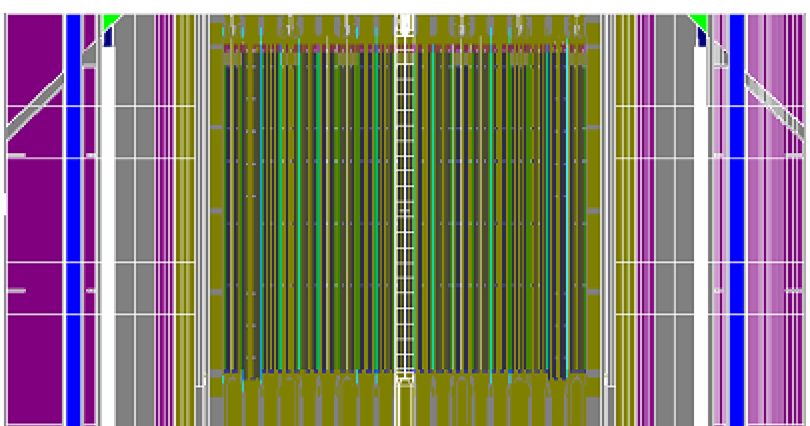




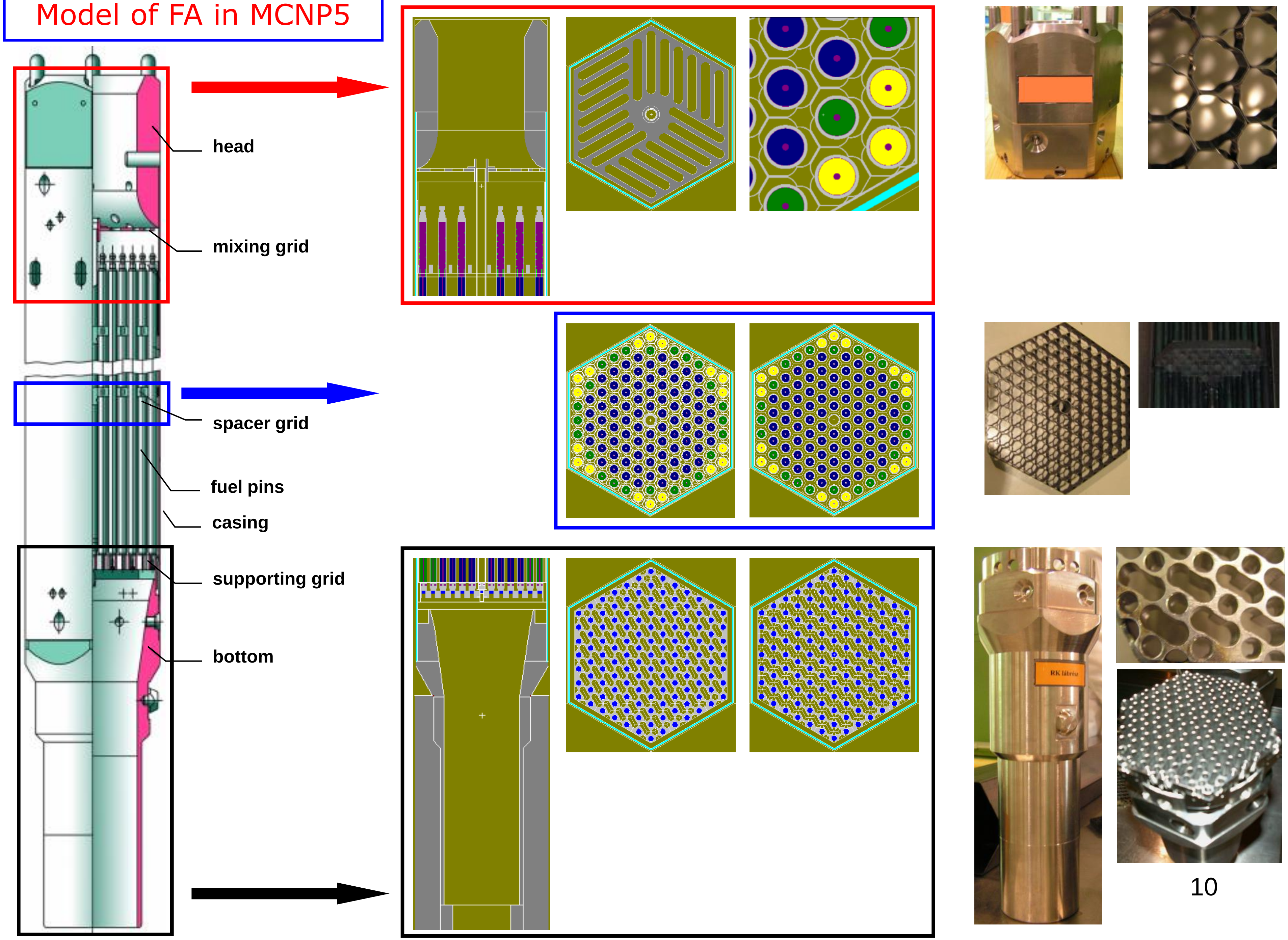




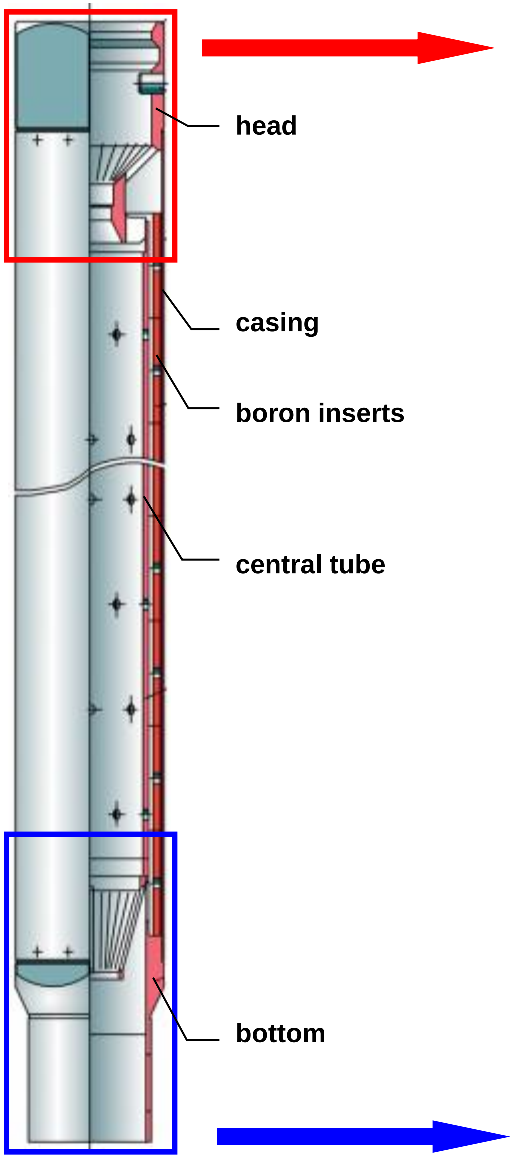


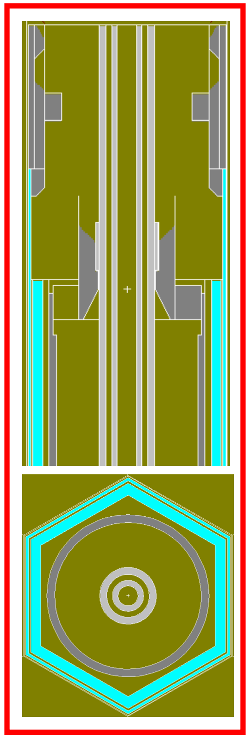


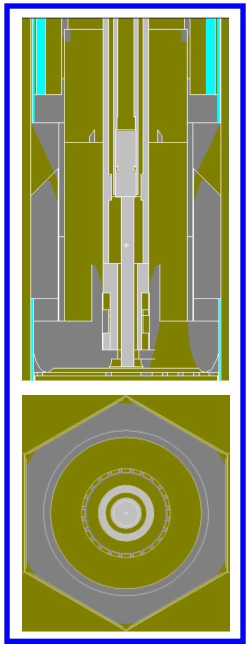
Model of FA in MCNP5



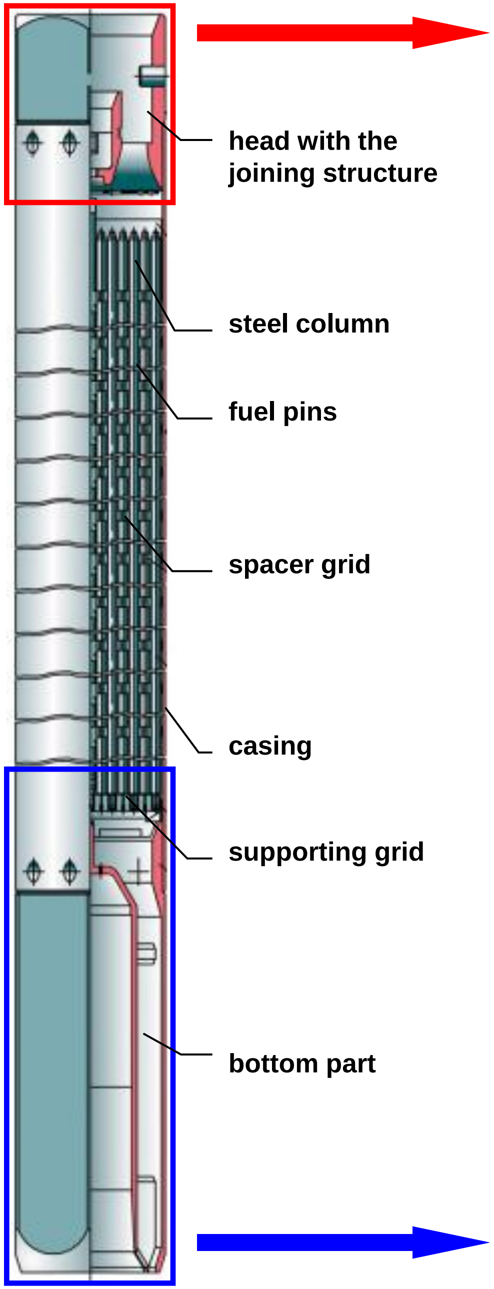
Absorber part of the CA in MCNP5

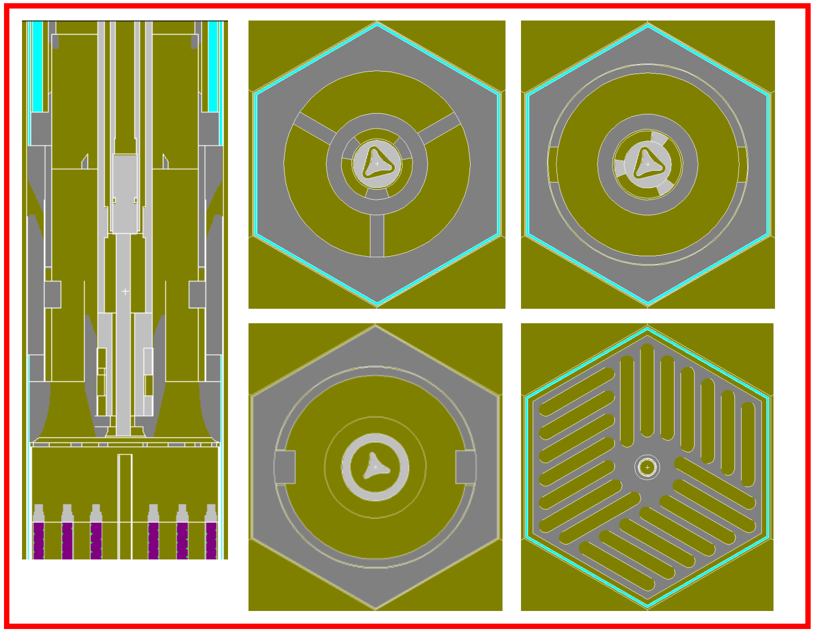


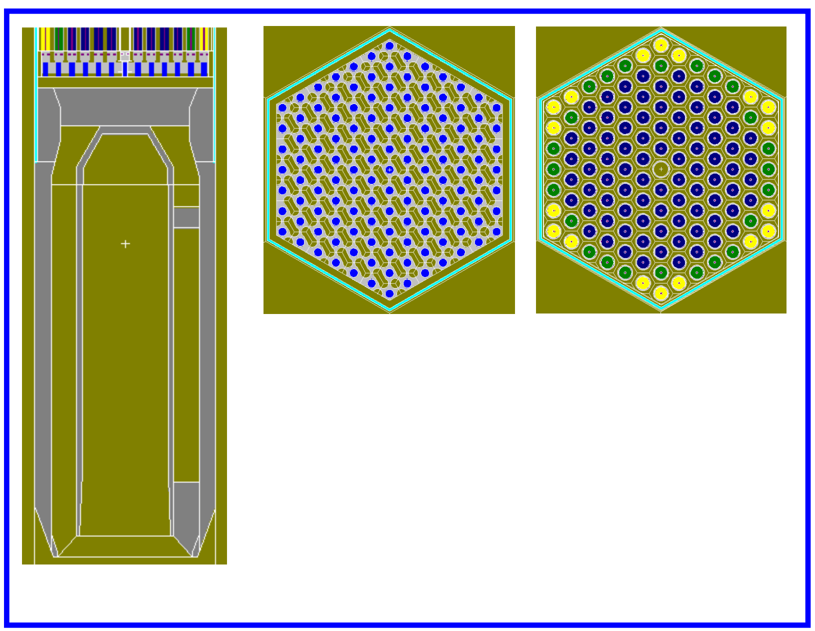


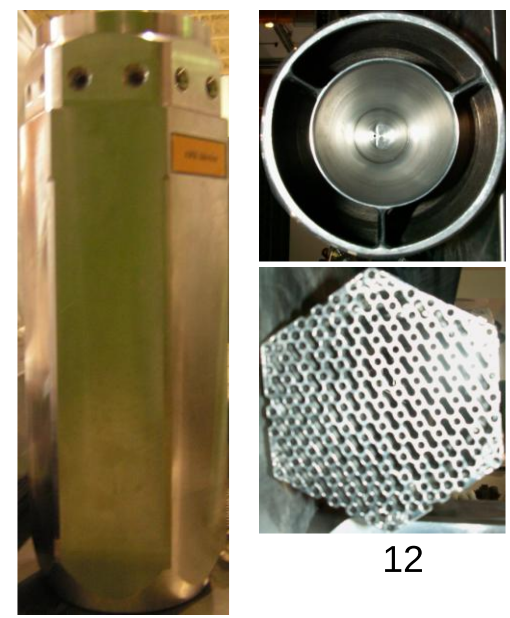


Fuel part of the CA in MCNP5



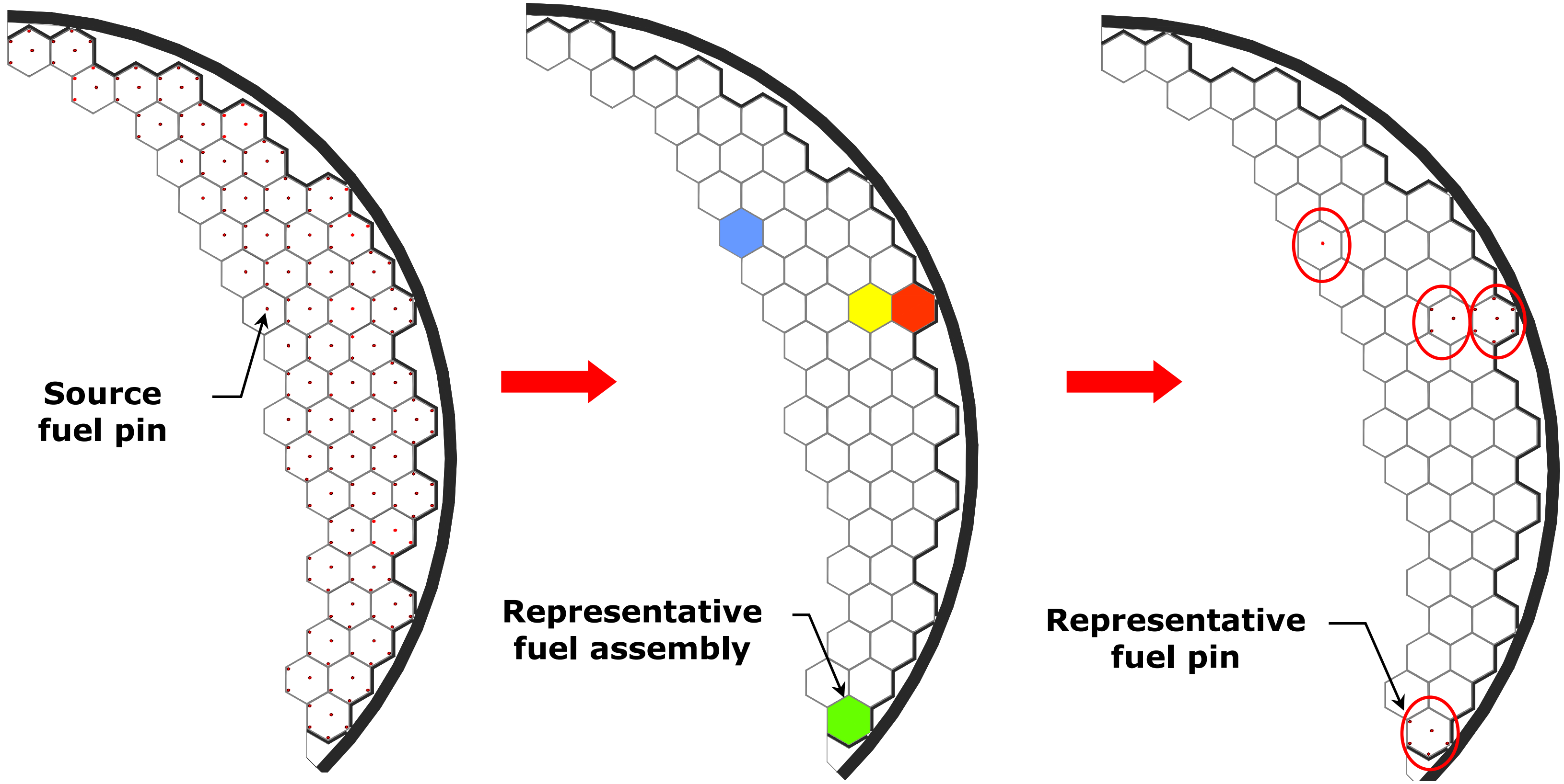






Results – axial weighting functions (1)

- Total number of source fuel pins ⇒ 193 (that is 3860 volume elements)
- Axial weighting factor (W_i) distribution presented for selected 16 source pins (320 elem.)

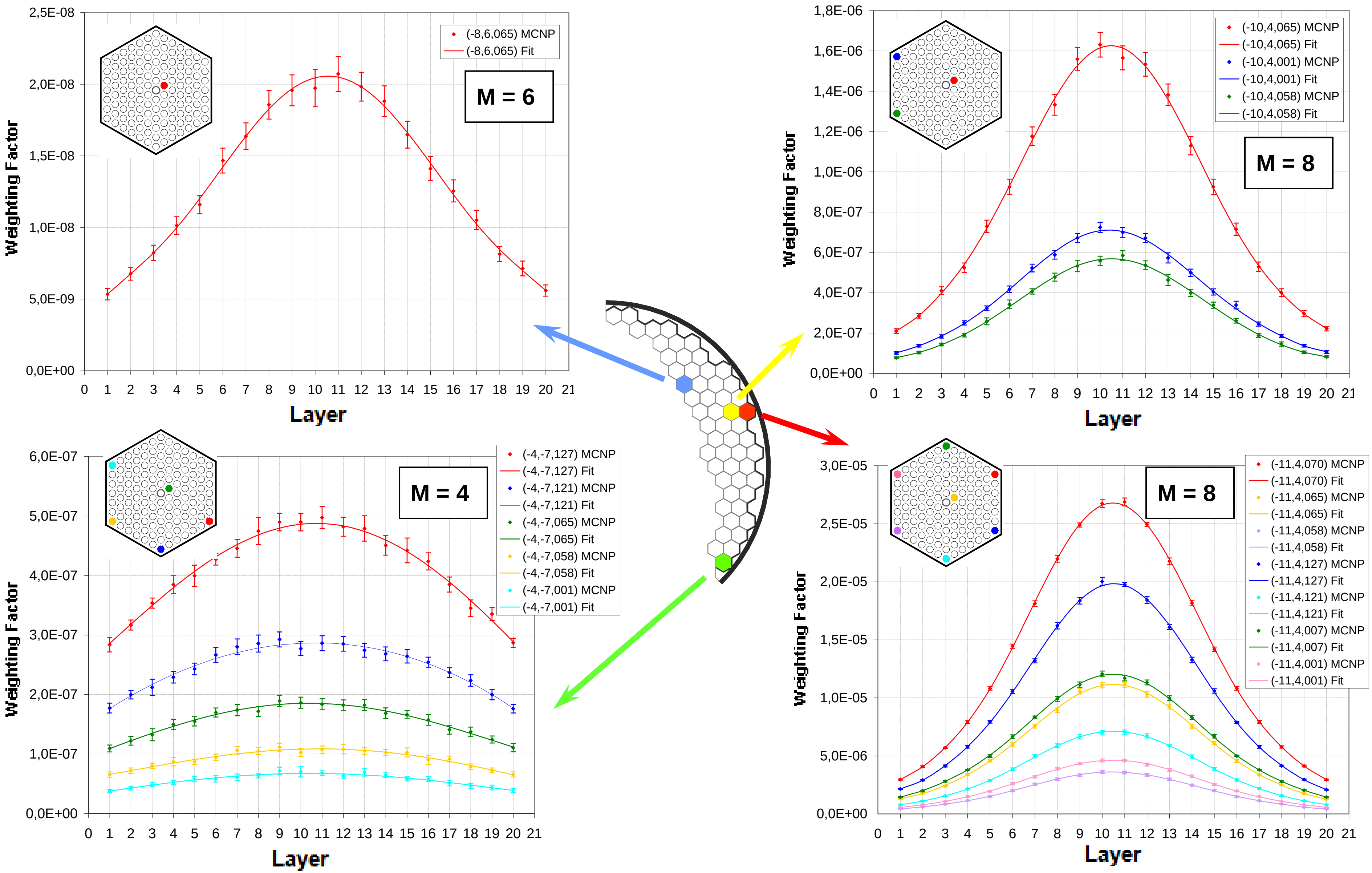


193 source pins (3860 elements)
54 FA

16 representative source pins
(320 elements) 4 FA

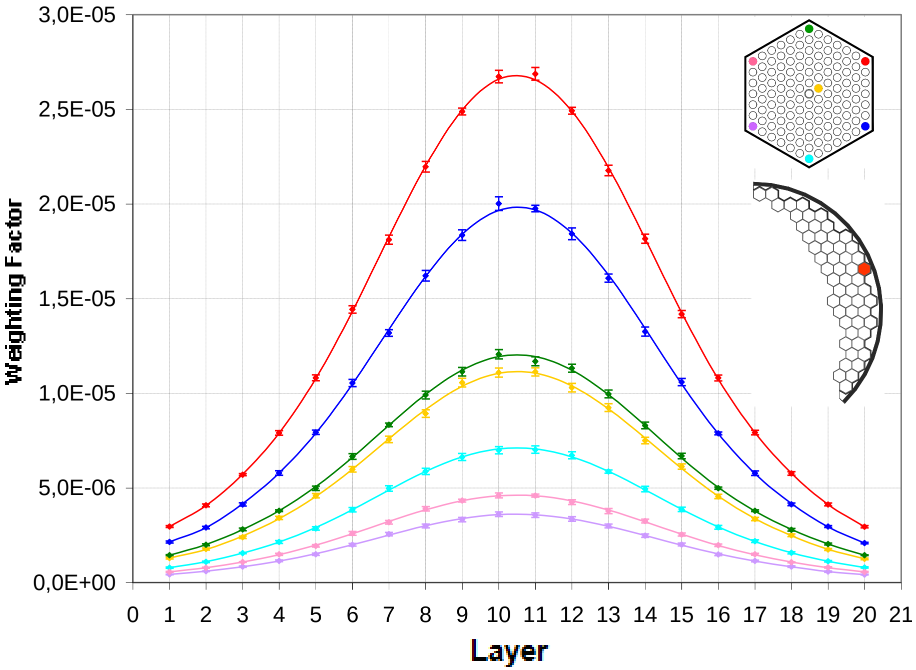
Results – axial weighting functions (2)

- The proposed polynomial function: $w_a(z) = a_0 + a_1 z + \ldots + a_M z^M$



Results – axial weighting functions (3)

Axial weighting functions of the FA (-11,4) source pins



$$w_a(z) = a_0 + a_1 z + a_2 z^2 + \ldots + a_8 z^8$$

M = 8

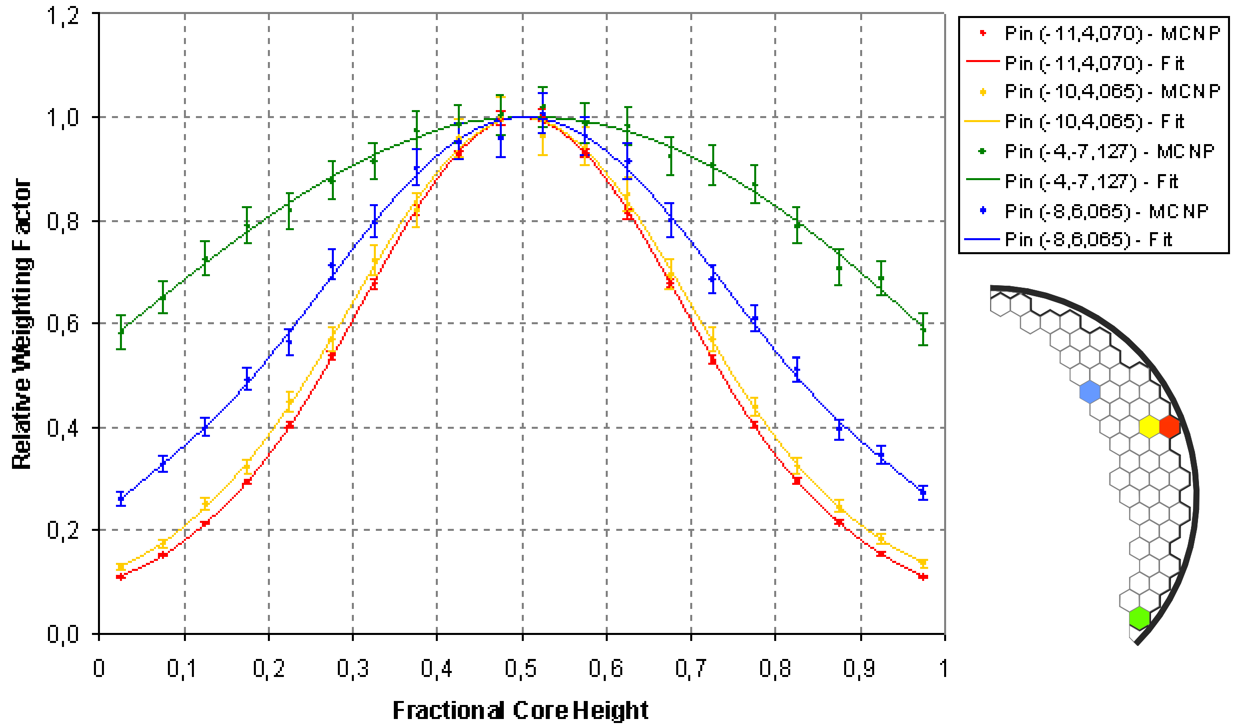
Approximation constants of the FA (-11,4) source pins

Koeficient	Prútik			
	001	007	058	065
a_0	4,61522E-06	1,20245E-05	3,61060E-06	1,11428E-05
a_1	-4,45771E-08	1,52928E-08	-7,18204E-08	9,20293E-08
a_2	-1,23627E-05	-3,34153E-05	-1,00324E-05	-3,17358E-05
a_3	1,51417E-07	-3,72827E-07	3,72486E-07	-3,77582E-07
a_4	1,70563E-05	4,90657E-05	1,48834E-05	4,72560E-05
a_5	-1,67125E-07	9,30753E-07	-6,16268E-07	6,10558E-07
a_6	-1,24447E-05	-3,83764E-05	-1,19704E-05	-3,75356E-05
a_7	6,08540E-08	-5,74920E-07	3,11775E-07	-3,44892E-07
a_8	3,70162E-06	1,21480E-05	3,93329E-06	1,21447E-05

Koeficient	Prútik		
	070	121	127
a_0	2,67885E-05	7,11860E-06	1,98341E-05
a_1	-2,15643E-07	2,08082E-08	2,39923E-07
a_2	-7,70887E-05	-1,99118E-05	-5,81343E-05
a_3	7,80787E-07	3,04597E-08	-1,59578E-06
a_4	1,13818E-04	2,85896E-05	8,81411E-05
a_5	-6,35873E-07	-6,73139E-08	3,00168E-06
a_6	-8,84713E-05	-2,17607E-05	-7,09715E-05
a_7	6,50860E-08	2,09473E-08	-1,67477E-06
a_8	2,79088E-05	6,75438E-06	2,32479E-05

Parameter	Degree of the polynomial function for source pin (-11,4,070)			
	8	7	6	5
χ^2	**1,85700E+01**	2,23427E+02	2,23917E+02	4,39923E+03
Q	**6,92634E-02**	4,61784E-41	1,61884E-40	0,00000E+00

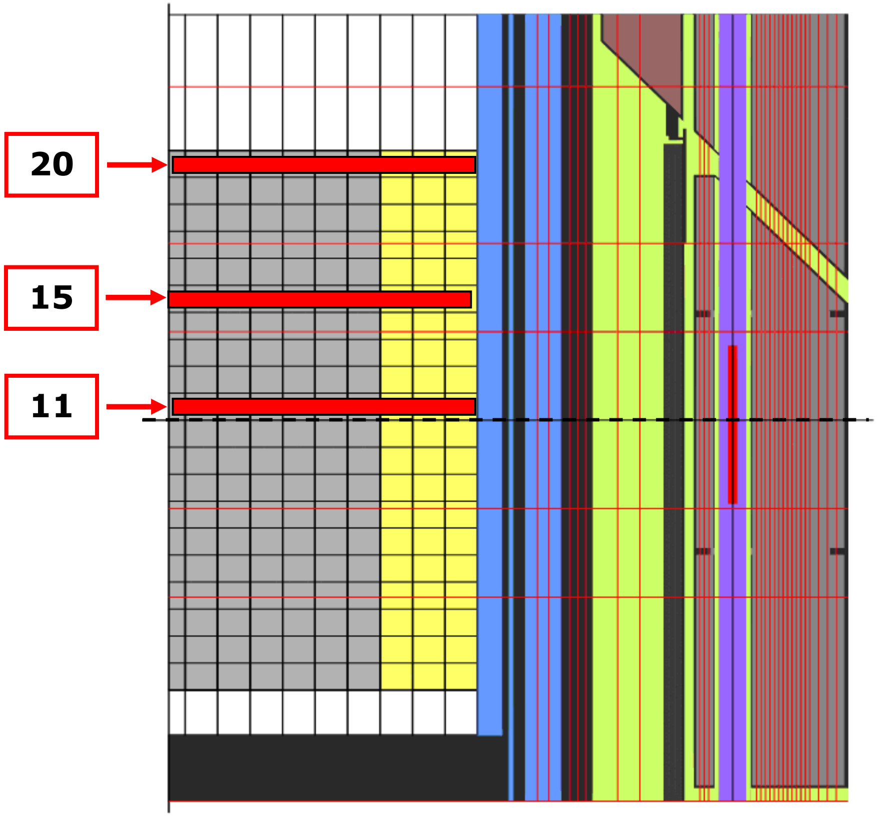
Results – axial weighting functions (4)

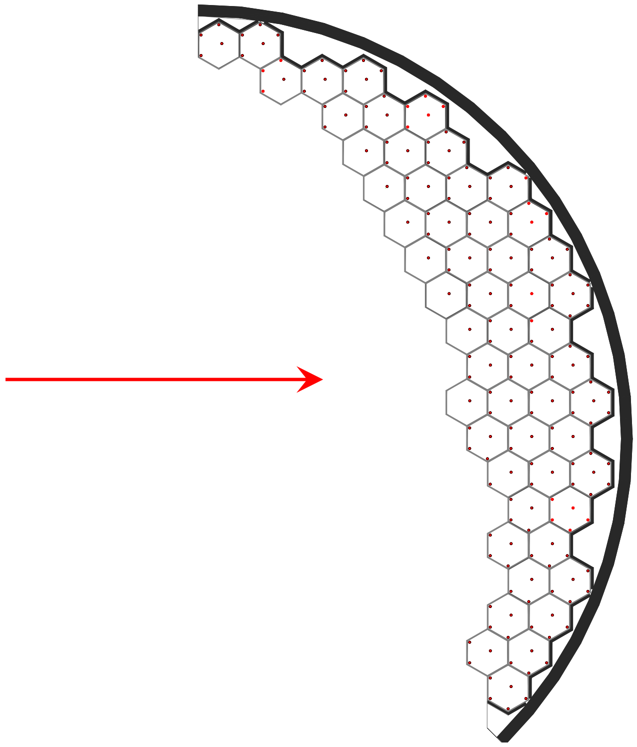


- The shapes of approximation curves correspond to the theoretically expected weighting factor distribution in vertical direction.
- Extension of the curves with increasing distance between the given fuel pin and the ex-core detector is mainly caused by geometrical reasons.
- Shapes of distribution curves in dependence on the position of source pins show transient character between a typical „bell” curve (close pins) and “arc” curve (distant pins).

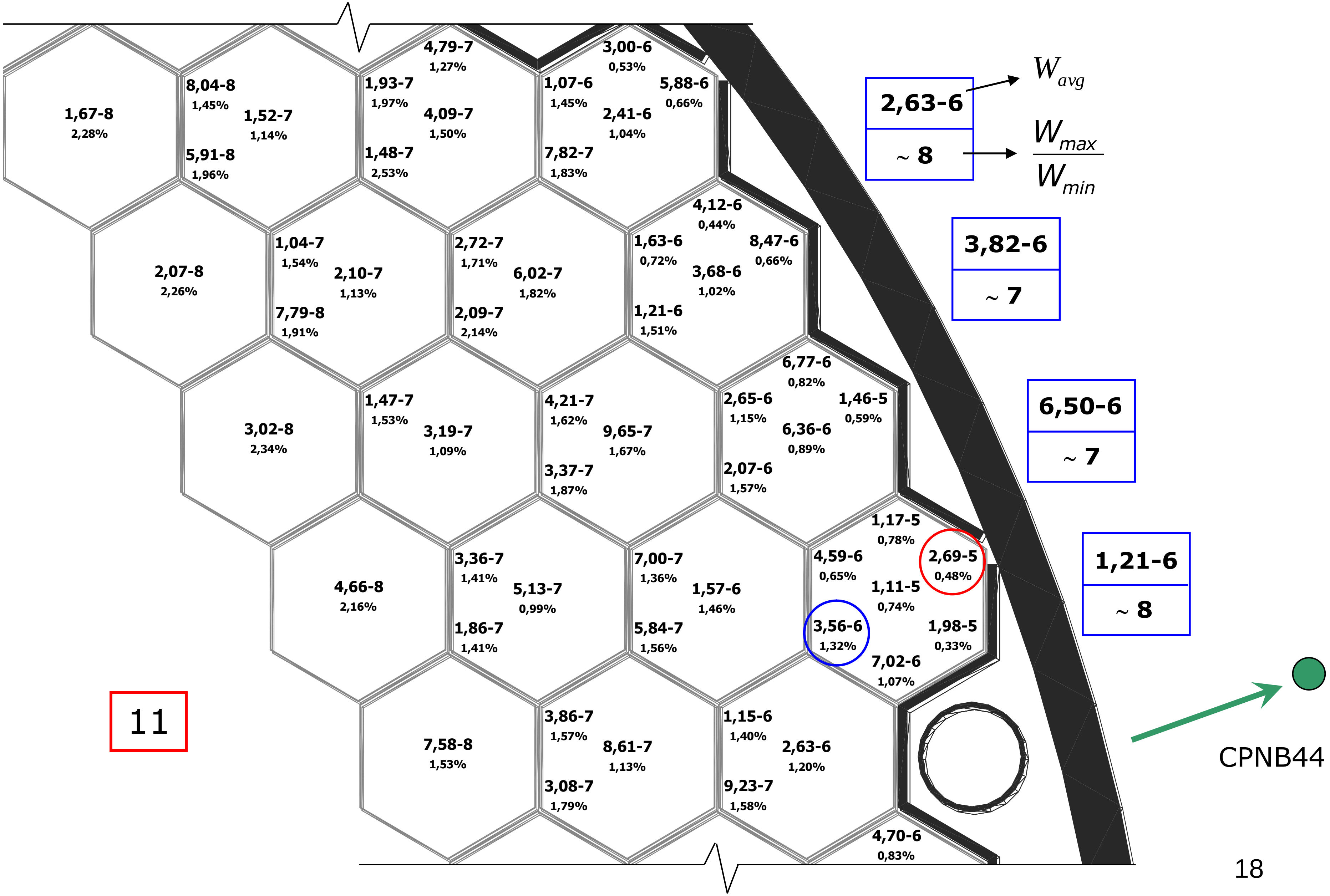
Results – horizontal weighting factor distribution (1)

- Horizontal weighting factor distribution presented ⇒ for 3 selected layers of the twentieth of fuel pin height – No.11 (central), No.15 & No.20 (upper peripheral).
- At average, 3 - 4 source pins were calculated for each FA, except core periphery where 5 – 7 pins per FA were computed.

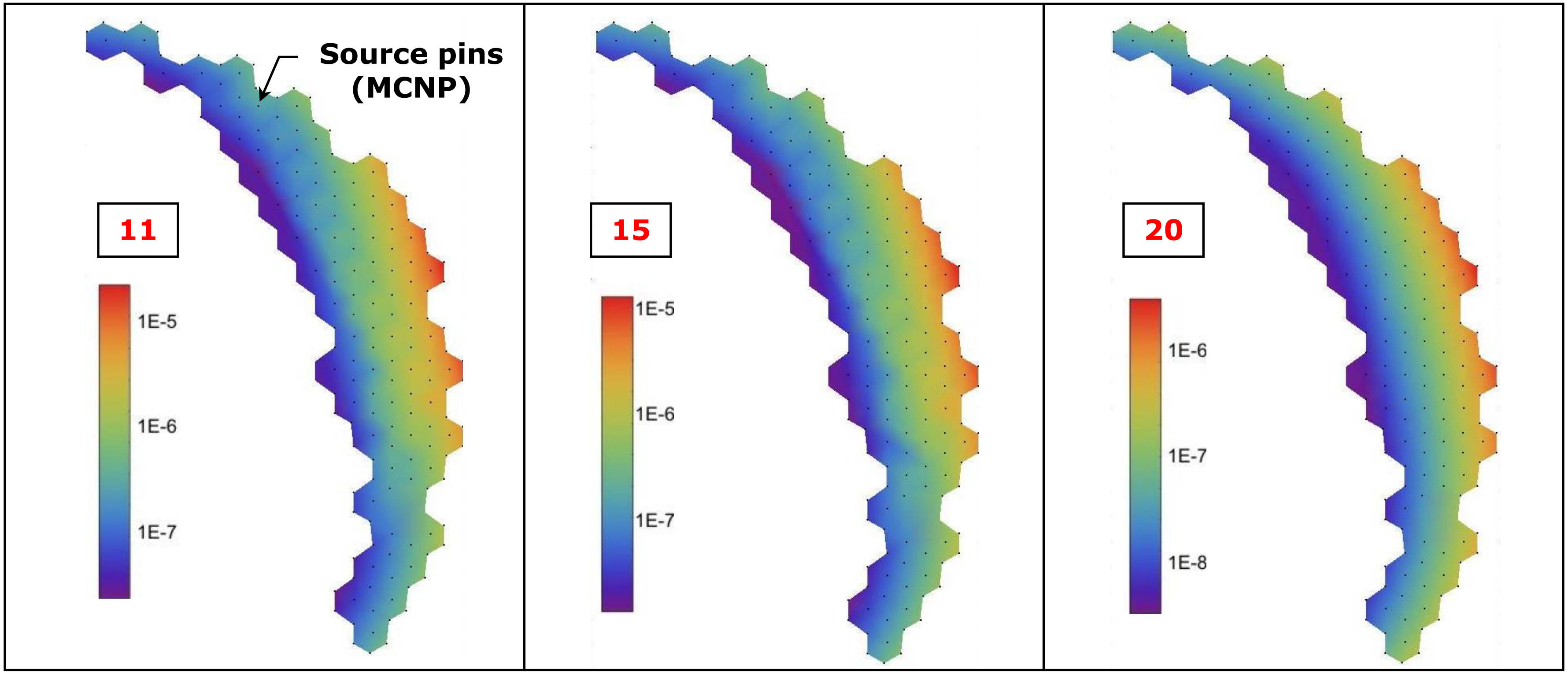




Results – horizontal weighting factor distribution (2)

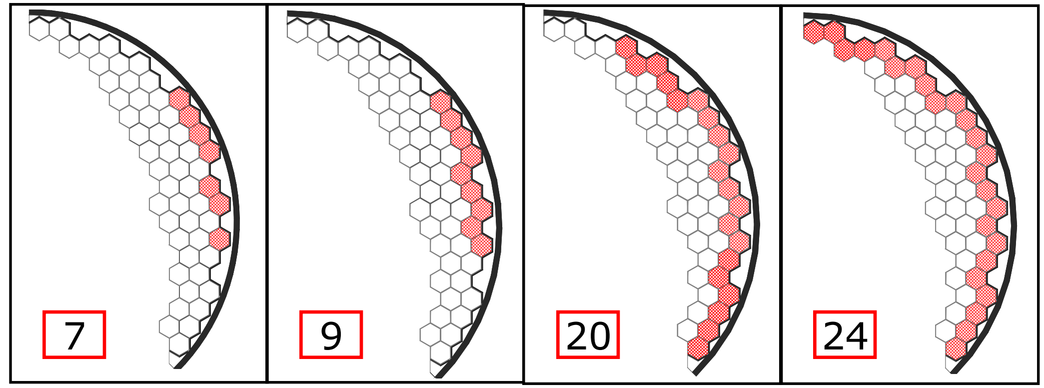


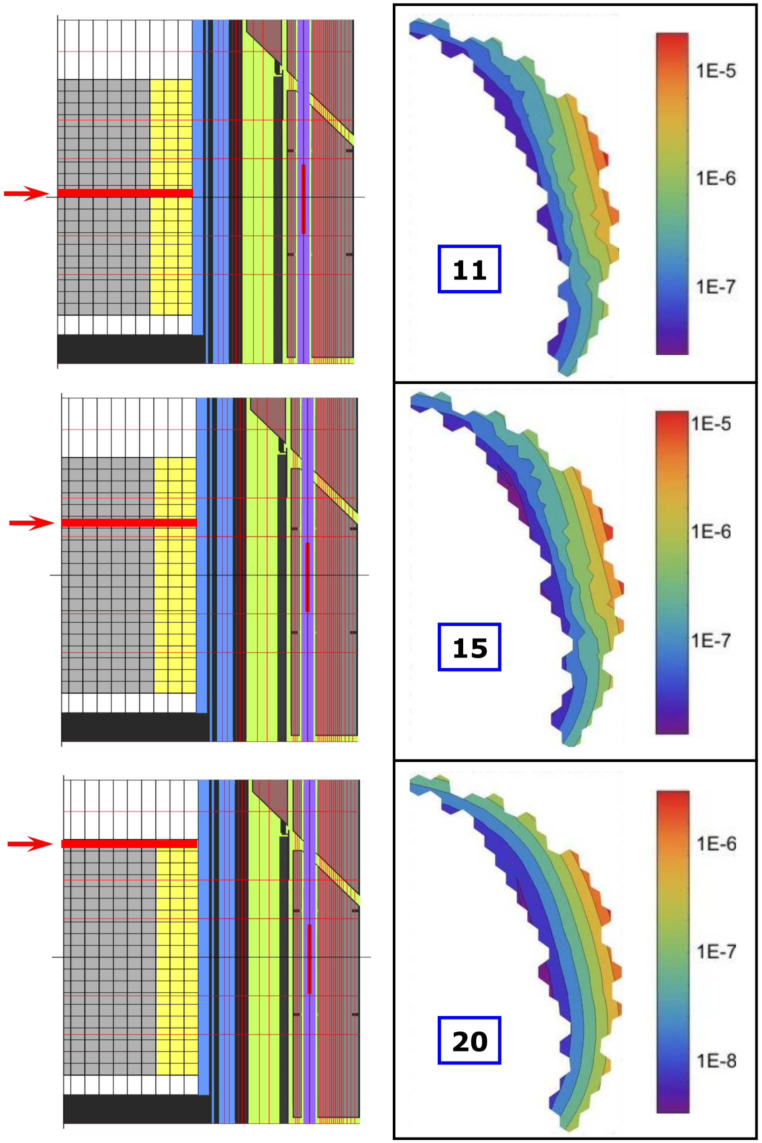
Results – horizontal weighting factor distribution (3)



- weighting contribution of the closest 20 peripheral fuel assemblies to the ex-core detector signal represents 92 % from the sum of the core weighting factor values,
- in the closest fuel assembly region to the ex-core detector, in the direction from the maximum weight position to the core centre, approximately eight-fold decrease of weighting factor values is observed,
- it can be expected that horizontal weighting function will "warp" in the upper and lower part of the source region, i.e. their values will not be mainly determined by the distance from the ex-core detector.

Results – contribution of peripheral FAs to the total weighting factor value in the given core layers (4)





$\frac{W_7}{\sum W}$	$\frac{W_9}{\sum W}$	$\frac{W_{20}}{\sum W}$	$\frac{W_{24}}{\sum W}$
82 %	86 %	92 %	93 %
80 %	83 %	92 %	93 %
73 %	76 %	92 %	94 %

Results – horizontal weighting factor distribution (5)

- it can be expected that the horizontal weighting function will have a character of exponential polynomial function of the 3rd - 8th order of magnitude, generally expressed by:

$$w_h(x,y) = \exp\left(\sum_{i=0}^{K}\sum_{j=0}^{L} a_{ij} x^i y^j\right)$$

- The following specific form can be designed:

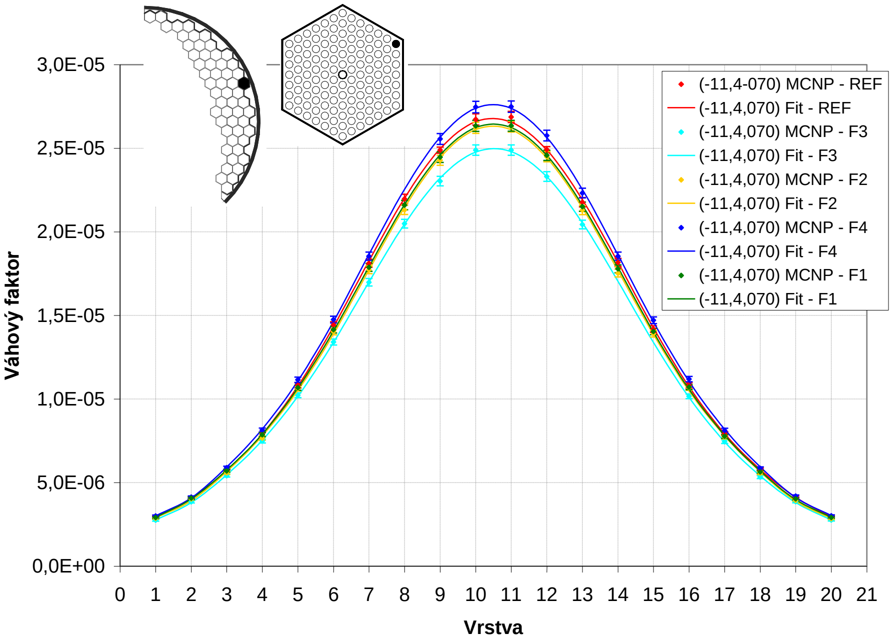
$$w_h(x,y) = exp(a_0 + a_1 x + a_2 y + a_3 x^2 + a_4 xy + a_5 y^2 + a_6 x^3 + a_7 y^3 + a_8 x^4 + a_9 y^4 + a_{10} x^5 + a_{11} y^5 + a_{12} x^6 + a_{13} y^6)$$

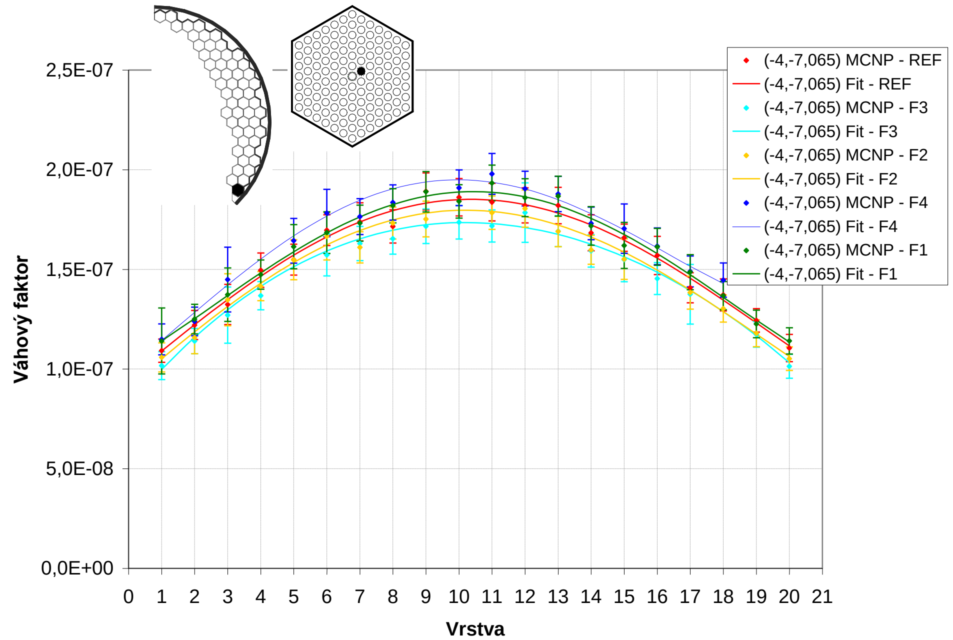
Results – sensitivity and parametric analysis (1)

Reference parameters					
c_B [g/kg]	B [MWd/t_{HW}]	ρ_{BET} [g/cm^3]	H_6 [cm]	T_M [°C]	Ex-core detector
2,3	26000	2,16	250 (HKP)	282	ICH axis, core center

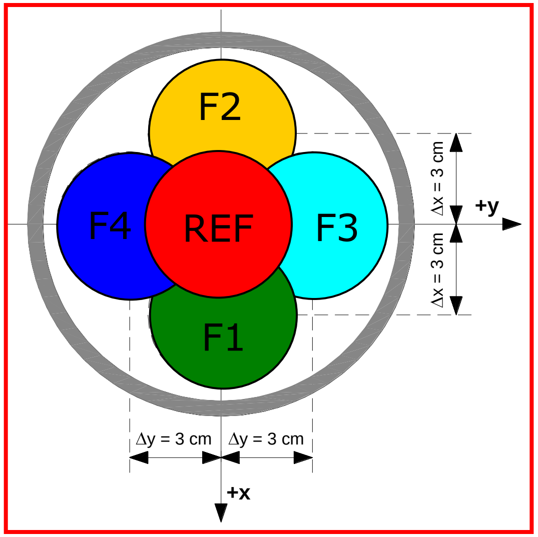
Parameter			Value	Analysis	Influence of the parameter on the W_i a w(r) — Deviation: REF - SA		Assessment
1	Boric acid concentration	c_B [g/kg]	0	A1	< 3 %		insignificant
			3,8	A2			
2	Burnup (fission neutron spectra)	B [MWd/t_{HM}]	0	B1	↓ W_i	~ 3 – 10 %	
			45000	B2	↑ W_i	< 1,5 %	insignificant
3	Reduction in serpentine concrete density	$\Delta\rho_{BET}$ [%]	5	C1	↑ W_i	~ 4 %	significant
			10	C2		~ 8 %	
	Reduction in water fraction in the serpentine concrete composition	$\Delta\nu_{H20}$ [%]	3	C3		~ 2 %	
4	Position of the 6th CA group	H_6 [cm]	225	D1	< 1,57 % ($R_{avg,MC}$)		insignificant
			200	D2			
			125	D3			
5	Coolant/moderator temperature	T_M [°C]	200 (c_B =7,6 g/kg & H_6 = 175 cm)	E1	↓ W_i	~ 33 %	significant
			260 (c_B =7,1 g/kg & H_6 = 175 cm)	E2		~ 8 %	
			268	E3	↓ W_i	~ 1 - 11 %	
			296,8	E4	↑ W_i	~ 1 - 13 %	
6	Shift of ex-core detector from the reference position	Δx [cm]	3 (+x)	F1	↑ ↓ W_i	~ 3 - 4 %	significant
			3 (- x)	F2			
		Δy [cm]	3 (+y)	F3	↓ W_i	~ 6 - 7 %	
			3 (- y)	F4	↑ W_i	~ 3 - 4 %	
		Δz [cm]	3 (+ z)	F5			

Results – sensitivity and parametric analysis (2)

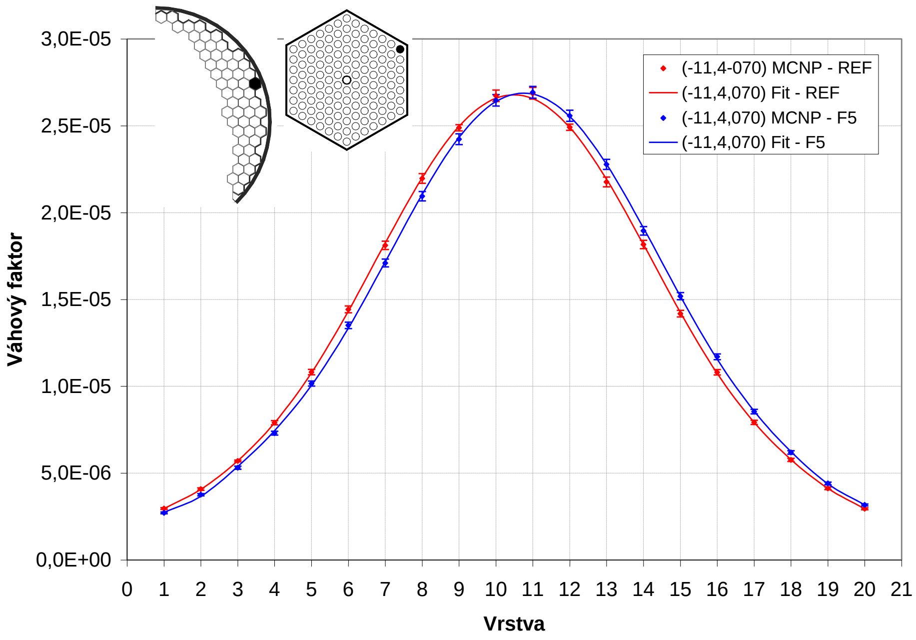


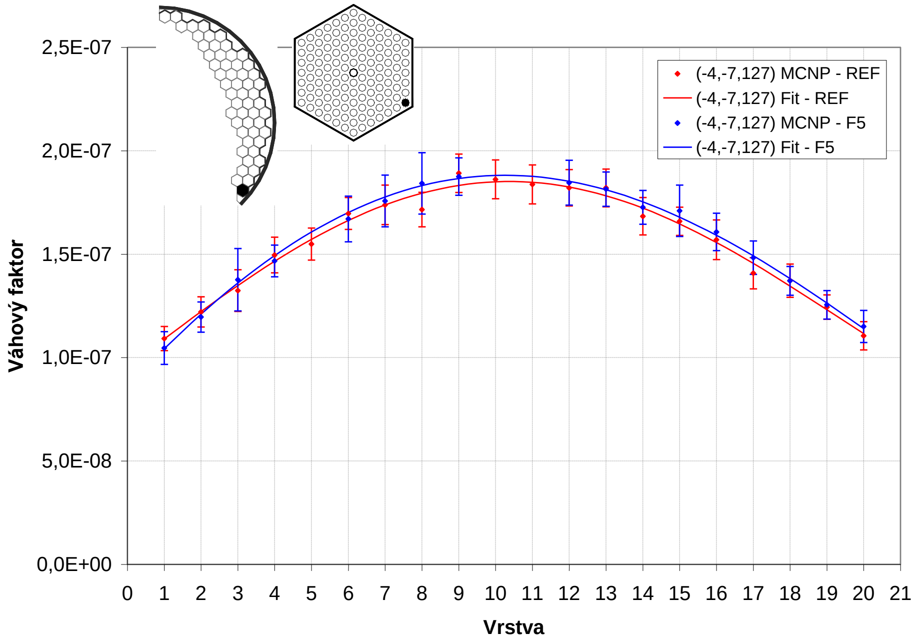


- Radial shift by 3 cm in the direction from the core (F3) ⇒ decrease (↓) of the w(z) value by ~ 6 – 7 %
- Radial shift by 3 cm in the direction to the core (F4) ⇒ increase (↑) of the w(z) value by ~ o 3 – 4 %
- Shift along the x axis (F1/F2) ⇒ variable positive and negative deviation in the w(z) value up to 3 – 4 %.
- In general ⇒ with increasing distance the w(z) value decreases and vice versa.

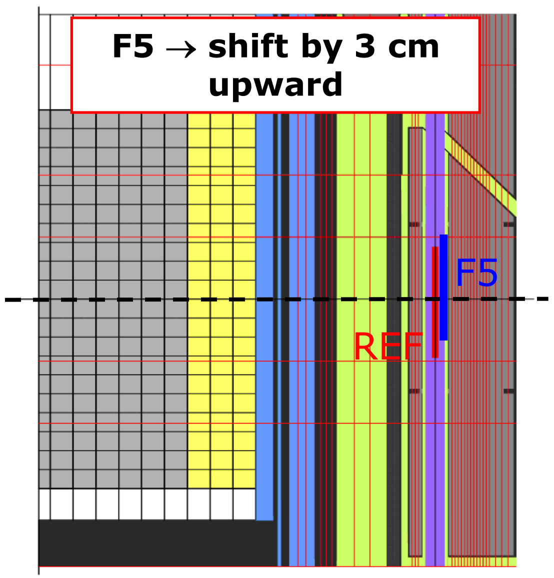


Results – sensitivity and parametric analysis (3)





- A very probable case of axis shift
- Axial shift of the ex-core detector ⇒ shift of the axial weighting function maximum in the given direction



Conclusion

- Precise and complex whole-core model of the VVER-440 was developed in MCNP5 and applied for solution of various reactor-physical problems (NPP Bohunice & Mochovce).
- Determination of weighting factors and weighting functions was performed for the source range ex-core detector CPNB44 (NPP Bohunice)
- At present, database of spatial weighting factors is generated.

Application areas

- Calculated weighting functions can be very beneficial for the solution of various reactor physical, operational, and safety problems. It can be useful for the proper interpretation of the startup test measurements, calculation of ex-core detector response in deep subcritical reactor states, evaluation of influence of the core loading pattern on the detector response, etc.
- A very important application area is the reactor safety analysis. In this case the elaborate weighting functions can be helpful in investigating how effectively certain transients which cause a sudden change in the power density distribution can be detected by the ex-core detectors.

Thank you for your attention