NUKLEONIKA 2020;65(3):161–166
doi: 10.2478/nuka-2020-0026

ORIGINAL PAPER

Fission chambers for space effect reduction in the application of the area method: A new approach

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Abstract. The possibility of preparing fission chambers for the experimental determination of subcriticality without time-consuming corrections has been presented. The reactor detectors set consists of monoisotopic chambers. Each chamber is intended for a specific position in the system. Individual weights, rated *a priori* for all detectors in their positions, allow for quick calculation of whole system subcriticality. The inconveniences related to the spatial effect are minimized. This is achieved by computational simulation of the area method results, for each detector position and all possible fissionable and fissile nuclides. Next, one nuclide is selected, specific for the given position, presenting the smallest difference from the MCNP KCODE precisely estimated k_{kcode}. The case study is made using the model of VENUS-F core.

Keywords: Subcriticality • Simulation • Area method • Fission chambers • Space effect

Introduction

Controlling the reactivity in a subcritical reactor presents some problems. They are posed, among other things, by the so-called space effect observed in the pulsed neutron source (PNS) method of reactivity measurement [1–5]. For several neutron detectors placed in different positions in reactor core and reactor reflector, the obtained results of reactivity differ from one another by non-negligible values. This effect is caused, among others, by differences of neutron spectra in different detector positions [6]. Numerical corrections of a particular reactor core can partially improve the situation. In this article, we would like to propose the possibility of a certain improvement.

The presented results are a continuation of previously reported work [7]. In this earlier stage, we proposed to use fission chambers with the sensitive material composed of two nuclides, one fissionable and the other fissile. We concluded that for some detectors it was not possible to find a proper mixture fulfilling the demand for total reduction of the space effect, and we declared a more detailed study to explain this phenomenon. We also planned to find the sensitivity of the proposed solution for several variables, such as changing reactivity, fuel composition, accuracy of the found detector composition, and so on. This part of our results, for the detectors with a mixture of the two nuclides, is presented in the section "Sensitivity".

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Received: 24 June 2019
Accepted: 17 January 2020

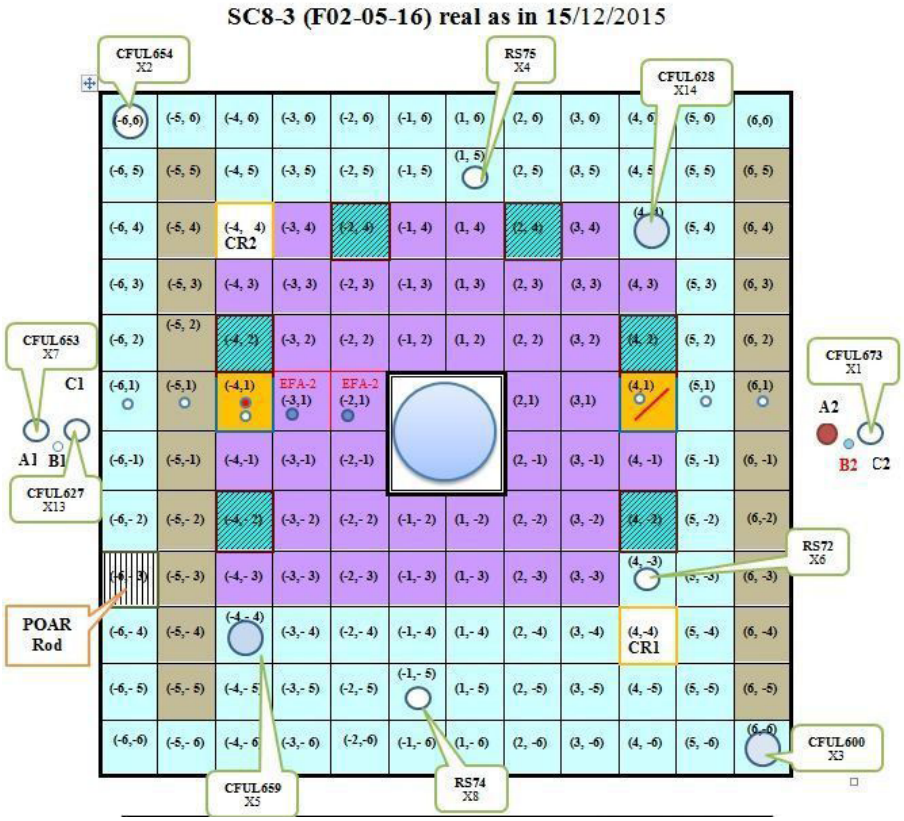

Fig. 1. Layout of the VENUS SC8-3 (F02/05/16) reactor core configuration [8] with marked detectors (X1–X8, X13, X14, and X15 in the cassette (–3, 1)), control rods (CR1 and CR2), and powder absorber rod (POAR). Assemblies are marked with colours: dark green – safety rods, violet – fuel, light green – lead, grey – graphite, and orange – polyethylene blocks with mock-up targets.

However, we considered that it is inappropriate to determine a whole system k_{eff} from the results of only part of the detectors installed, without these with inadequate material composition. Also, the preparation of isotopic mixtures would be difficult concerning precision of mixing and availability of constituents. Therefore, another approach is presented in the section "Monoisotopic chambers". Apart from monoisotopic materials such as ^{232}Th, ^{235}U, ^{238}U, ^{237}Np, and ^{239}Pu and natural U in fission chambers, simulations were also tried to use 96% enriched boron-10 (^{10}B) in a detector based on neutron absorption.

System parameters

The first condition for obtaining reliable results was a precise evaluation of the k_{kcode} and the delayed neutron fraction – β, values appropriate for the core. In this study, k_{kcode} is treated as a true system neutron multiplication factor, while k_{eff} is a result of experimentally determined one. We assumed that satisfactory precision (standard deviation) of k_{kcode} and β should be at least ~1 pcm. To achieve this precision, we used two methods: one long (1.1E9 neutrons) and 60 independent short (5.0E4 neutrons) computer runs of KCODE for the core VENUS SC8-3 (F02/05/16; Fig. 1) [8] with control rods (CR) in the 27.44 cm position. In our calculations, we used a calculation model with all 11 detectors. This is an experimental subcritical core driven by a fast neutron source – GENEPI-3C neutron generator based on *d*, *t* reaction. The core consists of fuel assemblies containing metallic uranium enriched to 30% ^{235}U by weight, placed between lead assemblies imitating the coolant. The core is surrounded by a lead reflector.

The results obtained are k_{kcode} = 96383 ± 2 pcm from the long run and k_{kcode} = 96384 ± 2.7 pcm from 60 short series; and β = 736 ± 3 pcm and 733 ± 4.1 pcm, respectively. The results for different depths of CR insertion are shown in Figs. 2 and 3.

Sensitivity

Another point while introducing a new experimental method of subcriticality determination is its sensitivity to changing parameters of the core. To determine this in simulations, we selected two parameters, CR position in the core and enrichment of uranium applied as fuel. The applied values of parameters and respective core k_{kcode} and β are presented in Figs. 2–5.

The sensitivity of the difference $k_{\text{kcode}} - k_{\text{eff}}$ to changes in system reactivity was tested for some detectors containing mixtures of two isotopes, described by Janczyszyn *et al.* [7]. Small variations of reactivity were modelled by changing the depth of CR insertion, while bigger reactivity changes were resulted from fuel enrichment variation simulation. The computed results for the sensitivity of the area method experiment are presented in Tables 1 and 2.

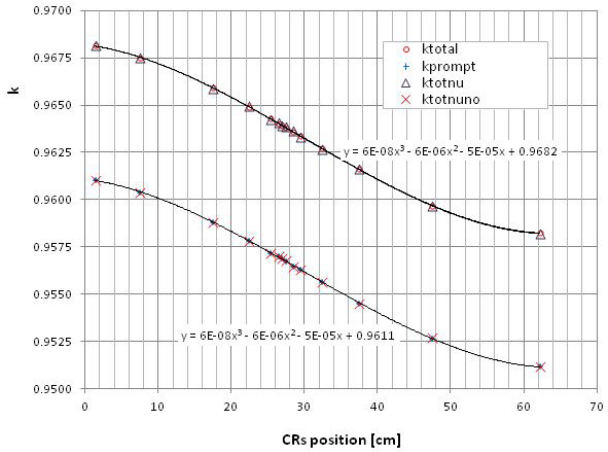

Fig. 2. MCNP KCODE computed values of k_{kcode} for different control rods (both) positions and 30% U enrichment.

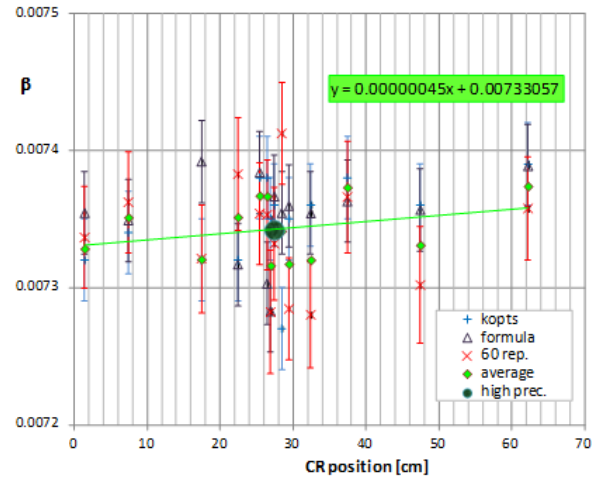

Fig. 3. Values of β computed for different control rods (both) positions and 30% U enrichment using the following methods: from MCNP KOPTS, from formula $\beta = 1 - (k_{\text{prompt}}/k_{\text{total}})$, and from formula $\beta = 1 - (k_{\text{totnuno}}/k_{\text{totnu}})$.

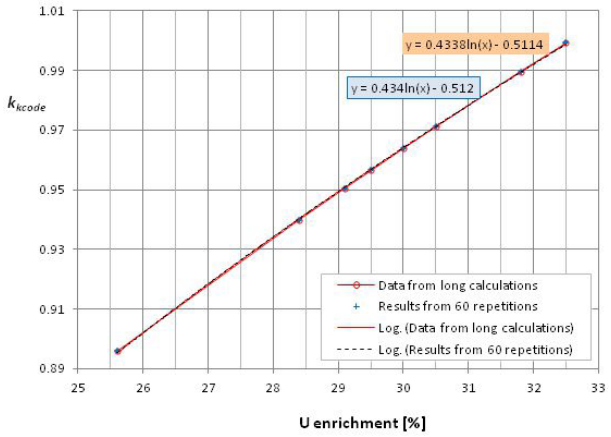

Fig. 4. MCNP KCODE computed values of k_{kcode} for 27.44 cm control rods position and different enrichment of fuel U.

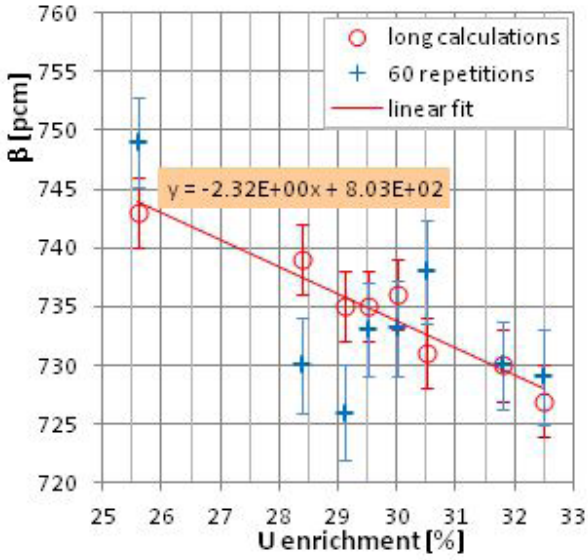

Fig. 5. Values of β computed for 27.44 cm control rods position and different U enrichment.

Monoisotopic chambers

Because of the difficulties found in applying the mixed fissile–fissionable sensitive detector material, presented earlier [7], we propose the idea of single isotope fission chambers, or other types of neutron detectors, to be used for subcriticality determination in a given reactor system. Each detector material

Table 1. Sensitivity of detectors results to changes of CR insertion depth, for 30% ^{235}U

Insertion [cm]	D10 (X15)	D1 (X8)	D3 (X6)	D4 (X13)	D5 (X1)	D7 (X3)	D8 (X7)	D11 (X5)
	$\Delta = k_{\text{kcode}} - k_{\text{eff}}$ [pcm]							
1.44	25	49	20	36	57	20	1	38
7.44	37	–19	23	98	26	58	37	49
17.44	10	4	15	76	58	24	–33	13
22.44	18	3	5	178	57	24	–64	28
25.44	27	–20	23	89	113	11	–25	10
26.44	30	–6	22	15	101	43	–35	–
26.94	36	28	16	26	75	28	–9	–
27.44	24	8	18	–14	114	6	40	37
28.44	41	46	35	133	–11	12	–50	35
29.44	11	–20	–4	–26	69	9	–70	4
32.44	40	–9	31	26	163	67	–48	37
37.44	51	11	32	115	28	67	–72	47
47.44	2	–61	–3	44	79	12	–65	–11
62.21	–38	–45	–44	–89	–57	14	–1	–47

Table 2. Sensitivity of detectors results to changes of fuel enrichment

	Enrichment of fuel in ^{235}U [wt%]						
	25.6	28.4	29.1	29.5	30.0	30.5	31.8
Detector	$k_{kcode} - k_{eff}$ [pcm]						
D1	–81.1	–112.8	–61.0	–122.8	–27.9	–55.4	–21.3
D3	–16.4	–30.3	–16.2	–25.0	–18.4	–17.2	–16.3
D4	666.3	–129.7	–23.8	91.7	–50.0	19.5	–6.4
D5	607.2	236.8	148.2	31.5	77.4	8.4	–21.1
D7	–39.6	–59.4	–38.8	–36.3	–30.0	–16.7	–17.6
D8	–372.9	–117.1	–110.2	–105.4	3.4	–23.9	–21.1
D10	24.4	0.1	4.5	–30.2	–12.2	–18.8	–16.8
D11	96.2	–2.4	–4.0	–40.2	0.4	–19.6	–17.1

Table 3. Example of results of neutron multiplication factor difference: MCNP k_{kcode} minus k_{eff} for selected materials in single simulation of area method

	$\Delta = k_{kcode} - k_{eff}$										
				Reflector	Reflector			Reflector			
Detector	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11
U-235	**7.7**	–149.9	–39.5	–207.1	–173.6	–158.5	–54.3	–741.5	163.8	–44.6	–47.1
U-238	306.4	–41.0	96.7	164.2	72.3	–58.6	238.0	155.0	–80.1	190.6	50.7
Th-232	332.5	**–35.0**	110.9	184.6	108.5	**–41.9**	261.3	165.0	**–74.6**	214.2	59.7
Np-237	151.3	–89.8	39.6	**–5.7**	**–11.7**	–109.5	86.3	**–50.7**	–121.1	83.9	8.7
Pu-239	39.7	–143.6	**–12.7**	–122.6	–153.8	–154.9	–45.1	–649.0	–124.2	**–33.6**	–54.8
U-nat	132.4	–78.1	46.9	–165.8	–153.2	–148.1	**–35.8**	–685.2	–110.3	146.1	**–1.1**
B-10	–13.1	–166.5	–39.1	–290.8	–224.2	–158.5	–69.4	–937.6	–154.1	–85.1	–51.2
Lowest $\lvert\Delta\rvert$	^{235}U	^{232}Th	^{239}Pu	^{237}Np	^{237}Np	^{232}Th	U-nat	^{237}Np	^{232}Th	^{239}Pu	U-nat

is optimized for the detector position in the reactor. First, detector positions in the well-defined reactor computer model should be proposed. Then, in the optimization procedure, from a set of fissile and fissionable nuclides and possibly other materials like natural uranium, ^{10}B, and others, one nuclide or material for each detector is selected. The computer simulation of Sjöstrand area method experiment is used to find a detector response for each material of the assumed set. Materials presenting the smallest value of difference $\Delta = k_{kcode} - k_{eff}$ are selected for detectors. This procedure must be repeated at least 10 times to eliminate the computation random effect. Then, the set of materials specific for all detectors and their positions in the reactor is definitively established.

On the basis of the results of simulation, it is possible to define the weight for each selected detector, to be used in the final determination of reactor neutron multiplication factor, as in Eq. (1):

$$k_{eff} = k_{kcode} \text{ for } \sum_{i=1}^{n} \Delta_i w_i \Big/ \sum_{i=1}^{n} w_i = 0 \text{ and } \sum_{i=1}^{n} w_i = 1 \tag{1}$$

where n – number of detectors and w_i – weight of the i-th detector with selected material.

Below, the procedure of selecting nuclides for detector positions is presented for the aforementioned model of reactor VENUS. Following nuclides were assumed as the potential detector materials: ^{235}U, ^{238}U, ^{232}Th, ^{237}Np, ^{239}Pu, U-nat, and ^{10}B (96%). For each detector position, for all of the nuclides, simulation of area method experiment yielded the value of ρ/β and consequently k_{eff}. The resulting differences $\Delta = k_{kcode} - k_{eff}$ are presented in Table 3.

Such computations were repeated 11 times and the set of selected nuclides optimally suited (with the lowest absolute value of Δ) for all positions are presented in Table 4.

Table 4. Set of nuclides from 11 repeated simulations for 11 detector positions

D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11
^{235}U	^{232}Th	^{237}Np	^{237}Np	^{238}U	^{232}Th	^{237}Np	^{237}Np	^{232}Th	^{237}Np	^{232}Th
^{235}U	^{232}Th	^{237}Np	^{237}Np	^{237}Np	^{232}Th	U-nat	^{237}Np	^{232}Th	^{239}Pu	U-nat
^{235}U	^{232}Th	^{237}Np	^{238}U	^{237}Np	^{232}Th	^{237}Np	^{237}Np	^{232}Th	^{239}Pu	^{237}Np
^{235}U	^{232}Th	^{237}Np	^{237}Np	^{237}Np	^{232}Th	^{237}Np	^{237}Np	^{232}Th	^{239}Pu	U-nat
^{235}U	^{232}Th	^{237}Np	^{237}Np	^{237}Np	^{232}Th	U-nat	^{237}Np	^{232}Th	^{235}U	^{237}Np
^{239}Pu	^{232}Th	^{239}Pu	^{237}Np	^{237}Np	^{232}Th	U-nat	^{237}Np	^{232}Th	^{239}Pu	^{237}Np
^{239}Pu	^{232}Th	^{239}Pu	^{238}U	^{237}Np	^{232}Th	^{239}Pu	^{237}Np	^{232}Th	^{239}Pu	^{237}Np
^{239}U/B	^{232}Th	^{237}Np	^{232}Th	^{237}Np	^{232}Th	U-nat	^{237}Np	^{232}Th	^{239}Pu	^{237}Np
^{235}U	^{232}Th	^{237}Np	^{237}Np	^{237}Np	^{232}Th	U-nat	^{237}Np	^{232}Th	^{235}U	^{237}Np
^{239}Pu	^{232}Th	^{237}Np	^{237}Np	^{237}Np	^{232}Th	U-nat	^{237}Np	^{232}Th	^{239}Pu	^{237}Np
^{235}U	^{232}Th	^{239}Pu	^{237}Np	^{237}Np	^{232}Th	U-nat	^{237}Np	^{232}Th	^{239}Pu	U-nat

Table 5. Weights of Δ for calculation of weighted average k_{eff} from 11 simulations of the area method experiment

	Weights of $\Delta = k_{\text{kcode}} - k_{\text{eff}}$											
				Reflector	Reflector						Reflector	
Detector	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	S
Simulation no.	U-235	Th-232	Np-237	Np-237	U-238	Th-232	Np-237	U-238	Th-232	Np-237	Th-232	1.000
3	0.095	0.099	0.089	0.097	0.082	0.095	0.085	0.079	0.109	0.083	0.086	1.000
4	0.111	0.122	0.068	0.138	0.053	0.131	0.045	0.065	0.170	0.036	0.061	1.000
5	0.098	0.103	0.084	0.110	0.077	0.103	0.079	0.077	0.112	0.074	0.082	1.000
6	0.134	0.126	0.084	0.127	0.015	0.136	0.075	0.022	0.143	0.064	0.074	1.000
7	0.111	0.122	0.087	0.124	0.024	0.131	0.080	0.036	0.134	0.071	0.080	1.000
8	0.101	0.126	0.086	0.106	0.054	0.113	0.075	0.060	0.133	0.066	0.080	1.000
9	0.099	0.104	0.089	0.104	0.063	0.103	0.082	0.077	0.115	0.080	0.083	1.000
10	0.096	0.105	0.085	0.108	0.058	0.100	0.078	0.095	0.115	0.077	0.082	1.000
11	0.105	0.118	0.091	0.111	0.053	0.118	0.078	0.036	0.139	0.069	0.083	1.000
12	0.090	0.088	0.092	0.090	0.097	0.088	0.094	0.089	0.085	0.094	0.093	1.000
13	0.107	0.136	0.085	0.116	0.063	0.141	0.053	0.009	0.164	0.055	0.071	1.000
Average	0.104	0.114	0.086	0.112	0.058	0.114	0.075	0.059	0.129	0.070	0.080	
SD	0.012	0.015	0.006	0.014	0.024	0.018	0.014	0.029	0.025	0.015	0.008	
Average SD	0.004	0.004	0.002	0.004	0.007	0.005	0.004	0.009	0.008	0.005	0.003	

Table 6. Final set of detector materials and weights of detector results

Detector	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11
Material	^{235}U	^{232}Th	^{237}Np	^{237}Np	^{238}U	^{232}Th	^{237}Np	^{238}U	^{232}Th	^{237}Np	^{232}Th
Weight	0.104	0.114	0.086	0.112	0.058	0.114	0.075	0.059	0.129	0.070	0.080
Weight SD	0.004	0.004	0.002	0.004	0.007	0.005	0.004	0.009	0.008	0.005	0.003

From the results, the following set of nuclides could be selected: D1/^{235}U, D2/^{232}Th, D3/^{237}Np, D4/^{237}Np, D5/^{237}Np, D6/^{232}Th, D7/U-nat, D8/^{237}Np, D9/^{232}Th, D10/^{239}Pu, and D11/^{237}Np. However, arbitrarily for D7, the U-nat was changed for ^{237}Np because among all 11 detectors there were only two with positive differences Δ. This change to three positive Δ caused that the weights of results became more uniformly distributed between all detectors.

A set of weights for all detectors was determined for each simulation of experiment by using the Excel Solver Simplex algorithm in such a way to obtain a zero result for the total difference Δ, as shown in Eq. (1). The final values of weights for the applied 11 simulations are presented in Table 5. Because the resulting weights depend on the adopted initial values, it was important to start the algorithm with equal values of weights for all detectors.

Finally, the set of selected detector materials and weights are as follows in Table 6 (see also Table 5).

Discussion

The role of the detector material in the Sjöstrand method has already been mentioned by Talamo *et al.* [9] and Janczyszyn *et al.* [7]. In the present article, the authors propose a new method of designing the quasi-mono-isotopic detector set for a new subcritical reactor. The method is based on:

- precise computer calculations of the reactor eigenvalue – k_{kcode} and delayed neutron fraction – β (using MCNP KCODE) and
- multiple simulations of the Sjöstrand experiment for all planned detector positions and for several possible sensitive detector materials (using the Talamo *et al.* methodology [10]), resulting in values of k_{eff} and differences $\Delta = k_{\text{kcode}} - k_{\text{eff}}$.

As a result, for each detector position, a sensitive material with the lowest absolute value of Δ is selected, and from multiple evaluations, the most frequently selected material for a given position/detector is proposed for application. From the same simulations, we obtain the set of weights to calculate the average statistical weight of the final detector result.

For the evaluation of the experimental k_{eff} of a given reactor, the set of detectors placed in the assigned for them positions in the reactor will produce a set of results Δ. The value of weighted average of Δ_i, called here Δ_{av}, should be around zero and resulting $k_{\text{eff,exp}} = k_{\text{kcode}} - \Delta_{av}$.

The sensitivity of the resulting eigenvalue to several variables, such as changing reactivity, fuel composition, and so on, was partially tested. The results in Tables 1 and 2 and Figs. 6 and 7 show rather small changes in the full range of CR insertion (between −70 pcm and 70 pcm for most of detectors) and exceptionally to 180 pcm for detectors D4 and D5, and much higher for enrichments below 30% ^{235}U, even −400 pcm to 700 pcm for D4, D5, and D8. This point should be further tested for new detectors and all positions. It is also possible that the best set of detector materials may be slightly different, from the point of view of better (lower) sensitivity.

At present, we are not able to check our method experimentally. We would like to test the presented methodology in a new project, similar to the FREYA one and we hope such an opportunity will prove possible.

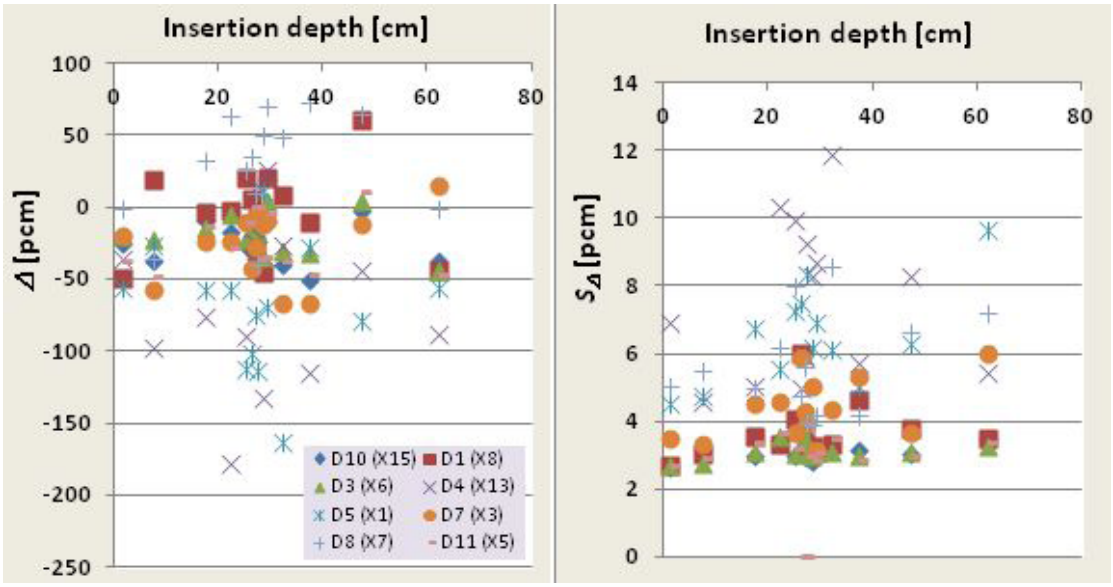

Fig. 6. Effect of CR insertion depth on $\Delta = k_{\text{kcode}} - k_{\text{eff}}$ (in pcm) and the standard deviation of Δ.

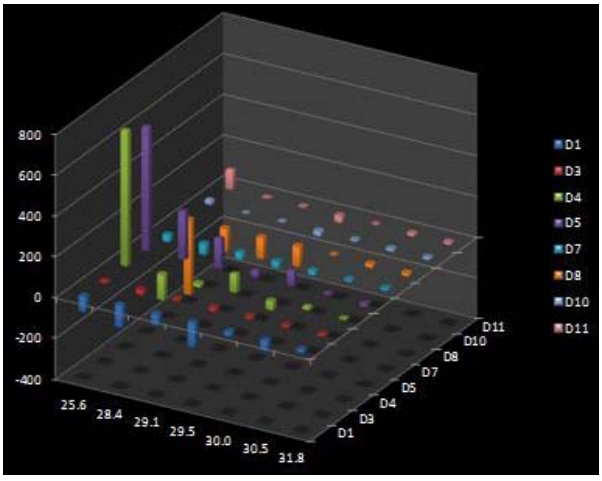

Fig. 7. Distribution of $k_{\text{kcode}} - k_{\text{eff}}$ changes (in pcm) for some detectors vs. fuel enrichment (% of ^{235}U).

Acknowledgments. This work was supported by the Polish Ministry of Science and Higher Education. The research was supported in part by PL Grid Infrastructure available at Academic Computer Centre CYFRONET AGH.

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