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APPLICATION OF SUHAM-U CODE FOR CALCULATION OF THE COMPUTATIONAL BENCHMARKS FOR THE DOPPLER REACTIVITY DEFECT

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ABSTRACT

Benchmarks for the Doppler reactivity defect in PWR fuel pin cells with uranium and MOX fuel were proposed by R. D. Mosteller. The temperature of the fuel is assumed to rise from 600 K to 900 K. It is supposed that radius of fuel pin depends on fuel temperature. Benchmarks were calculated by SUHAM-U code with different reflecting conditions on the cell boundary and with and without uniting the gap and cladding. Separate influence of changing the fuel temperature and radius of fuel rod were studied.

Key Words: Doppler reactivity defect, PWR fuel pin cell, SUHAM-U code.

1. INTRODUCTION

In work [1] Russell D. Mosteller proposed the computational benchmarks for the Doppler reactivity defect. The geometry for these benchmarks corresponds to an infinite array of identical, infinitely long PWR fuel pin cells. Such an array can be modeled as a single square pin cell with reflecting boundary conditions on the top, bottom and four sides. The objective of these benchmarks is to calculate the Doppler defect between hot full power (HFP) and hot zero power (HZP) conditions. Modules of SUHAM-U code [2] were used for calculation of these benchmarks. It should be noted that these benchmarks are the blind ones i.e. they have not published results.

2. DESCRIPTION OF BENCHMARCS

The geometry for these benchmarks corresponds to an infinite array of identical, infinitely long PWR fuel pin cells (see Fig. 1). Fuel pin cells consist of four zones: fuel, gap, cladding and moderator (borated water). The following types of fuel were considered: conventional UO_2, reactor-recycle mixed-oxide (MOX) and weapons-grade MOX. Table I indicates enrichment of uranium in seven considered variants and Table II indicates content of PuO_2 in fuel for MOX benchmarks.

The pin cells have been idealized in a number of ways to simplify the calculations. First, the fuel is assumed to be pure UO_2 or MOX with no impurities or fission products present. Second, the enriched uranium is assumed to contain only ^{234}U, ^{235}U and ^{238}U with ^{234}U content proportional

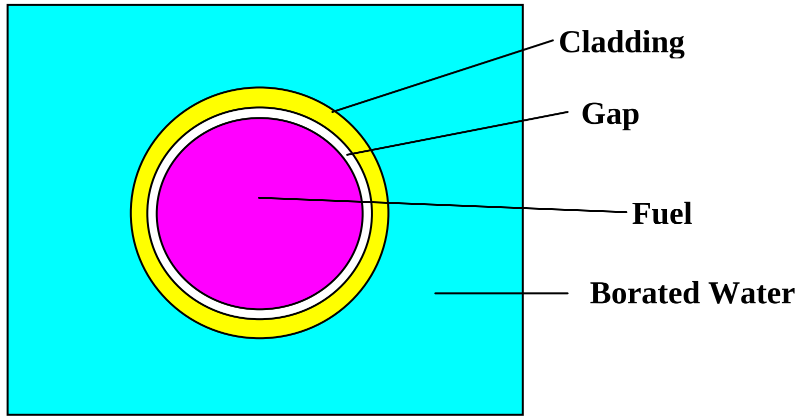

Figure 1. Geometry of Fuel Pin Cell.

Table I. Enrichments of uranium for UO_2 benchmarks

Variant	1	2	3	4	5	6	7
Enrichment (wt.%)	0.711	1.6	2.4	3.1	3.9	4.5	5.0

Table II. Content in % of PuO_2 in fuel for MOX benchmarks

Variant	1	2	3	4	5
Reactor-Recycle MOX	1.0	2.0	4.0	6.0	8.0
Weapons-Grade MOX	1.0	2.0	4.0	6.0	—

to the ^{235}U concentration. Similarly, the MOX fuel is assumed to contain only pure PuO_2 and UO_2 with the Pu containing only four principal isotopes of plutonium and with the U containing only two principal isotopes of uranium. Third, the cladding is taken to be pure zirconium with no minor constituents of Zircaloy present. Finally, the presence of any structural materials (e.g. spacers) has been ignored.

The objective of these benchmarks is to calculate the Doppler defect between hot full power (HFP) and hot zero power (HZP) conditions. The temperatures of the moderator and the cladding are assumed to remain at 600 K for both conditions. The temperature of the fuel is assumed to rise from 600 K for HZP to uniform 900 K at HFP.

Nuclear densities of cladding and moderator at 600 K and all types of fuel at 600 K and 900 K are known values and adduced in [1]. Geometrically, changing the fuel temperature is taken into account by the changing the radius of fuel pin. Dimensions for fuel, cladding and pitch at the temperatures of interest are given in Table III.

Table III. Radii and Pitch

Parameter	600 K	900 K
Outer Radius of Fuel (cm)	0.39398	0.39433
Inner Radius of Cladding (cm)	0.40226	0.40226
Outer Radius of Cladding (cm)	0.45972	0.45972
Pitch (cm)	1.26678	1.26678

3. BRIEF DESCRIPTION OF THE CALCULATIONAL TOOL

Benchmarks were calculated by SUHAM-U code. SUHAM-U code is elaborated for calculation of the neutron-physical processes in nuclear reactor core with triangular and square lattices. It unites the capacities of two codes – SUHAM [3] and UNK [4]. Modules of UNK code are used for preparation of multigroup cross sections. Modules of SUHAM code are used for solution of the multigroup neutron transport equation.

Calculation in SUHAM-U code is organized in the following way.

- Microgroup (about 7000 groups) calculation of each pin cell with isotropic reflecting condition on cylindrical cell boundary.
- Condensation of the microgroup cross-sections of materials to the multigroup ones (here 12 groups are used)
- Solving the multigroup neutron transport equation in calculated object by Surface Harmonics Method [5].

As a rule, reactor core is considered as a calculated object. One of stages of solving the multigroup neutron transport equation in a reactor core is the solving this equation in reactor cells, including the task searching k_{inf}. Module RACIA [6] is used for solving the last task, in so doing, Surface Pseudo-Sources method [7] is used for solving the multigroup neutron transport equation. Module RACIA cans model both isotropic reflecting condition on cylindrical cell boundary and boundary condition closed to mirror reflecting condition on the square cell boundary [8]. To model last reflecting condition, two-dimensional Green functions are used. Really, given cell surrounded by a number of the same cells is considered. For square lattice, this additional number of cells may be four, eight and still more and depends on mean free path in considered energy group and may be different one in different groups.

4. CARRIED OUT CALCULATIONS AND ANALYSIS OF RESULTS

The following four types of calculations were carried out.

1. Four-zone cells with mirror reflecting condition on the square cell boundary.
2. Four-zone cells with isotropic reflecting condition on cylindrical cell boundary.
3. Three-zone cells (cladding and gap are united to one zone) with mirror reflecting condition on the square cell boundary.
4. Three-zone cells with isotropic reflecting condition on cylindrical cell boundary.

Besides, calculations of four-zone cells with mirror reflecting condition on the square cell boundary with changing only fuel temperature by the transition from HZP state to HFP one were carried out.

The following values were results of calculations: $\Delta\rho$ and $\Delta\rho/\Delta T$, in so doing value $\Delta\rho$ was calculated by the following formula.

$$\Delta\rho = \frac{k_{\mathrm{HFP}} - k_{\mathrm{HZP}}}{k_{\mathrm{HFP}} k_{\mathrm{HZP}}} \tag{1}$$

Carried out calculations made it possible to estimate influence of the following effects on the Doppler defect:

- Influence of reflecting condition on the cell boundary.
- Influence of uniting the cladding and gap to one zone.
- Separate influence of changing the fuel temperature and radius of fuel rod.

Tables IV - VI show calculational results for four-zone cells with UO_2, reactor-recycle and weapons-grade MOX fuel correspondingly with mirror reflecting condition on the square cell boundary. One can see that:

- Doppler coefficient is negative for all fuels and all variants.
- For UO_2 benchmarks, absolute value of Doppler coefficient is reduced with increase the enrichment of uranium.
- For reactor-recycle MOX benchmarks, absolute value of Doppler coefficient is reduced with increase the content of PuO_2 in fuel.
- For weapons-grade MOX benchmarks, Doppler coefficient depends weakly on the content of PuO_2 in fuel.

Fig. 2 shows deviations of Doppler coefficient calculated with isotropic reflecting condition on cylindrical cell boundary from values calculated with mirror reflecting condition on the square cell boundary for UO_2 benchmarks. Fig. 3, 4 show the same values for reactor-recycle and weapons-grade MOX benchmarks correspondingly. One can see that these deviations of Doppler coefficient are practically independent from number of cell zones (from uniting the cladding and gap to one zone) and changed: 1) from 0.20 % till 0.29 % for UO_2 benchmarks; 2) from 0.64 % till 0.81 % for reactor-recycle MOX benchmarks; 3) from 0.31 % till 0.67 % for weapons-grade MOX benchmarks.

Fig. 5 shows deviation of Doppler coefficient calculated for three-zone cells from values calculated for four-zone cells for UO_2 benchmarks. Fig. 6, 7 show the same values for reactor-recycle and weapons-grade MOX benchmarks correspondingly. One can see that influence of uniting the cladding and gap to one zone on the Doppler coefficient is small: maximum deviation for all benchmarks doesn't exceed 0.12 %.

Table IV. Calculational results for cells with UO_2 fuel, calculation of first type.

Enrichment (wt%)	HFP, k_{inf}	HZP, k_{inf}	Doppler Defect ($\Delta\rho$), pcm	Doppler Coefficient ($\Delta\rho/\Delta T$), pcm/°K
0.711	0.661795	0.667017	-1183	-3.943
1.6	0.952523	0.960192	-839	-2.795
2.4	1.089246	1.097894	-723	-2.411
3.1	1.166761	1.175912	-667	-2.223
3.9	1.229345	1.238864	-625	-2.083
4.5	1.264909	1.274620	-602	-2.008
5.0	1.289428	1.299258	-587	-1.956

Table V. Calculational results for cells with reactor-recycle MOX fuel, calculation of first type.

MOX, Content PuO_2, (wt.%)	HFP, k_{inf}	HZP, k_{inf}	Doppler Defect ($\Delta\rho$), pcm	Doppler Coefficient ($\Delta\rho/\Delta T$), pcm/°K
1.0	0.934938	0.944339	-1065	-3.549
2.0	1.008650	1.019334	-1039	-3.464
4.0	1.062284	1.073660	-997	-3.325
6.0	1.090245	1.101706	-954	-3.181
8.0	1.113101	1.124506	-911	-3.037

Table VI. Calculational results for cells with weapons-grade MOX fuel, calculation of first type.

MOX, Content PuO_2, (wt.%)	HFP, k_{inf}	HZP, k_{inf}	Doppler Defect ($\Delta\rho$), pcm	Doppler Coefficient ($\Delta\rho/\Delta T$), pcm/°K
1.0	1.076706	1.085649	-765	-2.550
2.0	1.163920	1.174558	-778	-2.594
4.0	1.229156	1.240964	-774	-2.580
6.0	1.263880	1.275947	-748	-2.494

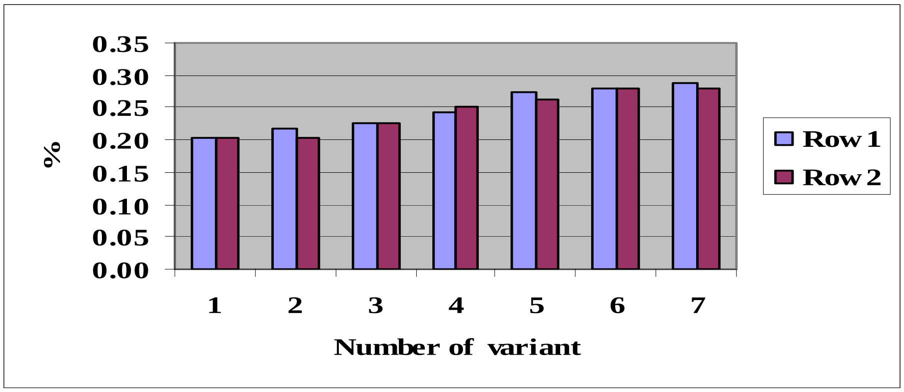

Figure 2. Influence of reflecting condition on cell boundary for UO_2 benchmarks. Row 1 – four-zone cells, row 2 – three-zone cells.

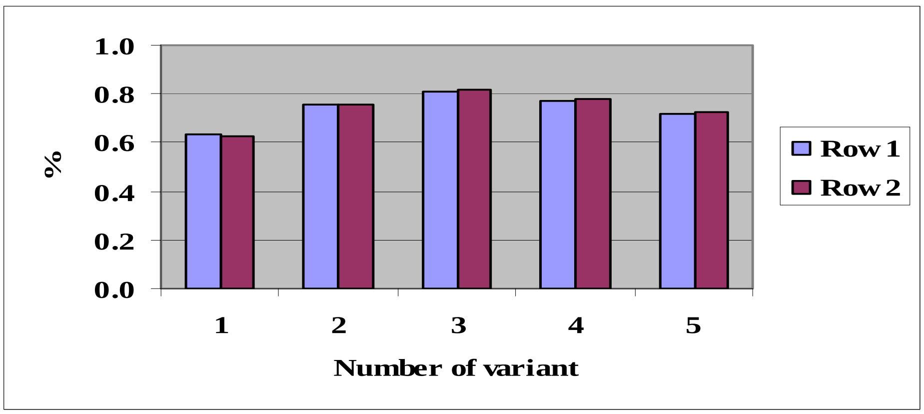

Figure 3. Influence of reflecting condition on cell boundary for reactor-recycle MOX benchmarks. Row 1 – four-zone cells, row 2 – three-zone cells.

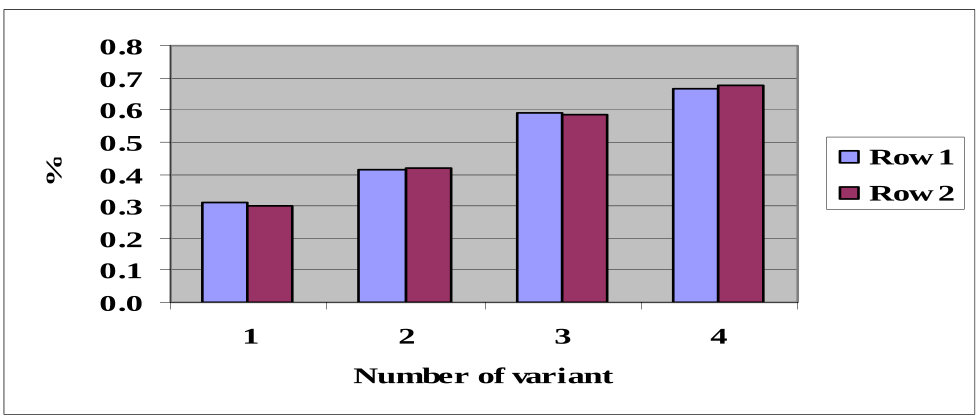

Figure 4. Influence of reflecting condition on cell boundary for weapons-grade MOX benchmarks. Row 1 – four-zone cells, row 2 – three-zone cells.

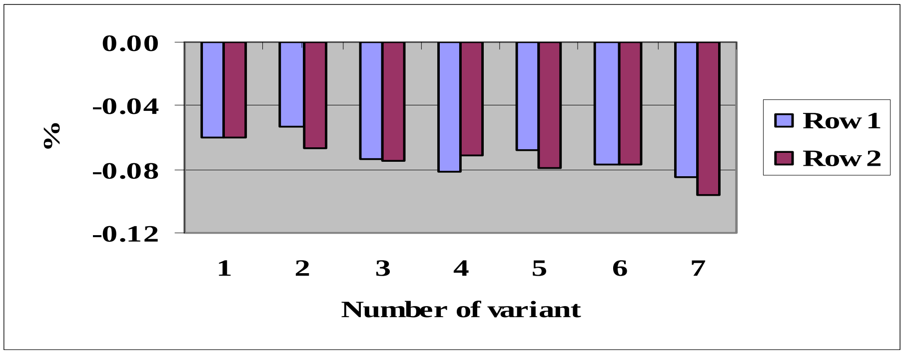

Figure 5. Influence of uniting the cladding and gap to one zone for UO_2 benchmarks. Row 1 – mirror reflecting condition on the square cell boundary, row 2 – isotropic reflecting condition on cylindrical cell boundary.

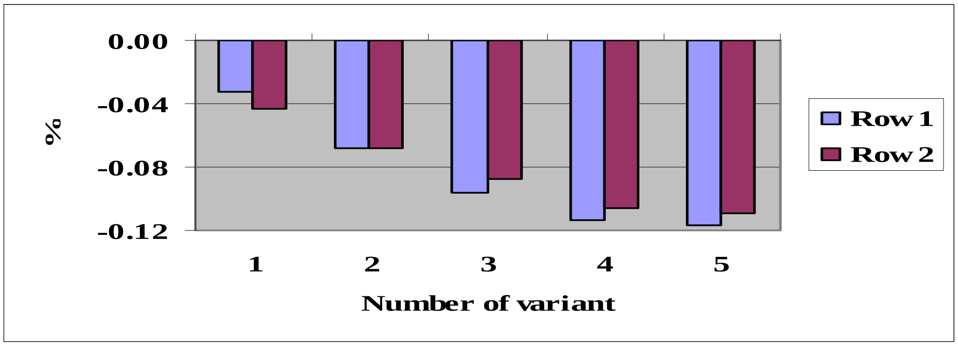

Figure 6. Influence of uniting the cladding and gap to one zone for reactor-recycle MOX benchmarks. Row 1 – mirror reflecting condition on the square cell boundary, row 2 – isotropic reflecting condition on cylindrical cell boundary.

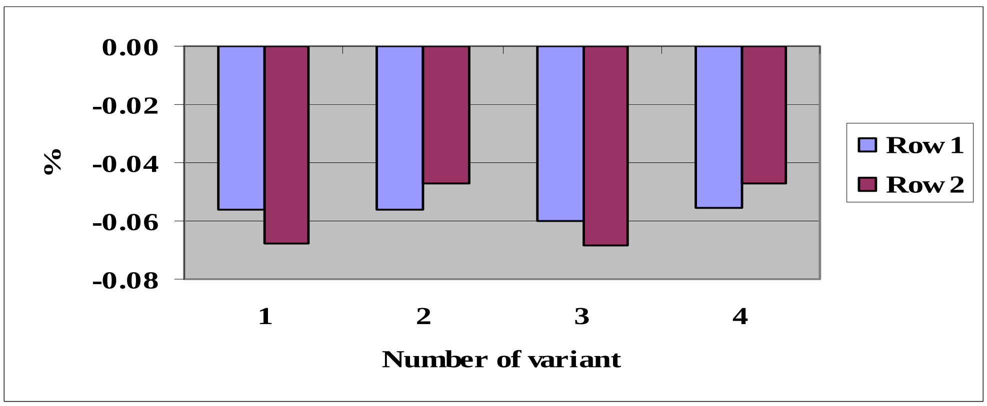

Figure 7. Influence of uniting the cladding and gap to one zone for weapons-grade MOX benchmarks. Row 1 – mirror reflecting condition on the square cell boundary, row 2 – isotropic reflecting condition on cylindrical cell boundary.

Fig. 8 – 10 show the values of Doppler coefficient for UO_2, reactor-recycle and weapons-grade MOX benchmarks correspondingly for two cases: 1) only fuel temperature is changed; 2) fuel temperature and radius of fuel rod are changed. One can see that for all considered fuels deviations of Doppler coefficient in these two cases are small. Fig. 11 – 13 show deviations of Doppler coefficient connected with changing only radius of fuel rod for UO_2, reactor-recycle and weapons-grade MOX benchmarks correspondingly. One can see that contribution to Doppler coefficient connected with changing only radius of fuel rod is small in comparison with full value when fuel temperature and radius of fuel rod are changed and doesn't exceed 1.7 % for all benchmarks.

4. CONCLUSIONS

Benchmarks for the Doppler reactivity defect in PWR fuel pin cells with UO_2, reactor-recycle MOX and weapons-grade MOX fuel were calculated by SUHAM-U code with different approximations. Carried out calculations made it possible to estimate influence of the following effects on the Doppler coefficient:

- Influence of reflecting condition on the cell boundary.
- Influence of uniting the cladding and gap to one zone.
- Separate influence of changing the fuel temperature and radius of fuel rod.

The following results were obtained:

- Doppler coefficient is negative for all fuels and all variants.
- For UO_2 benchmarks, absolute value of Doppler coefficient is reduced with increase the enrichment of uranium.
- For reactor-recycle MOX benchmarks, absolute value of Doppler coefficient is reduced with increase the content of PuO_2 in fuel.
- For weapons-grade MOX benchmarks, Doppler coefficient depends weakly on the content of PuO_2 in fuel.
- Deviations of Doppler coefficient calculated with isotropic reflecting condition on cylindrical cell boundary from values calculated with mirror reflecting condition on the square cell boundary are practically independent from number of cell zones (from uniting the cladding and gap to one zone) and don't exceed 0.3 % for UO_2 benchmarks, 0.8 % for reactor-recycle MOX benchmarks and 0.7 % for weapons-grade MOX ones.
- Influence of uniting the cladding and gap to one zone on the Doppler coefficient is small: maximum deviation for all benchmarks doesn't exceed 0.12 %.
- Contribution to Doppler coefficient connected with changing only radius of fuel rod is small in comparison with full value when fuel temperature and radius of fuel rod are changed and doesn't exceed 1.7 % for all benchmarks.

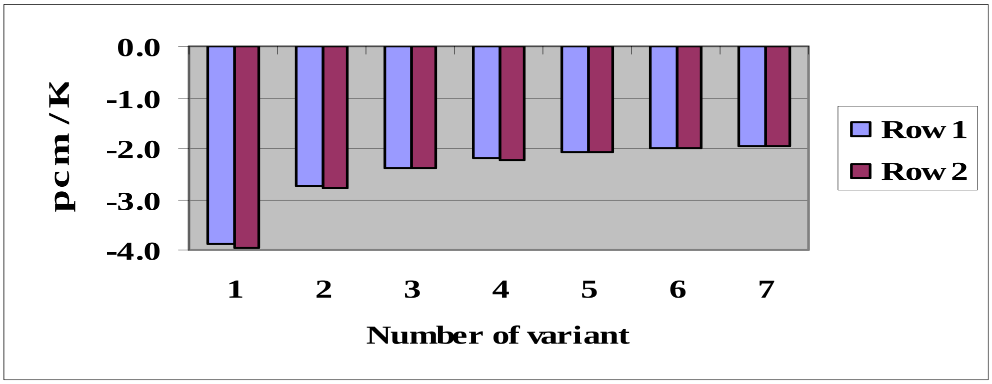

Figure 8. Doppler coefficient for UO_2 benchmarks. Row 1 – only fuel temperature is changed, row 2 – fuel temperature and radius of fuel rod are changed.

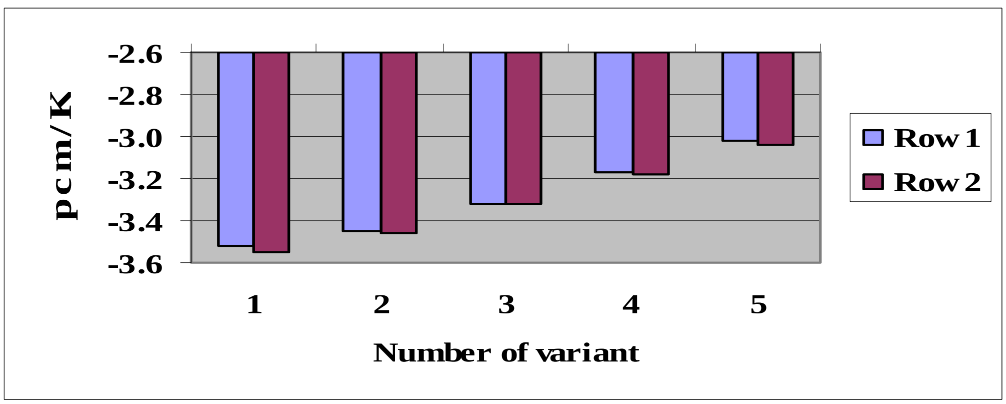

Figure 9. Doppler coefficient for reactor-recycle MOX benchmarks. Row 1 – only fuel temperature is changed, row 2 – fuel temperature and radius of fuel rod are changed.

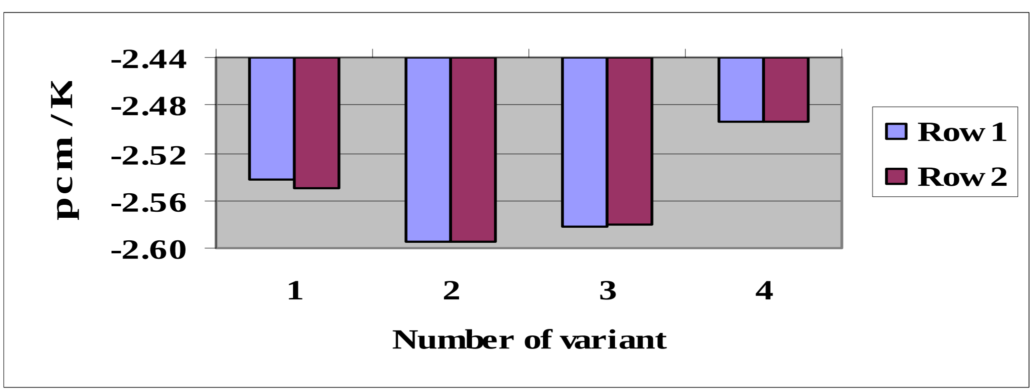

Figure 10. Doppler coefficient for weapons-grade MOX benchmarks. Row 1 – only fuel temperature is changed, row 2 – fuel temperature and radius of fuel rod are changed.

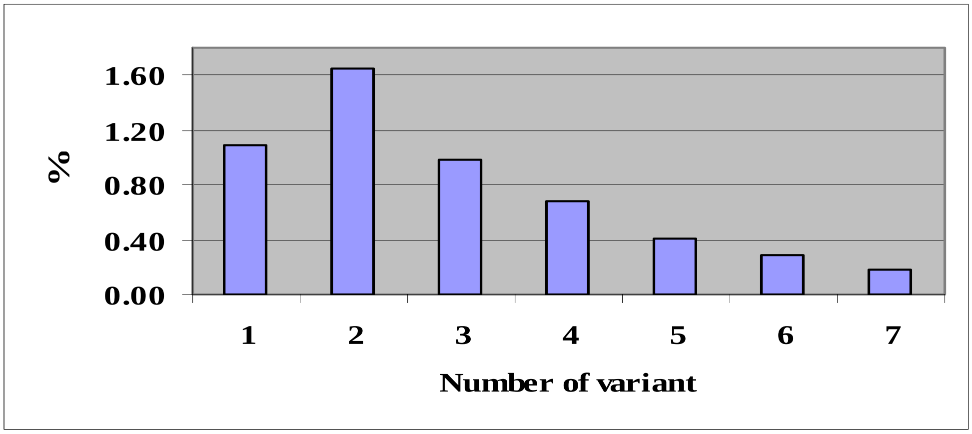

Figure 11. Contribution to Doppler coefficient connected with changing only radius of fuel rod for UO_2 benchmarks.

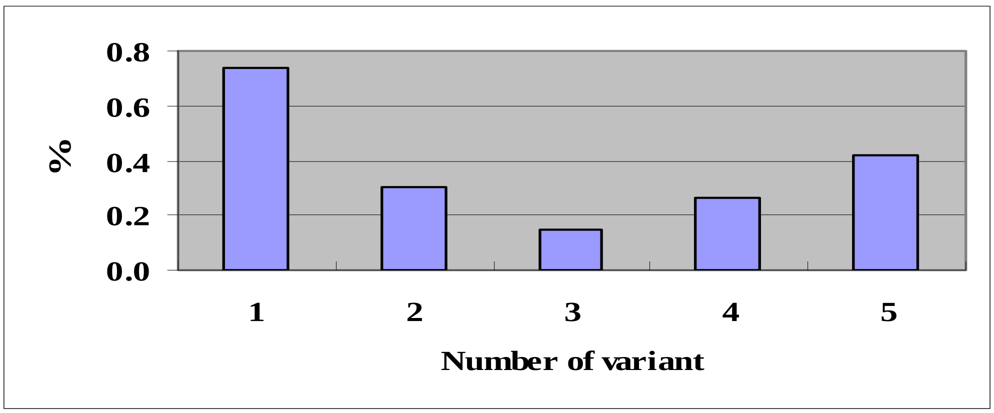

Figure 12. Contribution to Doppler coefficient connected with changing only radius of fuel rod for reactor-recycle MOX benchmarks.

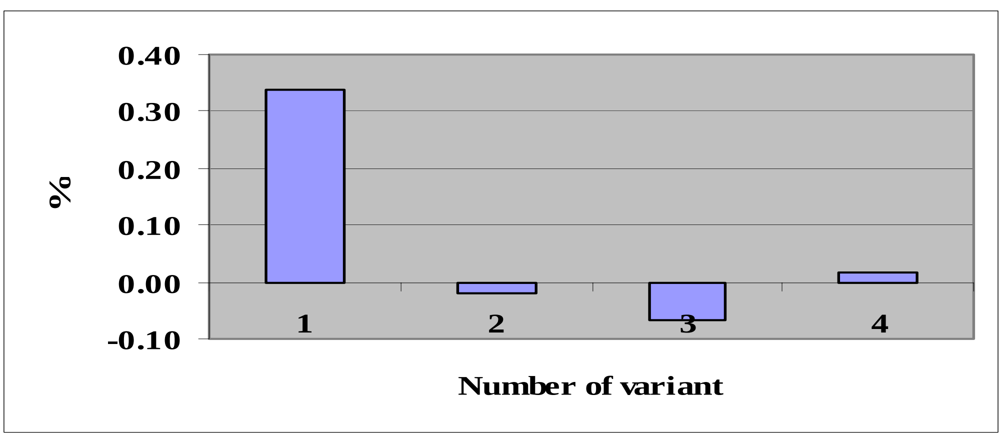

Figure 13. Contribution to Doppler coefficient connected with changing only radius of fuel rod for weapons-grade MOX benchmarks.

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