Analysis of Some Fuel Characteristics Deviations and Their Influence over WWER-440 Fuel Cycle Design

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1. Introduction

The aim of the research is to estimate the influence of some fuel assemblies (FA) characteristics deviations on WWER-440 fuel core design cycle.

Since one year we have at Kozloduy NPP the possibility to perform such a task for reactors WWER-440. Namely we have got and we apply:

- A spectral code HELIOS [6,7] for calculation of 2-group diffusion constants libraries for various kinds of nuclear fuel assemblies (FA);
- Methods [3,4,5] and computer codes pack [8] for generation of approximation coefficients libraries for SPPS-1.6 3D nodal diffusion code [1,2];
- SPPS-1.6 3-Dimensional nodal diffusion code for WWER-440 reactor core type calculation.

A large number of different fresh fuel assemblies (FA) with enrichment of 3.6 wt% for WWER-440 were examined. Deviations from the standard are observed mainly in the mass of initial metal Uranium and in ^{235}U enrichment. Due to manufacturing uncertainty every fresh nuclear FA has particular mass of initial metal Uranium, ^{235}U enrichment and assembly wall (shroud) thickness. In general one fresh FAs delivery has its mean initial metal Uranium mass, ^{235}U enrichment and assembly shroud thickness corresponding to standard.

The FA characteristics deviations analysed in this report are: ^{235}U enrichment and assembly shroud thickness.

2. Application of Spectral Code HELIOS

Evaluation of the effect of the deviation from the standard in the characteristics of fresh fuel working assemblies such as: enrichment, mass of initial metal Uranium and assembly wall thickness on K_{inf} (infinite multiplication factor in assembly calculated by HELIOS) [6,7].

As the base we have chosen WWER-440 working assembly with Zr spacer grid (SG) with:

- ^{235}U enrichment of 3.6 wt%, E_{ref}=3.6 wt%;
- Mass of initial metal Uranium 120.2 kg, M_{ref}=120.2 kg;
- Assembly wall thickness of 1.5 mm, D_{ref}=1.5 mm.

We have considered the following values of the deviations in the characteristics of fresh fuel working assemblies:

- ^{235}U enrichment of 3.6 wt%,
  $E_{\max}$=3.65 wt%, $E_{\min}$=3.55 wt%;
- Initial metal Uranium mass,
  $M_{\max}$=122.7 kg, $M_{\min}$=117.7 kg;
- Assembly wall thickness,
  $D_{\max}$=1.6 mm, $D_{\min}$= 1.4 mm.

First, we have calculated using the code HELIOS the K_{inf} (basic) evolution during burnup (BU) for the basic assembly $E_{ref}D_{ref}M_{ref}$.

Second, we have calculated by HELIOS the $K_{inf(i)}$ evolution during burnup for six (i=1,2,..,6) different FAs with single parameter deviation:

- $E_{\max}D_{ref}M_{ref}$ – only enrichment is maximum;
- $E_{\min}D_{ref}M_{ref}$ – only enrichment is minimum;
- $E_{ref}D_{\max}M_{ref}$ – only assembly wall thickness is maximum;
- $E_{ref}D_{\min}M_{ref}$ – only assembly wall thickness is minimum;
- $E_{ref}D_{ref}M_{\max}$ – only initial metal Uranium mass is maximum;
- $E_{ref}D_{ref}M_{\min}$ – only initial metal Uranium mass is minimum.

The single parameter deviation effect $\Delta K_{inf}=K_{inf(i)} - K_{inf(basic)}$ is presented in Figure 1.

We observe the following effects:

- $E_{\max}D_{ref}M_{ref}$ ($E_{\max}$=3.65 wt%) – there is weak dependence of ΔK_{inf} on burnup; ΔK_{inf} remains in the range of [300-350 pcm] during the burnup;
- $E_{ref}D_{\min}M_{ref}$ ($D_{\min}$=1.4 mm) – ΔK_{inf} is near 100 pcm for burnup in the range of [0-15 MWd/kgU]; after that it decreases down to -40 pcm;
- $E_{ref}D_{ref}M_{\max}$ ($M_{\max}$=122.7 kg) – for burnup in the range of [0-22 MWd/kgU] there is a weak dependence of ΔK_{inf} on burnup, ΔK_{inf} remains between [0--50 pcm]; after that it increases up to 200 pcm;
- $E_{\min}D_{ref}M_{ref}$ ($E_{\min}$=3.55 wt%) – there is symmetric to $E_{\max}D_{ref}M_{ref}$ dependence of ΔK_{inf} on burnup;
- $E_{ref}D_{\max}M_{ref}$ ($D_{\max}$=1.6 mm) – there is symmetric to $E_{ref}D_{\min}M_{ref}$ dependence of ΔK_{inf} on burnup;
- $E_{ref}D_{ref}M_{\min}$ ($M_{\min}$=117.7 kg) – there is symmetric to $E_{ref}D_{ref}M_{\max}$ dependence of ΔK_{inf} on burnup.

Third, we have calculated by HELIOS the $K_{inf(i)}$ evolution during burnup for four (i=1,2,3,4) different FAs with simultaneous deviation of two parameters:

- $E_{\max}D_{\min}M_{ref}$ ($E_{\max}$=3.65 wt%, $D_{\min}$=1.4 mm);
- $E_{\max}D_{\max}M_{ref}$ ($E_{\max}$=3.65 wt%, $D_{\max}$=1.6 mm);
- $E_{\min}D_{\max}M_{ref}$ ($E_{\min}$=3.55 wt%, $D_{\max}$=1.6 mm);
- $E_{\min}D_{\min}M_{ref}$ ($E_{\min}$=3.55 wt%, $D_{\min}$=1.4 mm).

The simultaneous two parameter deviation effect $\Delta K_{inf}=K_{inf(i)} - K_{inf(basic)}$ is presented in Figure 2.

We observe the following effects:

- $E_{\max}D_{\min}M_{ref}$ – there is weak dependence of ΔK_{inf} on burnup in the range [0-42 MWd/kgU], ΔK_{inf} varies near 330-440 pcm; after that it decreases down to 250 pcm;
- $E_{\max}D_{\max}M_{ref}$ – ΔK_{inf} increases slowly in the burnup range [0-35 MWd/kgU] from 210 pcm to 330 pcm; after that it is constant near 330 pcm;
- $E_{\min}D_{\min}M_{ref}$ – there is symmetric to $E_{\max}D_{\max}M_{ref}$ dependence of ΔK_{inf} on burnup;
- $E_{\min}D_{\max}M_{ref}$ – there is symmetric to $E_{\max}D_{\min}M_{ref}$ dependence of ΔK_{inf} on burnup.

Comparing the presented results in Figure 1 and Figure 2, we can see that the point values of the

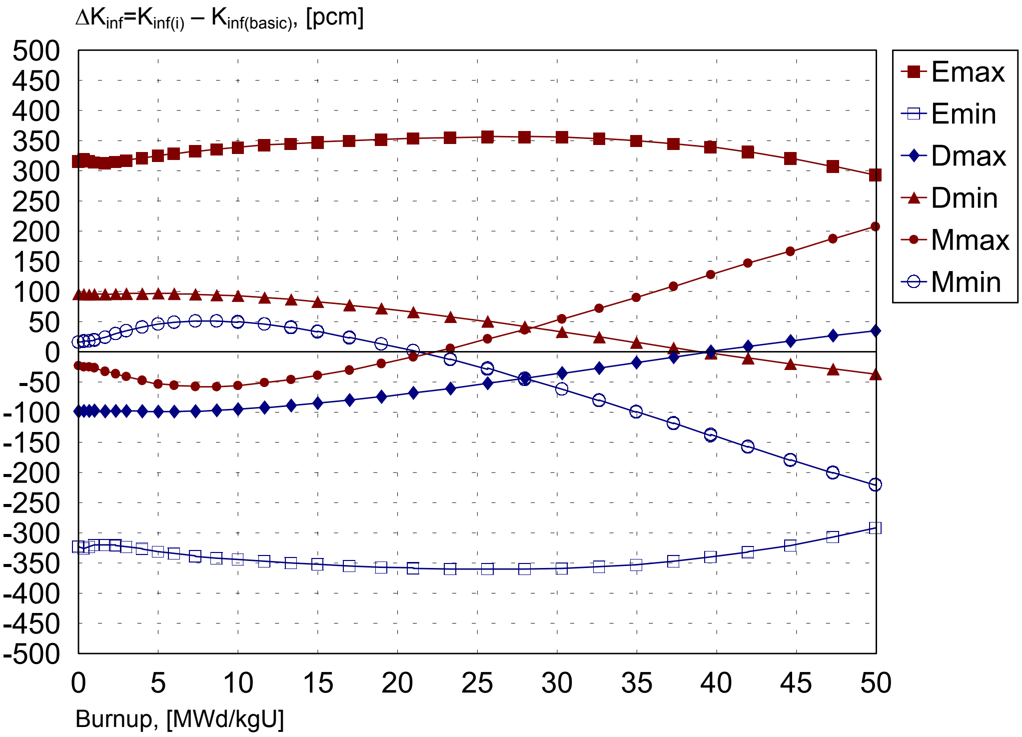

Figure 1. Dependance of ΔK_{inf} on the fuel burnup – single parameter effects

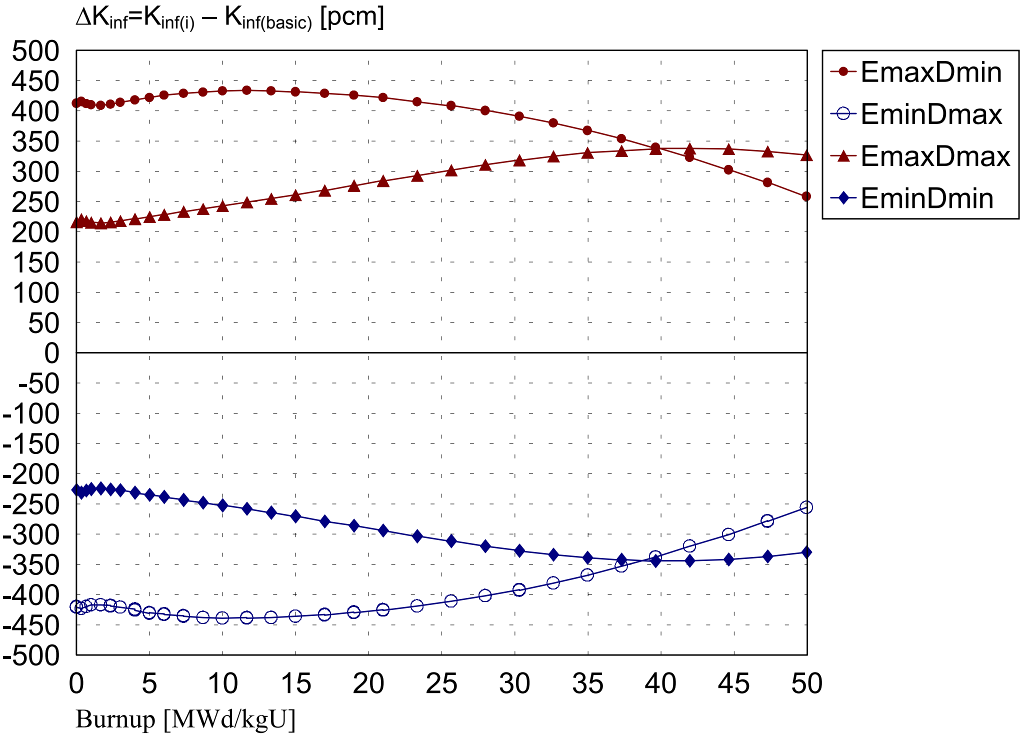

Figure 2. Dependance of ΔK_{inf} on the fuel burnup – simultaneous 2 parameters effects

curve $E_{\max}D_{\min}M_{ref}$ (Figure 2) are the sum of the corresponding point values of two curves $E_{\max}D_{ref}M_{ref}$ and $E_{ref}D_{\min}M_{ref}$ (Figure 1).

By analogy the point values of the curve $E_{\max}D_{\max}M_{ref}$ (Figure 2) are the sum of the corresponding point values of two curves $E_{\max}D_{ref}M_{ref}$ and $E_{ref}D_{\max}M_{ref}$ (Figure 1), etc.

Following the above results, we can expect the combination $E_{\max}D_{\min}$ to give maximum fuel cycle duration in SPPS-1.6 calculation and the combination $E_{\min}D_{\max}$ gives minimum fuel cycle duration.

It should be noted, that for the time being the computer code pack [8] for generation of approximation coefficients libraries for SPPS-1.6 reactor computer code is not able to account for different initial metal Uranium masses in assemblies.

For this reason our next analyses of the fuel characteristic deviation effects on neutron physics characteristics of a fuel core design cycle cover only the enrichment and assembly wall thickness.

3. Generation of Different Approximation Coefficients Libraries for 3D-coarse Mesh Diffusion Code SPPS-1.6 Based on HELIOS Code Calculations

3.1. SPPSn2h0.lib Basic Library for 3D-nodal Diffusion Code SPPS-1.6

The basic library SPPSn2h0.lib for the 3D-nodal diffusion code SPPS-1.6 [1,2] is generated using HELIOS spectral code, the computer code pack [8] and methods [3,4,5].

This library is calculated for all the reactor WWER-440 conditions, including all temperature range for:

- Cold Zero Power;
- Hot Zero Power;
- Hot Full Power.

SPPSn2h0.lib contains data on 12 kinds of FAs (Table 1), taking into account ^{235}U enrichment, material of spacer grids (SG) and assembly wall thickness. The initial metal Uranium mass in FA is assumed 120.2 kg. The mass of 115.2 kg for the Control Assembly is taken into account in the code SPPS-1.6.

3.2. Calculation of Number of Different 2-group Diffusion Constants Libraries for WWER-440 Hot Full Power (HFP) Condition

In this report our analysis is orientated only on WWER-440 HFP condition. We have generated a number of new different 2-group diffusion constants libraries for HFP only.

In the recent few years the loaded working WWER-440 fresh FAs are mainly with ^{235}U enrichment of 3.6 wt%, Zr SG and assembly wall thickness of 1.5 mm. This is the reason we pay particular attention to them.

Table 1. Kinds of assemblies in SPPSn2h0.lib - $E_{ref}D_{ref}M_{ref}$

Kind	Enrichment, [wt%]	Assembly wall thickness, [mm]	Spacer grids material
A	E_{ref}=3.60	2.1	Stainless Steel (SS)
B	E_{ref}=2.40	2.1	Stainless Steel (SS)
C	E_{ref}=1.60	2.1	Stainless Steel (SS)
D	E_{ref}=3.60	1.5	Stainless Steel (SS)
E	E_{ref}=2.40	1.5	Stainless Steel (SS)
F	E_{ref}=1.60	1.5	Stainless Steel (SS)
G	E_{ref}=3.60	1.5	Zirconium (Zr)
H	E_{ref}=2.40	1.5	Zirconium (Zr)
I	E_{ref}=1.60	1.5	Zirconium (Zr)
J	E_{ref}=3.60	2.0	Zirconium (Zr)
K	E_{ref}=2.40	2.0	Zirconium (Zr)
L	E_{ref}=1.60	2.0	Zirconium (Zr)

We have analyzed the effect of enrichment deviation and assembly wall thickness deviation on neutron physics characteristics of fuel loaded core design.

Each one of the new libraries includes thirteen (13) assembly kinds:

- Twelve (12) assembly kinds are identical to those in SPPSn2h0.lib;
- The additional thirteenth (13-th) kind (marked by letter *M*) is with ^{235}U enrichment E_{ref}=3.60 wt% or any deviation $E_{\max}$, $E_{\min}$, Zr SG, assembly wall thickness D_{ref}=1.5 mm or any deviation $D_{\max}$, $D_{\min}$ and initial metal Uranium mass in FA M_{ref}=120.2 kg.

4. FA Single Parameter Deviation Effect on Design Fuel Cycle Duration and Relative Power Peaking Factors

The calculation is carried out using the code SPPS-1.6 for full and small rector core volumes with the above new different libraries. A comparison is made with standard library SPPSn2h0.lib – $E_{ref}D_{ref}M_{ref}$.

To be concrete:

- Full core loading – the 16-th fuel loading of Kozloduy NPP, Unit 4, with eighty four (84) fresh FAs of kind *G* or *M* in the core of 349 assemblies;
- Small core loading – the 17-th fuel loading of Kozloduy NPP, Unit 3, with seventy eight (78) fresh FAs of kind *G* or *M* in the core of 313 assemblies and 36 dummy assemblies.

4.1. Effects on Design Fuel Cycle Duration

The calculated design durations of only one fuel cycle are presented in Table 2.

For the selected parameters deviations the observed effect of enrichment deviation is about two times higher than the effect of the assembly wall thickness deviation.

4.2. Effects on Assembly Radial Power Peaking Factor

The calculated maximum assembly radial power peaking factors are presented in Table 3.

In the presented case of a small core volume, using standard library SPPSn2h0.lib – $E_{ref}D_{ref}M_{ref}$ the calculated value of $K_{q\text{-max}}$ is 1.280. Using fuel of standard characteristics, $K_{q\text{-max}}$ does not exceed the limit value of 1.290. When the fresh FAs delivery is of kind *M* ($E_{\max}D_{ref}M_{ref}$), $K_{q\text{-max}}=1.294$ and exceeds the limit value 1.290.

That means that in all similar cases we have to choose a new fuel loading pattern with lower value of $K_{q\text{-max}}$ in order to meet the safety criterion.

The neglect of fuel enrichment deviation can lead to exceeding the limit value for $K_{q\text{-max}}$ or $K_{v\text{-max}}$.

5. Effects of FAs Parameter Deviations on Four Consecutive Design Fuel Cycles

Four (4) consecutive design fuel cycles are calculated, based on the assumption that the fresh FAs are of the same kind in all following fuel cycle loadings.

The first design cycle consists of 12 fresh FAs of kind *M* (for the new libraries), and 12 fresh FAs of kind *G* (for the library SPPSn2h0.lib – $E_{ref}D_{ref}M_{ref}$).

The second design cycle consists of 12 FAs for second year of kind *M* (for the new libraries) and 90 fresh FAs of the same kind *M* (for the new libraries).

The third design cycle consists of 12 FAs for third year of kind *M* (for the new libraries), 90 FAs for second year of the same kind *M* (for the new libraries) and 78 fresh FAs of the same kind *M* (for the new libraries).

The last fourth design cycle consists of 12 FAs for fourth year of kind *M* (for the new libraries), 90 FAs for third year of the same kind *M* (for the new libraries), 78 FAs for second year of the same kind *M* (for the new libraries) and 84 fresh FAs of the same kind *M* (for the new libraries).

Table 2. Calculated design fuel cycle duration of fuel loading for full core volume and small core volume; full core – 84 fresh FAs of kind *G* or *M* for reactor core with 349 assemblies; small core – 78 fresh FAs of kind *G* or *M* for reactor core with 313 FAs and 36 dummy assemblies

Single parameter deviation	$E_{\max}D_{ref}M_{ref}$	$E_{\min}D_{ref}M_{ref}$	$E_{ref}D_{\min}M_{ref}$	$E_{ref}D_{\max}M_{ref}$	$E_{ref}D_{ref}M_{ref}$
HELIOS prepared 2-groups library	Hel1_7.lib	Hel1_6.lib	Hel1_4.lib	Hel1_5.lib	SPPSn2h0.lib
Full core Fuel cycle duration, [FPD]	307.63	302.29	306.33	303.59	304.96
Full core $\Delta=T_{eff(i)}-T_{eff(0)}$, [FPD]	2.67	-2.67	1.37	-1.37	0.00
Relative Δ, [%]	0.88	-0.88	0.45	-0.45	0.0
Small core Fuel cycle duration, [FPD]	283.47	278.94	282.40	280.01	281.21
Small core $\Delta=T_{eff(i)}-T_{eff(0)}$, [FPD]	2.26	-2.27	1.19	-1.20	0.00
Relative Δ, [%]	0.80	-0.80	0.43	-0.43	0.0

Table 3. Maximum design assembly radial power peaking factor $K_{q\text{-max}}$ and core volume power peaking factor $K_{v\text{-max}}$ for full core and small core; full core – 84 fresh FAs of kind *G* or *M* for reactor core with 349 assemblies; small core – 78 fresh FAs of kind *G* or *M* for reactor core with 313 FAs and 36 dummy assemblies

Variant	$E_{\max}D_{ref}M_{ref}$	$E_{\min}D_{ref}M_{ref}$	$E_{ref}D_{\min}M_{ref}$	$E_{ref}D_{\max}M_{ref}$	$E_{ref}D_{ref}M_{ref}$
HELIOS prepared 2-groups library	Hel1_7.lib	Hel1_6.lib	Hel1_4.lib	Hel1_5.lib	SPPSn2h0.lib
	Value/No ass/No vol				
Full core BOC $K_{q\text{-max}}$	1.343/163	1.317/76	1.333/163	1.321/76	1.327/163
Full core BOC Δ, [%]	1.6	-1.0	0.6	-0.6	0.0
Full core BOC $K_{v\text{-max}}$	1.755/321/5	1.710/321/5	1.741/321/5	1.724/321/5	1.733/321/5
Full core BOC Δ, [%]	2.2	-2.3	-0.8	0.9	0.0
Small core BOC $K_{q\text{-max}}$	1.294/187	1.266/187	1.285/187	1.275/187	1.280/187
Small core BOC Δ, [%]	1.4	-1.4	0.5	-0.5	0.0
Small core BOC $K_{v\text{-max}}$	1.678/187/5	1.640/187/5	1.666/187/5	1.652/187/5	1.659/187/5
Small core BOC Δ, [%]	1.9	-1.9	0.7	-0.7	0.0

The fuel parameter deviations from the standard and their effect on consecutive design fuel cycles durations are presented in Table 4.

In case of one fuel parameter deviation from the standard, the effect on the calculated design fuel cycle duration due to enrichment is greater than the assembly wall thickness effect.

In case of two FA parameter deviation from the standard, the effect on the calculated design fuel cycle duration can be presented as a sum of two single parameter deviation effects. This can be seen in Table 4.

In the case of $E_{\min}D_{\max}$ the result is about 2% decreasing in fuel cycle duration. Assuming $E_{\max}D_{\min}$ in all four consecutive fresh FA loadings, the maximum relative fuel cycle prolongation can reach 2% in the fourth consecutive design fuel cycle.

6. Conclusions

6.1. FA Single Parameter Deviation Effects on:

- Design fuel cycle duration

The relative shortness of fuel cycle duration due to $E_{\min}$ for WWER-440 loadings with about 80-90 fresh FAs 3.6% is about 0.85%. Analogous prolongation is due to $E_{\max}$.

The relative reducing of fuel cycle duration due to $D_{\max}$ for WWER-440 loadings with about 80-90 fresh FAs 3.6% is approximately 0.45%. Analogous prolongation is due to $D_{\min}$.

- Relative power peaking factors

The FA enrichment deviation $E_{\max}$ gives $K_{q\text{-max}}$ greater than the standard E_{ref} with about 1.5%, and $K_{v\text{-max}}$ greater than the standard E_{ref} with about 2.1%.

The neglect of actual fuel enrichment deviation $E_{\max}$ can lead to exceeding the maximum values for $K_{q\text{-max}}$ or $K_{v\text{-max}}$.

In some cases when the actual ^{235}U enrichment is greater than the standard, it is possible that it will be needed to choose a new fuel core loading pattern with lower value of $K_{q\text{-max}}$ or $K_{v\text{-max}}$ in order to meet the safety criteria.

In case of one FA parameter deviation from the standard the effect on calculated design fuel cycle duration due to enrichment is greater than assembly wall thickness effect.

6.2. FA Two Parameters Deviation Effects on Design Fuel Cycle Duration

The maximum relative shortness of fuel cycle can be observed in the case of two FA parameters deviations form the standard – namely $E_{\min}D_{\max}$.

The maximum relative prolongation of the fuel cycle can be observed in the case of two FA parameters deviations form the standard – namely $E_{\max}D_{\min}$.

Table 4. The fuel parameter deviations from the standard and their effect on consecutive 4 design fuel cycles durations; abs. err. [FPD]=$T_{(i)}$-$T_{(basic)}$; rel. err. [%]=(($T_{(i)}$-$T_{(basic)}$)/$T_{(basic)}$)*100

Library		Sppsn2h0	Hel1_5	Hel1_4	Hel1_7	Hel1_6	Hel8_1	Hel8_2	Hel8_3	Hel8_4
Variables	Fresh fuel	E_{ref}	E_{ref}	E_{ref}	$E_{\max}$	$E_{\min}$	$E_{\max}$	$E_{\min}$	$E_{\max}$	$E_{\min}$
	Assembly	D_{ref}	$D_{\max}$	$D_{\min}$	D_{ref}	D_{ref}	$D_{\min}$	$D_{\max}$	$D_{\max}$	$D_{\min}$
	Number	M_{ref}	M_{ref}	M_{ref}	M_{ref}	M_{ref}	M_{ref}	M_{ref}	M_{ref}	M_{ref}
First design cycle duration: T, [FPD]	12	323.51	323.33	323.69	323.84	323.18	324.02	323.00	323.65	323.36
Second design cycle duration: T, [FPD]	90	316.28	314.79	317.75	319.36	313.17	320.84	311.70	317.85	314.64
Third design cycle duration: T, [FPD]	78	324.31	322.97	325.63	328.38	320.23	329.71	318.89	327.02	321.53
Fourth design cycle duration: T, [FPD]	84	311.78	310.33	313.21	316.41	307.14	317.85	305.69	314.94	308.55
Abs. err. for first design cycle, [FPD]			-0.18	0.18	0.33	-0.33	0.51	-0.51	0.14	-0.15
Abs. err. for second design cycle, [FPD]			-1.49	1.47	3.08	-3.11	4.56	-4.58	1.57	-1.64
Abs. err. for third design cycle, [FPD]			-1.34	1.32	4.07	-4.08	5.40	-5.42	2.71	-2.78
Abs. err. for fourth design cycle, [FPD]			-1.45	1.43	4.63	-4.64	6.07	-6.09	3.16	-3.23
Rel. err. for first design cycle, [%]			-0.06	0.06	0.10	-0.10	0.16	-0.16	0.04	-0.05
Rel. err. for second design cycle, [%]			-0.47	0.46	0.97	-0.98	1.44	-1.45	0.50	-0.52
Rel. err. for third design cycle, [%]			-0.41	0.41	1.25	-1.26	1.67	-1.67	0.84	-0.86
Rel. err. for fourth design cycle, [%]			-0.47	0.46	1.49	-1.49	1.95	-1.95	1.01	-1.04

In WWER-440 loadings with about 80-90 fresh FAs 3.6% with deviations $E_{\min}D_{\max}$ or $E_{\max}D_{\min}$ the relative changes of the design fuel cycle durations are approximately 1.4%.

Assuming $E_{\min}D_{\max}$ ($E_{\max}D_{\min}$) in all four consecutive fresh FA loadings, the maximum relative fuel cycle reduction (prolongation) can reach 2% in the fourth design fuel cycle.

For the design fuel core loading it is very important to know the actual characteristics of fresh FAs delivery, but it is not sufficient

In order to account the effect of fresh FA actual characteristics deviations on neutron-physics characteristics of the design fuel core loading it is necessary to perform all the reactor physics computations, described above.

The realization of this task requires the availability of the reactor-physics methods and computer codes as follows:

- A spectral code of HELIOS type for calculations of 2-group diffusion constants libraries for various kinds of nuclear fuel assemblies;
- Methods such as in Ref. [3,4,5] and computer codes packs such as [8] for generation of approximation coefficients libraries for 3D nodal diffusion code SPPS-1.6;
- 3-dimensional nodal diffusion code for reactor core type WWER-440 calculation such as SPPS-1.6 [1,2].

This work will continue in collaboration with the author of the References [1-5,8]. The next goal is to analyze the metal Uranium mass deviation in FA on WWER-440 design fuel core loading.

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