The in-core fuel management code system for VVER reactors

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In this paper the structure and methodology of a fuel management system for NPP VVER 1000 (NPP Temelín) and VVER 440 (NPP Dukovany) is described. It is under development in ŠKODA JS a.s. and is followed by practical applications.

The general objectives of the system are maximization of end of cycle reactivity, the minimization of fresh fuel inventory for the minimization of fed enrichment and minimization of BPs inventory. They are also safety related constraints in witch minimization of power peaking plays a dominant role.

General structure of the system consists in preparation of input data for macrocode calculation, algorithms (codes) for optimization of fuel loading, calculation of fuel enrichment and BPs assignment. At present core loading can be calculated (optimized) by Tabu search algorithm (code ATHENA), genetic algorithm (code Gen1) and hybrid algorithm – simplex procedure with application of Tabu search algorithm on binary shuffling (code OPAL_B). Enrichment search is realized by the application of simplex algorithm (OPAL_B code) and BPs assignment by module BPASS and simplex algorithm in OPAL_B code.

Calculations of the real core loadings are presented and a comparison of different optimization methods is provided.

1. INTRODUCTION

Optimization system OPAL, aimed to the maximization of EOC reactivity, maximization of discharge burnup, the minimization of fresh fuel inventory / or the minimization of feed inventory and the minimization of BP's numbers, has been developed in ŠKODA since 2001. Optimization system is designed for VVER Reactors, but main effort is now focused on VVER-1000 core to which all its features can be applied. Description of the basic system modules was provided on Symposium in 2003 [1,3]. The system consists of several modules that can be applied automatically or separately.

The whole optimization process can be divided into several steps, where the first step in this process is preparation of necessary set of cross sections, which is performed for requested cycle sequentially, where a set containing data for different fuel enrichments of fresh fuel assemblies is prepared as first followed by the data for selected enrichment(s) with different number of BP's (IFBA).

The searching of the enrichment linear programming algorithm (OPAL_B code) was provided in the second step.

The searching of the core loading is the next step of the optimization process. The general objective of this optimization is maximization of the EOC k_{eff} (boron concentration) for fixed cycle length with preserving radial peaking constraints. Two different algorithms were used for finding optimal loadings presented below: genetic algorithm (code GenA) (for cycle 3 and 4 of Temelin Unit II) and deterministic algorithm based on binary FA's shuffling (OPAL_B code) (for cycle 2 of Temelin Unit I).

Process of assignment of necessary number of burnable absorbers (BP's) in fresh fuel assemblies (FA's) in WWER-1000 (ETE) loading is an important step in loading optimization process. Simple method, which is based on the principle that such a number of BP's is to be found that prevents the power in all fresh FA's from exceeding that found at the end of the cycle (EOB) (BPASS code), was used with GenA code for cycle 3 and 4 of Temelin Unit II and linear programming algorithm (OPAL_B code) for cycle 2 of Temelin Unit I.

Results presented for third and fourth cycles are examples, which should show functionality of this process. More comprehensive analysis of cycle 2 leads to practical results, which show progress in relation to the original designs.

2. CROSS SECTIONS PREPARATION

The first step in the whole optimization process is preparation of necessary set of cross sections. This is relatively complicated task from the following reasons. For optimization process, we would need to have at our disposal physical data (cross sections) for large amount of fuel assemblies with different enrichment and number of burnable poisons. (We suppose that the design of FA is given, it means for example that placement of burnable poisons of integral type is fixed on selected positions for their given number). Nevertheless, the amount of possible number of fuel assemblies is very large because fuel enrichment in not known in advance and number of burnable poisons can also differ in suitable range. Next limitations are connected with NPP SW, where the most important is that only 60 different fuel structures are allowed in one ANC calculation (FA consists of more than one fuel structure due to common axial enrichment and burnable poison profiling of WWER-1000 fuel assemblies). The other fact is a sophisticated method of cross section preparation applying so called “pseudo-burnup” which means that cross sections are prepared with “really” decreasing concentration of boric acid. This methodology also supposes that real burnup of each structure in the end of the previous cycle is known. All these circumstances (and others not mentioned here) cause that precise data can not be pre-calculated for arbitrary large set of fuel assemblies, which can be requested in optimization process. It means practically that a set of data for fuel assemblies with different enrichment (in some range) is prepared as first and then, after desirable enrichment has been found (or desirable enrichments if split of enrichment has been applied), another set of data for different number of burnable poisons is prepared for this (these) enrichment(s). This process can be iterated. There are also other limitations in data processing. Process of data preparation is partially automated, it means that “auxiliary” programs have been created, which prepare or modify data for ALPHA (WEC code) that controls other WEC programs in data preparation process. As a result of this process, “pattern” input to ANC is prepared, which is then modified automatically in the next parts of optimization process. This “pattern” input is unique for defined (limited) set of fuel assembly enrichments or assemblies with different numbers of burnable poisons.

Based on process described above, first the data for cycle 2 Unit I (BP numbers (0-12, 42-54)) for existing enrichment were extended, then the data for different enrichments (from 3.5w% up to 4.25w% of U^{235} (by step 0.05w%) without BP’s were prepared. (Data for cycle 3 Unit I were also prepared, but analyses of this cycle are not included here.)

Next, for cycle 3 of Temelin Unit II, data for fuel enrichments in range from 3.2w% up to 4.25w% of U^{235} (by step 0.05w%) and for scale of BP numbers (0-96) for enrichments 3.2, 3.4, 3.45, 3.50, 3.75 and 4.0w% of U^{235} were prepared. With use of selected loading design for cycle 3 of Unit II, employing new FA’s with enrichment 3.5w% of U^{235} and with 0, 30 and 48 BP’s, data for cycle 4 of Temelin unit II for fuel enrichments in range from 3.35w% up to 4.2w% of U^{235} (by step 0.05w%) and for scale of BP’s (0-96) for enrichments 3.8, 3.9, 4.0 and 4.1w% of U^{235} were prepared. These data can then be used in subsequent optimization steps described below.

3. CALCULATIONS AND ANALYSES PERFORMED

3.1 Optimization of cycle 2 of Unit I of Temelin NPP.

The 2nd cycle loading of Unit 1 ETE designed by NPP Temelin consists two very close values of enrichment: 3 x 3.865%, 4x3.965% (average enrichment E_{av} = 3.908%). To avoid problems with limited number of fuel types in ANC-H input (as was mentioned above) we prepared library with fresh FA with only one enrichment E=3.91% and with the following numbers of IFBA in fresh FA: 0, 6, 12, 18, 24, 30, 36, 42, 48 and 54. For enrichment search was prepared new library with no IFBA in fresh FA and fresh fuel enrichment increment 0.05% (from 3.50% to 4.25%).

Optimization process was realized by code OPAL_B that is designed to be sufficiently fast. The reason are constraints which comes from software NPP Temelin (macrocode ANC-H) which enables only 3D burn up cycle calculations - each of them consumes 0.5 min. OPAL_B performs three functions that are covered by several options of the code:

- calculation fuel shuffling and optimization core loading (options BIN and GLPS)
- calculation enrichments of the fresh fuel (option E-split)
- Burnuble Poisson (BP) assignment (option BP-split).

Optimization process is divided into generations and every next generation starts from best loading pattern of previous that is chosen according fitness. At present in OPAL_B is fitness calculated in the form of composite objective function defined for radial power peaking limit and maximization of boron concentration at EOC. At present radial power peaking limit on pin-wise level is for NPP Temelin loadings F_{dhl}^{im} = 1.57. Algorithm and core FA shuffling options are described in [4] (BIN option is based on different algorithm (hill climbing or tabu search) of BINary exchange and GLPS (Generator of Loading Priority Schemes) option which generates Loading Priority Schemes by application of Simplex algorithm with maximizing boron concentration at BOC and preserving radial power peaking).

E-split option algorithm for searching enrichment distribution (split) is based on Simplex algorithm (was presented in [1]).

BP-split option algorithm for BP assignment is based on Simplex algorithm (was presented in [1]).

Some calculations with this code were presented on Symposium last year [1] on application with code MOBY-DICK. Results presented in this paper concerns upgrading original Unit 1, 2nd cycle ETE loading and were performed with NPP Temelin software (ANC-H). This original Unit 1, 2nd cycle ETE loading had following characteristics:

F_{dh}(max) =1.517 CB_{EOC}=0.017 198 IFBA E_{av} =3.91% 320.903 FPD

Fig. 1 Original Unit I, 2nd cycle ETE loading (radial pin-wise power distribution and number of IFBA in fresh FA)

```
   1.242 1.405 1.411 1.072 0.907 0.897 0.697

      30          36          18
0.734 1.476 0.991 1.501 0.919 1.387

         24
   0.929 1.523 0.993 1.302 0.919

                        36
      1.250 1.298 0.997 1.517
```

```
               24
         1.254 1.538  1.029

                  30
            0.944 1.517


               0.763
```

In the next are presented ***four examples*** of upgrading of this original loading.

As ***the first example*** was provided optimization with OPAL_B option BIN (in 60° symmetry) for limit F_{dh}^{lim}=1.50. The number of IFBA was preserved like in original loading: 198 IFBA. Resulted loading is presented in Fig. 2 and basic characteristics of this loading are:

F_{dh}(max) =1.50 CB_{EOC}=0.135 198 IFBA E_{av} =3.91% 320.903 FPD .

Fig. 2 The optimized Unit I, 2nd cycle of ETE loading (radial pin-wise power distribution and number of IFBA in fresh FA)

```
   1.320 1.374 1.365 0.949 0.968 0.933 0.711

      30          36          18
0.766 1.511 1.025 1.490 1.050 1.444

         24
   0.925 1.534 1.006 1.327 0.934

                        36
      1.209 1.370 1.079 1.493

               24
         1.168 1.520 0.989

                  30
            0.895 1.464


               0.665
```

You see that new loading has longer cycle by 4.5 FPD and pin-wise power peaking lower. But in both loadings (Fig. 1 and Fig. 2) is relatively high power of FA on the edge of the core.

In ***the second example*** was provided optimization with OPAL_B option BIN (in 60° symmetry). Optimization for higher radial pin-wise limit F_{dh}^{lim}=1.57 and for preserved original number of IFBA: 198. Basic characteristics of resulted loading are:

F_{dh}(max)=1.57 CB_{EOC}=0.328 198 IFBA E_{av} =3.91% 320.903 FPD.

For this new loading was provided BP assignment with OPAL_B options BP-split. In result we have god lower number of IFBA (=144):

$F_{dh}(max)=1.567$ $CB_{EOC}=0.279$ ***144 IFBA*** $E_{av}=3.91\%$ ***323.75 FPD***

and power distribution with number of IFBA is presented in Fig. 3.

Fig. 3 The optimized Unit I, 2nd cycle of ETE loading for 144 IFBA loading (radial pin-wise power distribution and number of IFBA in fresh FA).

.

```
   1.240 1.376 1.435 1.130 0.908 0.886 0.655

      12          30          0
0.651 1.553 1.162 1.588 0.936 1.408

         30
   0.823 1.522 1.122 1.340 1.022

            30          30
      1.199 1.532 1.031 1.576

               12
         1.208 1.574 1.166


            0.761 1.293


               0.539
```

In comparison with original loading we have got lower number of IFBA by (144-198)*6 = 324 IFBA and longer cycle length by 13.5 FPD. But you see from Fig. 3 that edge FAs power level (i.e. radial leakage) is still great. There is a room for designing Super Low Leakage Loading (SL^3).

In ***the third example*** was adopted fast attempt for designing low leakage loading SL^3. This methodology is aimed for ETE optimization system, because there are problems with time of calculation (as was mentioned above one core burn up calculation needs minimally 0.5 min). In the following process (divided into 5 steps) are applied two shuffle optimization options of OPAL_B code (option BIN and option GLPS):

Step 1.

As the first guess a priory position of FA with small kef (high burn up) on the edge of core (here is applied some expert knowledge in redistribution of FA on the edge of core).

Step 2.

Fix position of fresh FA.(In our example we used positions of fresh FA from original 2nd cycle). (see Fig. 4).

Step 3.

Fix number of IFBA - the same in each fresh FA (see Fig. 4).

Step4.

Provide simple searching of the loading by one of two options of code OPAL_B:
BIN or GLPS (in our case both in 60° symmetry).

Step 5

Choose optimal loading and minimize BP assigned by option BP-split of OPAL_B.

On the example of 2nd loading were analyzed several loadings for uniformly distributed number of IFBA in the same positions:

Fig. 4 Fixed positions of fresh FA with uniformly defined number of IFBA (xx)

```
  0   0   0   0   0   0   0

0  xx   0  xx   0  xx

  0  xx   0   0   0

    0   0   0  xx

      0  xx   0

        0  xx

          0
```

378 IFBA in 1/6 xx = 54
126 IFBA in 1/6 xx = 18
84 IFBA in 1/6 xx = 12.

Searching process in Step 4 was realized by two options of OPAL_B in four generation process: GLPS option with 130 ANC-H calculations per generation (total number of calculation was 520) and BIN option with 90 ANC-H calculations per generation (total number of calculations was 360).

From the results of Table 1 is seen that with increasing number of IFBA in low-leakage loadings decreases radial power peaking Fdh at BOC. From analyzed 3 variants xx is more close (or acceptable) to real radial limit peaking variant with xx=54, i.e. 378 IFBA. In option BIN optimization process continued including reshuffling more burned FAs on core edge (generation 6) which did not have significant impact on the achieved results in generation 4.

In Step 5 variant from generation 4 of BIN shuffle (see Fig. 5) was used for next processing in option BP-split and finally we have got the following low-leakage loading with minimum IFBA consumption:

F_{dh}(max)=1.530 CB_{EOC}=0.441 228 IFBA E_{av} =3.91% 323.75 FPD

which is approximately by 18 FPD longer cycle than original ETE cycle.

From the point of consumption of calculation time is important that we have got this new loading by no more then 700 calculations!

Table 1 The searching of low-leakage loading, Unit I, 2nd cycle of ETE loading

generation	OPAL_B option GLPS			OPAL_B option BIN		
	F_{dh}(max)	CB_{EOC}	Num. of calculations (cumulative)	F_{dh}(max)	CB_{EOC}	Num. of calculations (cumulative)
	Number of IFBA in 1/6 core = 378 (xx=54)					
Initial	1,715	0,394	0	1,715	0,394	0
4	1,553	0,394	520	1,521	0,400	360
6	with edge FA shuffling			1,510	0,392	738
	Number of IFBA in 1/6 core = 126 (xx=18)					
Initial	1,822	0,461	0	1,822	0,461	0
4	1,653	0,473	520	1,644	0,473	360
6	with edge FA shuffling			1,640	0,473	738
	Number of IFBA in 1/6 core = 84 (xx=12)					
Initial	1,838	0,460	0	1,838	0,460	0
4	1,643	0,468	520	1,660	0,472	360
6	with edge FA shuffling			1,657	0,476	738

Fig. 5 The low-leakage 2nd loading step 4 for OPAL_B BIN iteration (F_{dh}(max) =1.521, CB_{EOC} =0.400) with 378 IFBA (see Table 1) (radial pin-wise power distribution and number of IFBA in fresh FA).

```
   1.249 1.360 1.029 1.114 1.338 1.092 0.890

      54          54          54
0.662 1.472 1.416 1.521 0.989 1.493

         54
   0.840 1.413 1.118 1.354 1.087
```

```
                  54
0.803 1.238 1.028 1.505

         54
   0.760 1.412 1.377

            54
      0.749 1.421


         0.621
```

In ***the fourth example*** was used algorithm of option E-split for enrichment split and enrichment searching which was described in [1]. Applied objective function was formulated for radial peaking penalization at EOC (F_{dh} (EOC)).

Starting point of the optimization process was uniform enrichment 3.7% with F_{dh} (EOC) = 1.447 and CB_{EOC} = -0.238. After 16 cycle calculations (in option E-split) enrichment increases and split into two values: E_1 = 3.85% and E_2 = 4.00%.

In average the enrichment increases to 3.914% , radial peaking factor decreases to Fdh (EOC) = 1.426 and critical boron at EOC approaches zero : CB_{EOC} = -0.002.

It is seen that splitting of enrichment only with limited number of enrichments may have only slight impact on global radial power tilt. Splitting of enrichments into more then 2 enrichments was studied in [1], and it was found that more enrichments allow better flattening of the radial power distribution, but has worse impact on internal fuel cycle economy.

3.2 Optimization of cycle 3 of Unit II of Temelin NPP

Unit II of Temelin NPP has slightly different loading for cycle 2 then Unit I. Since the loading for the third cycle has not been designed (by WEC and NNP staff) at time of performing this work, we tried to design the loading of cycle 3 (based on known EOC2 and requests on cycle 3). Attempt to find an suitable loading configuration for cycle 3 has been performed by genetic program GenA under assumptions that only one selected enrichment (preliminary found by OPAL_B) of fresh fuel assemblies will be used and fixed number of them. Also cycle length was fixed.

GenA is genetic algorithm (GA) optimization program, which -in our case- utilize SPEA algorithm (Strength Pareto Evolutionary Algorithm); this type of GA creates a set of trade-off solutions instead of one best solution as is usual in traditional approach. Details can be seen in paper [2].

All computations were performed in 30° sector symmetry. Initial populations were created randomly (in 30° symmetry) by an internal subroutine. Small amount of BP’s of IFBA type (12) were used in fresh FA’s during optimization. The GA runs using population size of 75 individuals for 130 generations, giving a total of approximately 10000 trials, and set of 25 trade-off solutions.

Criterions used are boron concentration and F_{dH} of fuel assemblies at given cycle length, near EOC.

In Table 2 is example of the set of solutions, with variables boron concentration CB and pin power factor F_{dH}.

Table 2 Set of solutions (GenA), Unit II, Cycle 3

Num	CB[g/kg]	F_{dH}(EOC)
1	-0,347	1,4
2	-0,345	1,401
3	-0,321	1,404
4	-0,205	1,405
5	-0,017	1,407
6	-0,011	1,412
7	0,009	1,415
8	0,06	1,422
9	0,102	1,43
10	0,141	1,454
11	0,182	1,459
12	0,191	1,462
13	0,195	1,469
14	0,199	1,471
15	0,209	1,472
16	0,239	1,479
17	0,248	1,48
18	0,263	1,491
19	0,311	1,5
20	0,328	1,509
21	0,341	1,511
22	0,36	1,532
23	0,371	1,553
24	0,393	1,557
25	0,415	1,569

From this table can be easily seen that for higher boron concentration in the end of fuel cycle a higher pin power peak must be allowed.

As mentioned above, searching for an optimal loading is performed with fixed numbers of BP’s (here 12 in each fresh FA), therefore suitable number of BP’s has to be found.

Process of assignment of suitable number of burnable poisons in fresh fuel assemblies as a separate part of optimization process (in this case) was described on the Symposium last year [3].

Very shortly, this process is based on the assumption that power peak can be reduced by assignment of BP in accordance with known power distribution at the EOC. Most of the last year's effort was concentrated on application of the method using the MOBY-DICK code. But, implementation process started also on Temelin site with WEC codes and the effort is now focused fully in this direction. First results of BP's assignment for the second cycle of Temelin Unit I were presented last year. Next, some designs for the third cycle of Temelin Unit I have been found.

For validation of BP assignment process, some typical loadings for cycle 3 of Temelin Unit II were selected. Basic information about them is shown in Table 3 (these loadings are not listed in Table 2, but were also found by GenA code).

Table 3 Basic characteristics of selected solutions (GenA+BPASS)(cycle 3)

Case	"var"	C_{H3BO3}	F_{dH}(max)	F_{dH}(EOC)	No of IFBA
GenA (1)	4	0.074		1.455	84
GenA+BP's (1)	4	0.074	1.548 (4000)	1.469	216
GenA+BP's (1a)	4	(0.074)	1.545		240
GenA+BP's (1b)	4	(0.074)	1.561		186
GenA (2)	21	0.190		1.461	84
GenA+BP's (2)	21	0.195	1.575 (3000)	1.476	240
GenA+BP's (2a)	21	(0.195)	1.575		216
GenA+BP's (2b)	21	(0.195)	1.568		252
GenA (3)	1	0.250		1.492	84
GenA+BP's (3)	1		>1.6		>300

The **first case** is a typical one, and for this case suitable number of BP's has been easily found. This BP's placement is shown in Fig. 6, together with solutions (relative pin powers). For this case, also recalculation with different number of BP's, where in each FA 6 more or less BP's are allowed has been performed, and results show that F_{dH} can be reduced (Table 3, case 1a), but requested number of BP's is higher, or number of BP's can be reduced, but F_{dH} must be allowed higher (Table 3, case 1b).

Fig. 6 Optimized Unit II, 3rd cycle of ETE loading for 216 IFBA loading (enrichment, number of IFBA in fresh FA and radial pin-wise power distribution).

```
*     *     *     *     *     *     *
*     *     *     *     *     *     *
.759 1.238 1.307 1.248 1.303  .858  .549

   *     3.50  *     *     3.50  *
   *     0     *     *    48     *
   .584 1.394 1.333 1.282 1.545 1.019
```

```
*     3.50  *     *     3.50
*    36     *     *    48
.873 1.479 1.405 1.298 1.548

   *     3.50  *     *
   *    48     *     *
   .880 1.506 1.388 1.282

      *     3.50  *
      *    36     *
      .848 1.479 1.334

         *     3.50
         *     0
         .927 1.403

            *
            *
            .611
```

The **second case** is an interesting placement of fresh fuel assemblies in core loading, (see Fig. 7); therefore a lot of effort was spent finding adequate number of BP's. Although number of BP's does not exceed 96, pin peak is still above requested limit of 1.57. (Solution is shown also in Fig. 7, where relative pin powers are seen). Therefore searching process of finding adequate number of BP's was tested using the method already described in the paper presented last year. In principle this method is based on recalculations of all possible variants (variations) of BP's assignments: the problem is only the fact that it can be so many variations that time for calculation would be enormous. Therefore, based on preliminary assumption on possible range of BP's in each fresh fuel assembly, the number of variations can be significantly reduced. This was performed, and results are summarized in Table 3, from which it is clear that number of BP's can be reduced (case 2a), but for lower F_{dH}, higher number of BP's is necessary (case 2b).

Fig. 7 Optimized Unit II, 3rd cycle of ETE loading for 240 IFBA loading (enrichment, number of IFBA in fresh FA and radial pin-wise power distribution) - longer fuel cycle length

```
   *     *     *     *     *     *     *
   *     *     *     *     *     *     *
   .568 1.119 1.270 1.273 1.378 1.347  .912

*     *     3.50  3.50  *     *
*     *    48    54     *     *
.431 1.201 1.556 1.572 1.331 1.372

   *     3.50  *     *     *
   *    12     *     *     *
   .679 1.497 1.375  .993 1.330

      *     3.50  *     3.50
      *    18          54
      .918 1.515 1.381 1.575
```

```
*     3.50  3.50
*    12    42
.986 1.510 1.573

   *     *
   *     *
   .730 1.216

      *
      *
      .430
```

The **third case** is loading with very low leakage (see Fig. 8) found by genetic algorithm. Unfortunately, suitable number of BP’s has not been found. The reason is that it would be necessary to have many BP’s (more then 96, which is now formal limit in our calculations) and moreover, it is not sure that higher number of BP’s would be sufficient – in this case maximum of $F_{\Delta H}$ could be in non fresh FA. This shows a limitation of separate process of core loading and BP’s assignment that the loading found is not acceptable from BP’s assignment point of view.

Fig. 8 Case of not successful optimization of Unit II, 3rd cycle of ETE (enrichment of fresh FA’s)

```
   *     *     *     *     *     *     *

*     * 3.50      * 3.50      *

   * 3.50      *     * 3.50

      * 3.50      *     *

         * 3.50  3.50

            *     *

               *
```

As shown on these three examples, it is not ensured that to the loading configuration found on base of minimization of pin power peak and maximization of boron concentration in the end of fuel cycle, adequate number of BP’s can be assigned to fulfill requested limiting criterion on pin power peak during cycle. Especially for loading configuration with very low leakage this could be impossible.

Case 1 was selected as final loading configuration for third cycle and as a base for searching for loading configuration in fourth cycle.

3.3 Optimization of cycle 4 of Unit II of Temelin NPP

GenA was also used for optimization of fuel loading for cycle 4 of Unit II. Fresh FA's with no BP's were used, and F_{dH} from BOC was minimalized. Other conditions at calculations were similar to those, which were applied for the third cycle.

Two core loading configuration have been chosen for cycle 4 of Temelin Unit II, but suitable number of BP's that ensures fulfilling of power peak limit and cycle length has not been found (see Table 4). This can be caused by the fact that genetic algorithm is able to find loading that is very low leakage type, but very high number of BP's would be necessary for reducing the pin power peak. From this point of view it seems to be clear that loadings that are optimal from the point of view of neutron efficiency would not be acceptable from other point of view.

Table 4 Basic characteristics of selected solutions (cycle 4)

Case	"var"	C_{H3BO3}	F_{dH}(max)	F_{dH}(EOC)	No of IFBA
GenA+BP's (4)	t7	-0.625	1.584 (4000)	1.508	516
GenA+BP's (4a)	t7	-0.627	1.568 (5000)	1.515	552
GenA+BP's (5)	t8	-0.048	1.681 (0)	1.555	612

Fig. 9 (Table 4, case 4) shows example of BP's assignment, but this loading is not of very low leakage type and the boron concentration in the end of cycle would be negative (this means that desirable cycle length would not be reached). Using variation principle, pin power peak can be reduced (see Fig. 9a and Table 4, case 4a), but cycle length is short.

Fig. 9 Unit II, 4th cycle of ETE loading for 516 IFBA loading (enrichment, number of IFBA in fresh FA and radial pin-wise power distribution) - short fuel cycle length and high F_{dH}

```
   4.00  *     4.00  *     *     *     *
  54     *    90     *     *     *     *
  1.473 1.309 1.558 1.107 1.066  .824  .502

*     4.00  *     *     4.00  *
*    72     *     *    78     *
.772 1.480 1.148 1.034 1.584 1.175

   *     *     *     *     4.00
   *     *     *     *    78
   .879 1.199 1.211 1.210 1.582

      *     4.00  *     *
      *    78     *     *
     1.020 1.503 1.211 1.066

         *     *     *
         *     *     *
        1.023 1.199 1.159
```

```
            *     4.00
            *    66
            .878 1.479

               *
               *
               .722
```

Fig. 9a **Unit II, 4th cycle of ETE loading for 516 IFBA loading (enrichment, number of IFBA in fresh FA and radial pin-wise power distribution) - short fuel cycle length**

```
    4.00  *     4.00  *     *     *     *
   54     *    90     *     *     *     *
   1.458 1.298 1.553 1.106 1.067  .837  .521

*     4.00  *     *     4.00  *
*    72     *     *    90     *
.771 1.470 1.142 1.034 1.568 1.170

   *     *     *     *     4.00
   *     *     *     *    90
   .881 1.189 1.199 1.202 1.565

      *     4.00  *     *
      *    84     *     *
     1.016 1.492 1.199 1.063

         *     *     *
         *     *     *
        1.019 1.189 1.153

            *     4.00
            *    72
            .878 1.466

               *
               *
               .719
```

Last case (5), Fig. 10 shows an attempt to design loading with very low leakage, but this has not been successful. Although cycle length is almost sufficient, pin power peak is very high.

Fig. 10 **Case of not successful optimization of Unit II, 4th cycle of ETE loading for 612 IFBA loading (enrichment, number of IFBA in fresh FA and radial pin-wise power distribution) – much high F_{dH}(max)**

```
   *     *     *     *     *     *     *
   *     *     *     *     *     *     *
   .780 1.240 1.216 1.267 1.104 1.054  .688

*     *     4.00  *     4.00  *
```

```
*     *    96     *    96     *
.408 1.083 1.642 1.440 1.681 1.274

   *     *     4.00  *     4.00
   *     *    72     *    96
   .640 1.614 1.437 1.411 1.676

      *     4.00  *     *
      *    90     *     *
      .936 1.627 1.431 1.428

         *     4.00  4.00
         *    66    96
         .937 1.623 1.633

            *     *
            *     *
            .605 1.072

               *
               *
               .404
```

From what was shown in the above, it can be concluded that it is more difficult to find loading that fulfils all criteria for cycles with higher enrichment. Probably more fresh fuel assemblies would be necessary to be loaded into core or to use higher enrichment and more BP’s. (Is should be also mentioned that FA’s with higher number of BP’s have not been internally optimized.)

4. CONCLUSION

In OPAL core optimization system there are included different algorithm which can provide searching for optimal FA loading, searching optimal fuel enrichment (including enrichment splitting) and can assign burnable absorption. All this options were performed in communication with NPP software system (PHOENIX-H and ANC-H) for fuel cycles of NPP Temelin Units for reaching objective criteria on radial pin-wise power peaking and maximization of boron concentration at EOC on 3D level calculation.

It was found that the process of cross section preparation for NPP Temelin system comprises several problems and specific features that must be taken into consideration. It is also intention to simplify this process for multi-cycle optimization, where cross sections for great number of FA’s have to be at disposal at the same time.

Presented optimization process of Unit1 loading presents the applicability of a relatively fast algorithm of OPAL_B code for upgrading given fuel loading. The transformations of standard fuel loading into low leakage loading with minimization of BA consumption were demonstrated on several examples. Reached extension of cycle length by 18 FPD was enabled by increasing radial power peaking up to the limit values and increasing number of burnable absorbers. Applied enrichment split process into two enrichment decrease radial power peaking only slightly.

The extensive analysis of the third and fourth fuel cycle Unit 2 loading was provided by genetic optimization code GenA and burnable absorber assignment code BPASS. A new option of GenA code based on relatively time consuming SPEA algorithm provides sets of very low leakage (very long cycle) loading with non-standard fresh fuel distribution. Some of these loadings (namely the fourth fuel cycle with high enrichment), therwise attractive from the point of cycle length, need assigning enormous number of BA's for control of radial peaking factor under given limit. The credibility of such conclusion was approved by several options of BPASS code.

We intend to continue in development of this optimization system.

5. LIST OF NOMENCLATURE

$\mathbf{F_{dh}}$	-pin-wise max radial power peaking
$\mathbf{CB_{EOC}}$	-boric acid concentration from the EOC [g/kg]
$\mathbf{C_{H3BO3}}$	-Boric acid concentration [g/kg]
$\mathbf{E_{av}}$	-averaged enrichment of the fresh FA
FPD	-cycle length in equivalent full power days (FPD)
WEC	-Westinghouse Electric Company
BOC	-Begin of cycle
EOC	-End of cycle
NPP SW	-Nuclear Power Plant Software
IFBA	-Integral Fuel Burnable Absorber
GA	-Genetic algorithm
BP's	-Burnable Poisons
FA's	-Fuel Assemblies
$\mathbf{F_{dH}}$	-Pin-wise max radial power peaking (at burnup step)
$\mathbf{F_{dH}(max)}$	-Pin-wise max radial power peaking (maximum over cycle)
$\mathbf{F_{dH}(EOC)}$	-Pin-wise max radial power peaking (end of cycle)
$\mathbf{F_{dh}^{lim}}$	-Pin-wise radial power peaking limit
"var"	-Variant
ETE	-Temelin NPP

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