OPAL - THE IN-CORE FUEL MANAGEMENT CODE SYSTEM FOR VVER REACTORS

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ABSTRACT

Fuel management optimization is a complex problem namely for VVER reactors, which at present are utilizing burnable poisons (BP) to great extent. In this paper, first the concept and methodologies of a fuel management system for VVER 440 (NPP Dukovany) and NPP VVER1000 (NPP Temelin) under development in Skoda JS a.s. are described and followed by some practical applications.

The objective of this advanced system is to minimize fuel cost by preserving all safety constraints and margins. Future enhancements of the system will allow is it to perform fuel management optimization in the multi-cycle mode.

The general objective functions of the system are the maximization of EOC reactivity, the maximization of discharge burnup, the minimization of fresh fuel inventory /or the minimization of feed enrichment, the minimization of the BP inventory. There are also safety related constraints, in which the minimization of power peaking plays a dominant role.

The core part of the system requires meeting the major objective: maximizing the EOC Keff for a given fuel cycle length and consists of four coupled calculation steps. The first is the calculation of a Loading Priority Scheme (LPS), which is used to rank the core positions in terms of assembly Kinf values. In the second step the Haling power distribution is calculated and by using fuel shuffle and/or enrichment splitting algorithms and heuristic rules the core pattern is modified to meet core constraints. In this second step a directive/evolutionary algorithm with expert rules based optimization code is used. The optimal BP assignment is alternatively considered to be a separate third step of the procedure. In the fourth step the core is depleted in normal up to 3D pin wise level using the BP distribution developed in step three and meeting all constraints is checked.

One of the options of this optimization system is expert friendly interactive mode.

1. INTRODUCTION

The objective of the Skoda JS a.s. optimization system OPAL is to minimize fuel cost by preserving all safety constraints and margins. Future enhancements of the system OPAL aimed to perform automate fuel management optimization in the multi-cycle mode.

The core of OPAL system is based on two alternative algorithm *directive/evolutionary* - supported with maximum expert rules . Evolutionary algorithms have proved to be robust optimization methods for complex engineering tasks characterized by discontinuities in the search space, a high combinatorial dimensionality and non-linear objectives and constraints [1,2]. The application of this concept needs very powerful software. More practical approach is at first stage to solve this multi-objective problem [3] as a single-objective one, which minimizes only a single objective and other objectives are constrained.
The general objective functions of OPAL system are the maximization of EOC reactivity, the maximization of discharge burnup, the minimization of fresh fuel inventory /or the minimization of feed enrichment, the minimization of the BP inventory. There are also safety related constraints, in which the limitation of power peaking plays a dominant role.
Application above mentioned objective functions in optimization process is very complicated and tiny problem.

At present the core part of the system requires meeting the major objective: maximizing the EOC Keff (with preserving power peaking constraints) for a given fuel cycle length and consists of four coupled calculation steps. The first is the calculation of a Loading Priority Scheme (LPS), which is used to rank the core positions in terms of assembly Kinf values. In the second step the Haling power distribution is calculated and by using fuel shuffle and/or enrichment splitting algorithms and heuristic rules the core fuel pattern is modified to meet core constraints. In this second step a directive algorithm with expert rules based optimization code is now used and evolutionary (see [3,6]) algorithm with expert rules is under preparation. The optimal BP assignment is alternatively considered to be a separate third step of the procedure. In the fourth step the core is depleted in normal up to 3D pin wise manner using the BP distribution developed in step three and reaching of all constraints is checked.

Some adjustments are allowed in the core configuration including FA rotation to bring checked values into compliance with the constraints.

According to the design of OPAL the single cycle part of the system is enveloped into loops, which are controlled by special subroutines for reaching the demanded cycle length while preserving the imposed constraints on assembly discharge burnup, relative cycle cost, peak pin power (rodded and unrodded conditions) and safety criteria (TMC, sub-critical margin, and etc.).

The future development of the code system includes modifications allowing all fuel assemblies exposures to be calculated from their BOL to their EOL in order to maximize discharge burnup. Fuel cycle cost analyses will be performed to follow the effect of increasing discharge burnup with decreasing consumption of BP and fresh fuel assemblies.

2. BASIC ALGORITHM TOOLS OF THE OPAL SYSTEM

In this chapter are given definitions and explanations of basic methodological tools used in construction of OPAL system.

2.1 Loading Priority Scheme (LPS) [11]

The LPS is developed by ranking the FA loading positions according to the magnitude of their BOC Kinf values and assigning a priority number to each loading positions according their ranking. It defines the specific loading position for each of the given FA_s to make the loading pattern have the maximum EOC Keff. The priority rankings LPS at BOC and EOC are similar and are valid for cycle length of a certain range (e.g. 3000 MWd/t). For the first schedule of the loading the LPS can be constructed for lower number groups of ranking (3 groups, 4 groups, ...). It is known that LPS is efficient tool for starting point of optimization also for human optimal solution.

The LPS which can be generated by the Space-Covering Approach and Modified Frank-Wolf algorithm, SCAM-W [4] which was adopted in Skoda JS a.s. within collaboration with PSU [11]. This algorithm is applied to the EOC state to provide global optimal Kinf distribution by maximizing EOC Keff for given fuel inventory and core exposure. A backward Haling power depletion calculation is further performed to define LPS for BOC. In general the LPS for given loading can be constructed by experience from previous loading.

2.2 Haling Principle and Haling Power Distribution (HPD)

The Haling Principle proposed by Haling states that if the normalized power distribution is kept unchanged through cycle , then the power peak during the cycle is the minimum for the given loading. Therefore the main issue of the Haling principle is the constant normalized power distribution during the depletion. This constant power distribution during the depletion is called the Haling Power Distribution (HPD) and is unique for this loading.

The Haling Principle has been used in BWRs in developing the reload pattern and as a guide for the control rod scheduling in order to control the power peak. The PWRs are generally operated with control rods out of the core . The power distribution in PWRs can only be controlled by the use of burnuble poisons (BP). Depletion of the burnuble poisons can be modeled so that it can follow the Haling principle, again in order to reduce the peaking factors.

The applicability of Haling Principle for VVER-1000 reactor has been analyzed and presented paper shows its as a attractive tool for multicycle optimization and BP assignment. HPD was calculated by MOBY-DICK macrocode system [7] where HPD was iterated in one step burnup option (between BOC and EOC) :

$$HPD = (1-\omega) \cdot Q_{BOC} + \omega \cdot Q_{EOC} \qquad (1)$$

where Q_{BOC} and Q_{EOC} is power distribution in BOC and EOC respectively and ω acceleration factor.

2.3 Multiobjective optimization (MOO)

Fuel cycle optimization comprises task of finding optimal fuel pattern of suitable FAs for reaching optimal characteristics (economics, safety and operational) of fuel cycle. These optimal characteristics can be treated like objective functions or constraints of the optimization procedures. In general we should to solve MOO optimization problem. But

there is no notion of optimum in MOO and correct interpretation of this term is Pareto optimum based on the so called dominance [8]. Unfortunately, the Pareto optimum in MOO almost always gives not a single solution, but a set of solutions so called Pareto front.

Traditional fuel cycle methods are based on the Weighting Objective Method which consists of adding all objective functions together (into so called Composite objective function se chapter 4.2) using different weighting coefficients for each one of them. Note that these weighting coefficients do not reflect proportionally the relative importance of the objectives, but are only factors which, when varied, locate points in the Pareto set (Pareto front).

2.4 Direct methods

These methods usually works with limited number of loading modifications by means with determined algorithm. These methods are combined with many expert and heuristic rules which significantly decreases number of recalculated loadings.

2.5 Evolutionary algorithm

Kim et al. [13] stated that pure binary exchange process does not ensure a global optimum solution. One way to overcome this difficulty is to apply more expert rules or other methods e.g. evolutionary methods (like tue PSU genetic algorithm [6]).

Evolutionary algorithm is powerful optimization techniques for complex engineering tasks which are based on biological evolution. Rather then searching from one solution to the next, they search from one collection (or generation) of trial solutions to another one, according to the well-known principle of the biological evolution: survival of the fittest. The measure of the fitness is usually value of some objective function (Composite objective function).

3. STRUCTURE OF THE PROPOSED OPAL SYSTEM

OPAL system is developed on the modular structure in which individual programs (subroutines) are replaceable to be applicable either for VVER-440 or for VVER-1000 core loading optimization. Core of this system in multicycle mode is based on the HPD methodology. For single system is supposed like HPD methodology (at present) or in future optimization on the real burnup cycle calculation. Basic functions of the OPAL system are as follows:

3.1 Multicycle mode

Originaly program version OPAL in multicycle mode OPAL_B [9] was developed without BP assignment. The present version cooperates with module BP assignment [10] which module is used in the end of best HPD loadings validation of each cycle. The OPAL_B

works with coarse-mesh (i.e. assembly) power distribution only and core of the optimization (fuel shuffle) is based on direct algorithm (binary FA change).

Multi cycle mode OPAL_B
(optimization based on the HPD, BP assignment on HPD and real burnup with BP):

1. Cycle loop
2. Definition LPS and derivation a set of initial loadings
3. Fuel shuffle (direct/evolutionary)
4. Calculation HPD
5. Enrichment and enrichment split › go to 2.
6. BP assignment
7. 3D cycle depletion
8. Single cycle evaluation › go to 1.
9. Multicycle evaluation

Interaction between optimization system OPAL and standard macrocode (MOBY-DICK or in future ANC-H), archive organization and flow of data are based on standard evolutionary flow of data, i.e on generations (populations).

Combination of standard macrocode and optimized subroutines is backbone of the system OPAL. The macrocode should work on 2D and 3D coarse-mesh and pin-wise level. In the present version the 2D level MOBY-DICK calculations were adopted by some burnup scale adjustments to provide the same cycle length (boron concentrations at EOC during HPD calculations) as on 3D level.

3.2 Future development of the OPAL system

Single cycle mode
(based on the HPD, BP assignment on HPD and real burnup with BP)

1. Definition LPS and derivation a set of initial loadings
2. Fuel shuffle
   (evolutionary/direct algorithm)
3. Calculation HPD
4. Enrichment and enrichment split
5. BP assignment
6. FA rotation › go to 2.
7. 3D cycle depletion
8. Evaluation and final optimal design

(based on the full cycle burnup calculation)

1. Definition LPS and derivation a set of initial loadings
2. Fuel shuffle, enrichment split, BP assignment, FA rotation
3. Cycle burnup (2D/3D) › go to 2.
4. 3D cycle depletion

5. Evaluation and final optimal design

At present are in collaboration with The University of West Bohemia finalized and validated different heuristics (stochastic) and evolutionary algorithm [3] (tabu-search, simulated annealing and genetic algorithm, ...).

4. MULTICYCLE MODE OPAL_B

Multicycle mode OPAL_B is now working only with version of macrocode MOBY-DICK calculating HPD [7].

4.1 Organization of the optimization process in OPAL_B

The optimization process of OPAL_B system is structured in

Variants > *Tree (of loadings)* > *Trial* > *Population*

1. *Variant*
   Each *Variant* can consist up to 5 *Trees* (of the loadings) or up to 5 cycles

2. *Tree* (of loadings)
   For each *Tree* is defined collection of FAs of given cycle and within each *Tree* initiate up to 10 *Trials* how to rearrange them. For each *Tree* is generated its own macrocode library which predetermines changes in enrichment and connection to the previous cycles.

3. *Trial*
   For defined collection of FAs from given *Tree* is defined formula of Composite objective function (fitness) and each *Trial* initiate up to 5 calculation branches with its own Initial fuel loading. Initial fuel loading and macrocode Input Patterns produces input in to the standard macrocode system. Calculation in each branch is organized in the routine of generations during which are processed populations. By the variations of Initial fuel loadings and Input Patterns can be modeled changes in the enrichment, number of batch and length of the cycle. Final result of each *Trial* is 5 best loadings, which are archived in temporary archive.

4. *Population*
   In the case of evolutionary algorithm the size of population is constant during the each *Tree* calculations, in the case of direct calculations the number of solutions in *Populations* can be dynamically changed.
   Interactive option is organized on the level of *Populations*: the user can change all input data before going into the next population.
   Present version of OPAL_B code is working in 30°and 60°rotational symmetry.

4.2 Composite multiobjective function

In the present version system OPAL_B is defined following composite objective function.

$$\textit{Composite objective function} = \sum_i w_i \left(\frac{f_{i,max}}{f_i} \right) + \sum_j w_j \left(\frac{f_j}{f_{j,min}} \right) \qquad (2)$$

$$\textit{Penalty terms} = -\sum_i w_{i,p}\, p_i(\Delta_i) - \sum_j w_{j,p}\, p_j(\Delta_j) + \text{PCYC} \qquad (3)$$

where

$$\Delta_i = \left(\frac{f_{i,min}}{f_i} - 1 \right) \qquad \text{for} \quad 0 < f < f_{i,min}$$

$$\Delta_j = \left(\frac{f_j}{f_{j,max}} - 1 \right) \qquad \text{for} \quad 0 < f_{j,max} < f_j$$

p_i , p_j are polynomials and $p_i = p_j = 0$ *for* Δ_i , $\Delta_j \le 0$.

$f_{i,min}$ *and* $f_{j,max}$ are the lower and upper bounds (constraints) of criteria f_i *and* f_j

w is the weighting factor

$\sum_i$ is sum for maximization

$\sum_j$ is sum for minimization

PCYC is penalty term from the multicycle formulation

The criteria f_i *and* f_j can be tradicional objective funtions which should be maximized/minimized or constraints (EOC Keff, EOC boron concentration, peaking factor, enrichment, number of BPs, number of feeded FAs, ...).

Penalty term PCYC which increases the discharge burnup BU_k of each FA k consistent with the maximum allowed burnup BU_{max} is defined by formula

$$PCYC = - \sum_k w_k . (BU_{max} - BU_k)^2 \qquad (4)$$

where w_k are assembly-wise dependent weighting factors which can reflect multicycle optimum.

In principle application of this composite objective function needs more experience namely on the multicycle level. More complicated Composite objective function may bring to the instability and slowing down calculations. In our paper are in next chapter presented results only for maximization of boron concentration with penalization of power peaking at EOC in the Haling principle approximation.

4.3 Fuel shuffling and shuffling constraints

Initial loading is shuffled using dynamically optimized built-in or interactively adjusted binary exchange subroutine. Shuffling routine is repeated using successful loading as a new loading.

Under user decisions are :

- the first assessment feed batch and enrichment
- burned fuel inventory
- BP palette
- target length of fuel cycle
- limited radial power peaking
- limited burnup of FAs

Initial loading is provided according LPS.

Initial core coarse shuffle of group of FA is provided according LPS with lower number group in priority ranked regions.

Within routine are applied following shuffling constraints like:

- no discrete burn up absorbers under control rod locations
- exclude feed fuel placement in designated locations
- force specific fuel placement in designed locations
- force given symmetry (30°or 60°)

4.4 Validation process

The best fuel loadings designed on the bases of HPD are so artificially good loadings, that real design with BP can only approach to the HPD peaking and fuel cycle length. That is a reason to provide recalculation of the calculated loadings with BP before going to the next cycle.

7. BP ASSIGNMENT

The optimal control BP strategy is considered to be a separate and following step of the in-core fuel management procedure. An alternative formulation of the objective function as the overall cost of the fuel reload allows direct introduction of economic parameters into the optimisation process. First, the PSU PSDPI (Power Shape Driven Progressive Iteration Method) [5,11] methodology of BP assignment in WWER has been adopted in SKODA JS a.s. [10]. This method is divided into two steps, where in the first step so called equivalent thermal absorption is found in the fresh fuel assemblies to reach Haling power in these assemblies. In the second step this equivalent thermal absorption is transferred into number of BPs using pre-calculated library of these relations in dependence on enrichment, burnup and number of BPs using four point Lagrange interpolation. This process has been applied, but it is not quite correct, because the relation is based only on thermal absorption and the other effects were neglected. Therefore, a modified process has been applied, which consists in direct searching of necessary number of BPs. This process can be described by the following formulae:

$$dBP(ik,i)=dPOW(ik,i)/SE \quad (5)$$

$$NBP(ik,i)=NPB(ik,i-1)+dBP(ik.i)*\alpha \quad (6)$$

where:

dBP(i,k)	- change of number of BPs in FA ik in iteration step i
dPOW(ik,i)	- difference in relative power in FA ik in iteration step i between real distribution and HPD
SE	- sensitivity coefficient (change in relative power caused by change of one BP)
NBP(ik,i)	- number of BPs in FA ik in interation step i
α	- relaxation parameter for underrelaxation of iteration process

Iteration process is terminated after convergence is reached. (It means that found number of BP in all FAs are the same in the subsequent iteration step). Process is repeated for discrete number of burnup steps during depletion process, because requested numbers of BPs can differ with fuel and BPs depletion. As the last step is selected this lowest number of BPs which meets limit on power peaking.

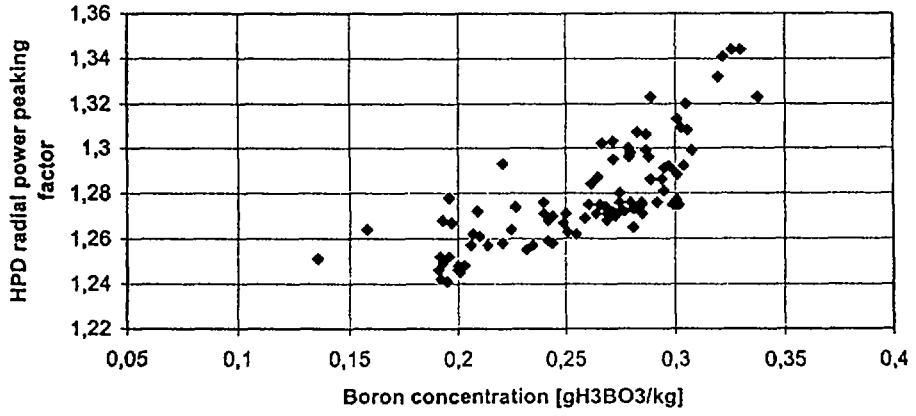
The power peak in the HPD calculation must be lower (about 4 %) than the power peaking criteria in order one to be able to perform practical assignment of BPs, which preserves power distribution during normal depletion within the operational limits. However, further lowering of HPD peak can cause shortening of cycle lifetime, in any case, real cycle

length is shorter that calculated by Haling principle. In chapter 9 are given practical examples of BPs assignment based on cycle calculation in the next chapter.

8. SOME ONE CYCLE CALCULATIONS WITH OPAL_B SYSTEM

Presented calculations were provided with multicycle coarse-mesh mode on the level of one fuel cycle 4 of NPP Temelin. Starting solution (initial loading) was taken from human optimised fuel loading of cycle NPP Temelin (Levine [12]). This loading was relatively good optimized only by manual shuffling: burned fuel assemblies were calculated by regular burnup process from the first cycle to third cycle and enrichment of loaded 9 fresh FAs was splitted into 3 FAs with 4.05 % and 6 FAs with 3.0 %. In this case coarse mesh HPD peaking was 1.267 with zero boron concentration for 306.05 FPD. With the code OPAL_B were generated some loadings on the level of 2D MOBY-DICK calculations and some typical are provided for subsequent processing in BP assignment module (see Table 1). Used composite functional (see eq. (2)) was very simple: maximisation of EOC boron concentration with penalization on radial power peaking. The resulting Pareto. front of this Composite funkcional is seen from Fig.1 on which is depicted one of the sets of calculation for 306.05 FPD. The Variant 1 ranks into the shortest cycles but longer and with very low radial HPD peaking in comparison to initial loading (humanly scheduled). This variant is in some sense "theoretical" because real limitation of power peaking of present NPP Temelin cores is given by radial pin-wise power peaking $F_{\Delta H}$ = 1.57. For this reason next three variants were optimized for higher radial peaking factor and has character of low-leakage loading (namely Variant 2 and 4) with longer cycle length. Variant 3 has uniform enrichment of fed FAs (3.35 %) and Variant 4 opposite enrichment splitting (3.6% / 2.85%) then Variant 2 (3.0% / 4.05%). From this results is seen that we can reach relatively good FA loadings (on the level of HPD) with no enrichment splitting of fed FAs.

FIG. 1 HPD radial power peaking factor versus boron concentration (Cycle 4 NPP Temelin, cycle length 306.05 FPD)



9. BP ASSIGNMENT AND HALING PRINCIPLE TESTING

In this chapter are presented results of calculations (of selected loading) shortly described from the point of basic parameters which are testing functionality of the Haling principle for WWER.

For examples given below, the following numerating of FAs is used (in one 60° symmetry sector):

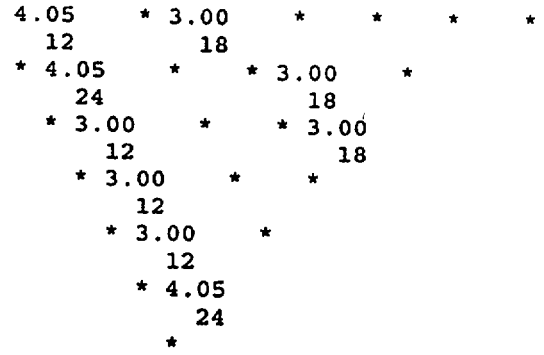
```
  22  23  24  25  26  27  28

16  17  18  19  20  21

  11  12  13  14  15

     7   8   9  10

       4   5   6

         2   3

           1
```

Next, positions of fresh fuel assemblies into 4th cycle with their initial enrichment and found number of BPs in the fresh FAs are given for all five variants (variant „0" is this initial human optimized loading scheme, „*" means non-fresh FAs);

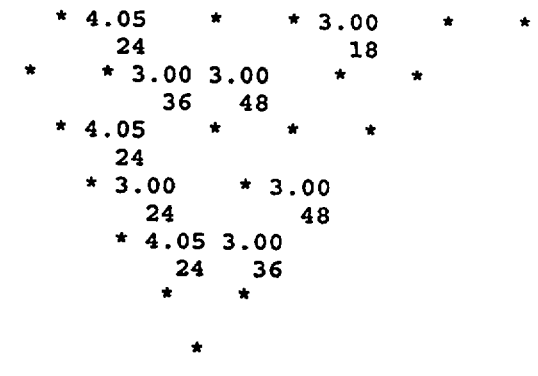
Variant 0:

```
 4.05     * 3.00     *     *     *     *
    6         24
 * 4.05     *     *  3.00     *
     24                24
   * 3.00     *     *  3.00
       12                24
     * 3.00     *     *
         12
       * 3.00     *
           12
         * 4.05
             24
           *
```

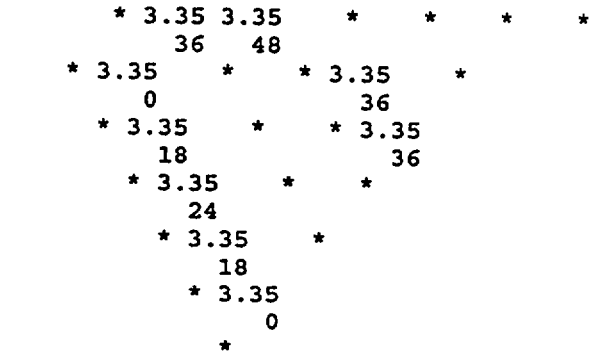
Variant 1:



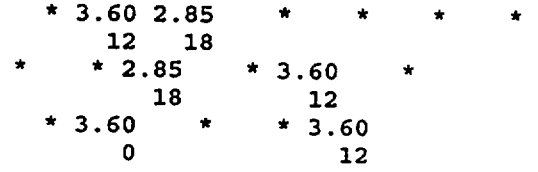
Variant 2:



Variant 3:



Variant 4:



```
* 3.60     *     *
    18
  * 3.60 2.85
       0   18
    *     *

       *
```

Variants „0" and „1" differ only by different assortment of non-fresh FAs, nevertheless longer cycle length and lower power peaking have been reached. Other three variants show much longer fuel cycle, although power peaking is much higher. The overview of results is given in Table 1, where HPD (max,As) gives maximal power peaking according Haling principle and FA number, in which this maximum occurs; Length(HAL) is a Haling theoretical cycle length, RPD(max,As) is real maximal power distribution in FA found, Length(real) is real cycle length with assigned BPs in the fresh fuel assemblies and in the last column is number of BPs in one 60° symmetry segment of core.

Table 1 NPP Temelin Cycle 4 optimization

variant	HPD(max,As)	Length(HAL)	RPD(max,As)	Length(real)	Num. of BPs
0	1.263 (15,20)	308.80	1.296 (15,20)	304.49	162
1	1.254 (3,17)	315.20	1.292 (24)	310.66	150
2	1.348 (10,19)	334.70	1.390 (23)	328.72	282
3	1.366 (24)	331.00	1.399 (24)	326.09	216
4	1.342 (15,20)	333.45	1.414 (23)	326.82	108

From this table is seen that for variants with longer cycle length (very low leakage) is difficult to ensure sufficiently low power peaking. For variant 4 the number of BPs is relatively low, but power peaking is very high and power peak is on position „14" in non-fresh FA. Such power peak is practically impossible to reduce by BPs, because these are applicable only in fresh FAs. Data in Table 1 also show limitations of Haling principle for multicycle optimization, because length of cycle is in reality shorter than predicted by Haling principle.

10. CONCLUSION

The presented one option of OPAL system for VVER core loading optimization based on the HPD approximation has shown that methodology based on splitting of fuel loading optimization and BP assignment is hopeful namely for multicycle calculation.

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