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APPLICATION OF NEW METHODOLOGY OF FORM-FUNCTIONS CALCULATIONS IN SCORPIO-VVER SYSTEM

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ABSTRACT

An accurate reconstruction of the pin-wise power distribution is an important part of the limit checking of reactor operation. In SCORPIO-VVER core monitoring system, this is provided by the RECON module on the basis of pre-calculated form-functions. A new technique was implemented for improvement of the accuracy of pin-wise power reconstruction via a new methodology of form-functions calculations.

1. INTRODUCTION

Pin-wise power reconstruction is an essential part of the VVER-SCORPIO monitoring system. With an advent of Gd-fuel need arose of the more precise reconstruction. Here we describe our effort in this field.

2. BASIC OF RECONSTRUCTION METHODOLOGY

Reconstruction methodology is based on modulation method, i.e. dividing of actual solution into smooth, local coarse-mesh (homogenous) power distribution solution and heterogeneous form function [1].
Heterogeneous fission form function $f_G(\bar{r})$ for fission of group G is given by 3D pin-wise finite-difference power distribution calculation normalized to meet following modulation equation for pin-wise core power distribution $q(\bar{r})$:

$$q(\vec{r}) = A\sum_{G=1}^{2} \phi_G^{\text{hom}}(\vec{r})\,\Sigma_f^G(\vec{r})\,f_G(\vec{r}) \qquad (1)$$

where $\phi_G^{\hom}(\bar{r})$ is local homogeneous flux of group G

$\Sigma_f^G(\bar{r})$ is local homogeneous macroscopic fission cross-section

A relates fission reactor rates to power

These local homogeneous values are determined by the 2D interpolation on the base of coarse-mesh finite-difference calculation (produced by SIM unit). In our procedure $f_G(\bar{r})$ is also time (burn-up) dependent.

3. APPLICATION OF FORM-FUNCTION METHODOLOGY IN REAL SITUATION

In this part we show outline of form-functions applications inside SCORPIO-VVER system. In SCORPIO-VVER system is provided by RECON module, newly in tandem with TVF_ONLINE sub-module.

Form functions are basically created as a ratio of pin-wise calculations and coarse-mesh calculation (interpolated to position of pins in FA) of reactor core; core mesh calculations (and therefore form-functions) are for 6 and 24 points per assembly. This is because of time-related reason- reconstruction must be quick. During normal reactor operation only 24 points form-functions are used (necessary inputs are provided by module SIM, for 24 points per FA) and reconstruction for one 60-degree segment is performed; but when asymmetry in core is introduced (such as a case of accidental fall of control fuel assembly), need of whole-core reconstruction arises; in such case SIM module provides 6 points per FA input and reconstruction (of the whole core) occurs.

All form functions are calculated for expected cycle history with appropriate nominal parameters (power, coolant flow, inlet temperature, height of FA). Concrete time stamps are calculated for same nominal parameters as previous, except of height fuel assembly, which must be in a sufficiently low height (~190 cm) to render anomalies around coupler between fuel and absorption part of control fuel assembly.

Previous model of form functions

With only profiled enrichment fuel assemblies (FA), situation with power reconstruction situation allowed simpler approach. Basic structure of form function was as follows:

1. common form function for all FA, derived for axial height of about half of reactor core height. This was shown as sufficient for gradual and monotonic change of macroscopic fission cross-sections along height of ordinary fuel pin. Form function in the center was chosen because of the most representative substitution.
2. special form functions for assemblies in the FA in the neighborhood of control assemblies (for coupler between fuel and absorption part of control assembly).

Form functions are stored in particular file, called INITREC2.DAT file (off-line form-functions). There are two time steps inside. These time steps are read during initialization of RECON module and afterwards stored in internal memory. Actual value of form function is obtained by interpolation between them (and extrapolation otherwise).

These power functions were prepared by special RELOAD module (off-line SCORPIO-VVER module).

New model of form functions

Previous reconstruction model showed to be inconvincible with introduction of the fuel assemblies with gadolinium absorber so we have decided to make changes to increase accuracy of power reconstruction. New structure of form-functions is as follows:

1. five common form functions for all FA: 2 axial layers in the upper part of FA, 2 axial layers in the bottom part of FA, one in the middle of the of the core
2. special form functions for positions of pins with gadolinium absorber; these form functions are for all axial layers (i.e. for each assembly 6 values for all 42 axial layers)
3. special form functions for assemblies in the FA in the neighborhood of control fuel assemblies (for coupler between fuel and absorption part of control fuel assembly)

Next, on the ground of strong non-linearity of power peakings created by presence and depletion of gadolinium absorber, we have decided to increase the number of time steps of the form functions. It's now possible to use up to six different form functions; now we are using five of them.

4. ON-LINE RECALCULATION OF FORM-FUNCTIONS (ON DEMAND)

Reconstruction with off-line form functions assumes that reactor is running as pre-planed (as was planned during off-line form-functions calculation). To put this more precisely, we introduced new feature: on-line, on demand form-function recalculation. This will allow retaining of real history of the fuel depletion.
Off-line methodology is still preserved as a backup of on-line one.

Calculation of on-line form-functions (TVF_ONLINE module)
TVF_ONLINE is an auxiliary task of the RECON module and is called by RECON. Task can be forced to run by using initialization file named LIAISON. Task is called mainly because of the amount of effective time elapsed, with default value 10 days (can be changed by user).
It runs on-line form-function calculations, which include real history of fuel depletion. These are used by module RECON for correction of default off-line form-functions. It's still possible to force their use regardless of on-line form-functions.
RECON module creates file SCOREHIS, which includes history of reactor operation (global reactor parameters with appropriate time interval – reactor thermal power, coolant flow, inlet temperature, height of FA). Each calling of RECON module creates one record in SCOREHIS file.
TVF_ONLINE reads last time of calculation from archive files and uses these files to create compressed history. Factors for creation of one step in compressed history are maximum length of time interval and restriction to power variation. (for zero power is compression treated differently – there isn't restriction to length of time of compressed variant).
For form-function calculation we need (in our case) three types of calculations: coarse-mesh 6 and 24 points/FA and pin-wise calculation. Each calculation is made in separate sub-directory of main directory and uses compressed history for calculation of history of reactor operation. After that, in the same sub-directory, special form-function calculations are accomplished. Results are handed back to module TVF_ONLINE and synthesized to create on-line form function.
If it is successful in creation of form-functions, TVF_ONLINE signals it to RECON module. These on-line form-functions are used by RECON module to update off-line form-functions. Unsuccessful attempt to create form-functions is signaled to RECON module and user is notified.

TVF_ONLINE also checks if calculations were somehow interrupted. If it detects such interruption, it'll attempt to restore itself to the correct state. It is provided by backup files, which are created after successful creation of on-line form-functions.

Using of on-line form-functions (RECON module)
Generally speaking on-line form-functions are used as correction of off-line form-functions. If there aren't any on-line form-functions calculated, RECON module uses off-line form-functions. After any on-line form-function is calculated, RECON automatically attempts to use it (if it isn't forbidden explicitly by user). Transition between two form-functions is linear and takes certain time interval (default value is 1 day). In the time between two on-line recalculations of form-functions (and during transition periods), trend of change of off-line form functions is used.
Before any attempt to use new on-line form function, RECON checks it and if anomalies or big discrepancies are found, RECON rejects it.

5. ACCURACY OF PIN-WISE POWER DISTRIBUTION RECONSTRUCTION

Testing of accuracy of our new reconstruction was carried on comparison of power peakings between 3D pin-wise calculation and 3D coarse-mesh calculation with reconstruction (with 6 or 24 points per FA), for 42 axial layers. Calculations were performed for Dukovany NPP Unit 3, Cycle 19 with Gd-2 fuel.
Power distribution comparison table description:
Differences (per thousand) of pin power distribution from reconstruction used in SCORPIO system and 3D pin-wise calculation are given in the following table. The nodal power values of SCORPIO were normalized on the nodal values of referenced pin-wise MOBY-DICK-TH calculation.

The following variables are defined.
T_{eff} effective time [d]
CB critical concentration of H_3BO_3 [g/kg]
POWER core power [MW]
HRK6 HRK6 position [cm]
IHPD axial layer number (HRK6) – position of working fuel assembly
Xe information about concentration of Xe^{135} (0 zero, 1 equilibrium; -1 from reference variant)

K_o max. value of pin relative power in core (from reconstruction)
K_{ov} max. value of nodal pin relative power in core (from reconstruction)
K_{on} as K_o, but for FA n
K_{ovn} as K_{ov}, but for FA n
er. deviation of variable (reconstructed – 3D pin-wise calculation, per thousand)
mp. max. positive deviation
mn. max. negative deviation

M.D. No. of FA (Moby-Dick numeration)
BIPR No. of FA (BIPR numeration)
IROD pin number (1-127)
IAX axial layer number (1-42,from bottom)

Boun.err. boundaries of histogram of deviations
Max.pos.err. max. positive deviation in histogram for chosen interval
Max.neg.err. max. negative deviation in histogram for chosen interval
LAX number of axial layer or expression "ALL" for average value of whole pin
AVER. VALUES 3 variables: average value of pin-wise relative power, average value of reconstructed relative power, deviation (per thousand)
Remark. Every deviation (per thousand) are calculated as denominator would be 1.000 (or 1000.0)

In the head of each table are given the basic parameters of core at calculation; eff. time, boric acid concentration, core power, HRK6 position, axial layer of HRK6 and information about Xe^{135} concentration (XE = 1 - equilibrium Xe^{135} concentration, XE = 0 - zero Xe^{135} concentration). Next are variables K_o, mean, maximal and minimal differences (similar for K_{ov}) and their position in reactor core. In the bottom of the table are maximum positive and negative differences of K_{on} and K_{ovn}; these differences are in the histogram form for chosen intervals. Values 1.550 for K_{on} and 2.537 for K_{ovn} (it corresponds linear power of 325 W/cm) are the limiting upper values of these variables.
We must highlight that deviations are calculated after normalization of reconstructed values; these values are normalized on the same average pin-wise level (for whole assembly or axial layer). In this way we eliminate in our comparison differences originating in (possible) differences in FA power for pin-wise and coarse-mesh calculations. *So our errors represent pure effect of reconstruction* (see values behind AVER. VALUES).
Here we present time stamp Teff=180 days because of the depletion of Gd absorber in this time and also biggest errors in this time for earlier version of reconstruction.

6. CONCLUSIONS

Results of our effort in improvement of the pin-wise power reconstruction are presented. The new version of form-functions is capable of an accurate pin-wise power reconstruction with Gd-fuel and was successfully implemented in SCORPIO-VVER core monitoring system of Bohunice NPP.

REFERENCES

[1] Krýsl V., Razým L., Šůstek J., Švarný J.
Unit Development Folder – Limit Checking and Thermal Margin Calculation, NPP Bohunice, 2006

Table1. Summary of deviations.

```
  Teff=180.0000  CB=  1.771  POWER=  1375.0  HRK6=178.0  IHPD=  31  XE= -1

     Ko   er.Ko  mp.Kon  mn.Kon     Kov  er.Kov mp.Kovn mn.Kovn
   1.531     3.     8.     -7.    1.869     0.    30.    -22.
M.D.       6823   6809    6809            6853   6817    6853
BIPR         23      9       9              53     17      53
IROD         15      7      51               6    127      52
IAX                                        14     40      39


 Boun. err.   Kon    0.000  1.000  1.200  1.300  1.400  1.500  1.550

 Max.pos.err. Kon          6.     7.     8.     7.     8.     3.     0.
 Max.neg.err. Kon         -4.    -7.    -7.    -6.    -3.     0.     0.

 Boun. err.   Kovn   0.000  1.000  1.500  1.800  2.100  2.350  2.536

 Max.pos.err. Kovn        30.    28.    12.     2.     0.     0.     0.
 Max.neg.err. Kovn       -22.   -19.    -5.    -2.     0.     0.     0.
```

Fig. 1
Detail maps of deviations for fuel assembly 6809 (fresh FA with Gd absorber in BIPR position 9).
Matrix of average values and two concrete axial layers (40, worst case, and 21, common case) are shown.

```
                    ASSEMBLY NO.  6809    BIPR     9

                          LAX =    ALL

                       AVER. VALUES   1221.   1225.      4.

                          7     5     0    -1     0     5     8

                       4     4     4    -2    -1     5     2     6

                    0     4     5     0    -2     0     6     5     0

                 -1    -2     0    -1    -3    -3    -2    -1    -1    -1

              0    -1    -2    -2    -3    -4    -4    -3    -2    -1     0

           4     4     0    -3    -4    -6    -5    -5    -3     0     4     4

        6     4     5    -2    -3    -6     0    -6    -4    -2     4     3     5

           5     3     0    -3    -4    -5    -6    -5    -3    -1     4     4

              0    -1    -1    -3    -4    -4    -4    -3    -3    -2     0

                 -2    -1     0    -2    -3    -4    -2    -1    -2    -2

                    0     4     5    -1    -2    -1     3     3     0

                       4     3     5    -1    -1     4     2     4

                          7     5     0    -2     0     4     5
```

Fig.1, cont.

LAX = 40

AVER. VALUES 661. 644. -17.

24 21 2 -3 2 20 24

17 7 17 -5 -6 15 7 20

0 14 17 -3 -9 -4 17 16 2

-5 -7 -4 -6 -12 -12 -6 -3 -5 -1

0 -6 -9 -13 -15 -17 -15 -11 -7 -4 3

17 15 -4 -13 -17 -20 -19 -15 -12 -4 14 19

24 8 17 -6 -16 -20 0 -18 -14 -7 13 5 22

20 16 -4 -13 -17 -20 -19 -16 -11 -3 13 17

0 -5 -8 -13 -15 -15 -14 -11 -8 -5 0

-4 -7 -5 -7 -12 -12 -7 -4 -5 -4

0 14 15 -3 -9 -4 12 11 0

17 8 15 -5 -5 13 6 15

22 18 2 -2 2 17 21

LAX = 21

AVER. VALUES 1487. 1492. 5.

0 0 0 0 0 0 0

0 0 0 0 0 0 0 0

0 0 0 0 0 0 0 0 0

0 0 0 1 0 0 1 0 0 0

0 0 0 0 0 0 0 0 0 0 0

0 0 0 0 0 0 0 0 0 0 0 0

0 0 0 0 0 0 0 0 0 0 0 0 0

0 0 0 0 0 0 0 0 0 0 0 0 0

0 0 1 0 0 0 0 0 0 0 0

0 0 0 0 0 0 0 0 0 0

0 0 0 0 0 0 0 0 0

0 0 0 0 0 0 0 0

0 -1 0 0 0 0 0

Fig.2
Detail maps of deviations for fuel assembly 4703 (FA with profiled enrichment in BIPR position 8) (between HRK and positiom 9). Matrix of values in one axial layer (42, worst case) is shown.

ASSEMBLY NO. 4703 BIPR 8

LAX = 42

AVER. VALUES 457. 430. -27.

```
                  6    6    4    5    5    9   11
             4    0   -1   -2   -2    0    3    7
          2   -2   -3   -2   -2   -2   -2   -1    4
       2   -2   -3   -3   -4   -4   -3   -3   -2    2
    2   -2   -3   -3   -6   -5   -5   -4   -4   -3    2
 3   -2   -3   -3   -5   -4   -3   -5   -5   -3   -3    5
6    1   -1   -4   -4   -4    0   -4   -5   -4   -2    2    9
 5   -1   -3   -4   -4   -3   -4   -4   -4   -2    0    8
    4   -1   -3   -4   -5   -5   -5   -4   -2    0    8
       6   -2   -3   -3   -4   -4   -3   -2    0    8
          6    0   -1   -2   -3   -2    0    0    9
            10    4    0    0   -1    0    4   11
               13   10    7    6    7   10   13
```