Software Package KASKAD for Neutronic Calculation of VVER Cores. Status and Features

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Abstract

The paper provides a brief description of the current state of the KASKAD (KASKAD 2007) software package widely used in Russia and abroad and intended for calculating the neutronic parameters of VVER reactor cores. The package includes some calculation and service modules operating together within a graphical shell and ensuring:

- elaboration of the Nuclear Core Design and Reload Design;
- preparation of the input data for the fuel rod design and the thermal-hydraulic design software;
- data preparation and check of the compliance of the limitations of the Check-list referring to the neutron-physical characteristics of the core;
- data preparation to perform the experiments at physical start-up and analysis of the data obtained;
- in-service data analysis, including the analyses of power distribution;
- calculation of the isotopic content, residual heat and activity of the burnt-up fuel.
- generation of the reporting materials in WORD processor.

The issues related to various aspects of usage and development of the software are considered in the paper.

1. Introduction

The software package KASKAD [1], developed in NRC “Kurchatov Institute” and intended for calculating the neutronic parameters of VVER reactor cores, is widely used in Russia and abroad. The software package is an integrated media that ensures:

- elaboration of the Nuclear Core Design and Reload Design;
- preparation of the input data for the software of the thermal-hydraulic design;
- preparation of the input data for the fuel rod design software;
- data preparation and check of the implementation of the limitations of the Check-list referring to the neutron-physical characteristics of the core;
- data preparation for the systems of monitoring and control;
- data preparation to perform the experiments at physical start-up and analysis of the data obtained;
- in-service data analysis, including the analyses of power distribution;
- calculation of the isotopic content, residual heat and activity of the burnt-up fuel.
- generation of the reporting materials in WORD processor.

The issues related to various aspects of usage and development of the software are considered in the paper.

1) KASKAD: TVS-M (ver.1.4) / BIPR-7A
2) KASKAD 2007: TVS-M (ver.1.4) / BIPR 2007

At present among the users of the KASKAD software are specialists from various countries: Russia, Armenia, Bulgaria, China, India, Slovak, Ukraine and some others. All users have passed appropriate training course and receive necessary technical support. To improve this support in 2014 the Club of KASKAD users was organized.

2. The KASKAD package structure and functionality

The software package KASKAD gives the opportunity to calculate:

- imitation of core operation, refueling, fuel loading life time;
- core criticality parameters: liquid boron concentration in moderator and control rods position corresponding to core burnup, power, coolant pressure and temperature;
- spatial assembly-wise and pin-by-pin power distributions including power peaking factors;
- reactivity coefficients and effects;
- fuel isotopic composition, decay heat and radioactivity.

The KASKAD package consists of the following basic calculation and service modules operating under the control program shell with a graphical interface:

- BIPR-7A code [3] is a coarse-mesh diffusion code of 3-D calculation of core neutronics
- (power distribution, criticality parameters, reactivity coefficients etc.);
- PERMAK-A code [4] is a 2-D 4/6-group code for pin-by-pin core calculation, it is used for multi-layer power calculation in the core scope and for obtaining radial boundary conditions for BIPR-7A code;
- PIR-A code, intended for comparison of calculation results with operational data, obtained at operating NPPs, for the system verification;
- PROROK-A code intended for the interactive or automated selection of the equilibrium or current fuel loading;
- SC-1 code intended for the assessment of the thermal-physical parameters for the consideration of feedbacks at performing the neutronic calculations and for the preliminary discarding the refueling patterns;
- TOPRA-s code intended for the assessment of the fuel parameters at performing the neutronic calculations;
- SFUEL module intended for the calculation of the residual heat and activity of the burnt-up fuel;
- ALBUM code, intended for the report generation in WORD processor on the neutron-physical design.

The KASKAD 2007 [5] is an advanced version of software package KASKAD including new computational modules both for coarse-mesh 3-D core calculation and for pin-by-pin 2-D calculation. But at the same time the opportunity of using the old modules was kept.

The generation of few-group libraries, boundary conditions, isotope contents of FAs, residual heat and FA activity and other neutronic parameters required for the KASKAD (KASKAD 2007) software package is realized with the following codes:

- TVS-M code [6] is designed for the generation of the neutronic constant libraries needed for codes BIPR-7A and PERMAK-A in cases of a change in either FA enrichment or a change in their design;
- TVS-RAD [7] is a version of TVS-M code that includes the code ORIGEN-S (ORNL) [8] and is intended for the calculation of the isotope content and the activity of the spent fuel;
- PERMAK-3D [9] is a 3-D rod-wise calculation code intended, in particular, for obtaining the boundary conditions on the edge reflectors for the BIPR-7A code.

As it was mentioned above the basic neutronic calculation codes from the packages KASKAD and KASKAD 2007 were certified and their validation was based on comparisons both with the measurements on the operating units and with precise calculations. It allows estimating calculation errors for the basic functionals. The values of estimated errors taken from the codes. Certificates are given in Tables 1 and 2.

3. Features of recent versions

The basic areas of the KASKAD package development are:

- improving the computation accuracy and reducing the required design conservatism level as a result;
- extending the possibilities provided by the package and its application areas;
- enhancing the level of computational automa-
tion; improving the user interface.

Accumulated experience in the use of neutronic calculation codes included in the package KASKAD (KASKAD 2007) indicates the presence of some systematic deviations of the results of calculations of the critical concentration of boric acid and power distribution from the corresponding measurements on the operating units.

The observed deviations may be caused by a large group of various reasons related to both the measurement error and uncertainty of operating parameters of a particular unit, and with calculation errors. Some of these reasons are the following:

- errors caused by various simplifications of calculation model used when preparing the few-group constant libraries (for instance, using fixed irradiation parameters averaged over the core when calculating burnup, calculation model of single FA with zero-current boundary conditions and so on);
- errors of the coarse-mesh code (BIPR) and of calculation model used (cross-sections are constant within FA, isotopic content of soluble boron is changeless and so on).

To improve the agreement between calculations and measurements the following changes were implemented:

- the special module [10] estimating the change of $^{10}$B content in soluble boron and correcting the critical boric acid concentration value was developed (see, for example Figure 1);
- the methodology of accounting for the influence of spectral history on FA cross-sections (implemented in the BIPR 2007 code, an example of affecting 3-D power distribution is given in Figure 2);
- it was realized an opportunity of using assembly-wise radial power distribution calculated with fine-mesh code PERMAK for obtaining pin-wise 3-D power distribution in the core by means of synthesis of 3-D coarse-mesh and 2-D fine mesh calculations.

In recent years the comparison with precision codes, namely with the MCU-PD code [11-12], has become increasingly important in KASKAD validation process. To be able to generate automatically 3-D computer model of VVER core and then to perform automatically comparative analysis of calculation results obtained with precision and design codes the special interface KASKAD-MCU was developed. Figures 3 and 4 show the example of VVER-1200 model used to perform calculations for more than 100 states of the fresh core loading including feedback states. Some comparison results are given in Figures 5 and 6 as well as in Tables 3-4.

Since 2007 the application area of the KASKAD software package has been expanded by including SFUEL module for operative calculation of total activity and decay heat of spent fuel. The module obtained these values by interpolating data previously calculated with the TVS-RAD code. By now, SFUEL allows obtaining additional data on the activity of individual fission products, as well as activity and decay heat values for individual fuel rods. Besides, the new code TVS-M/BURNUP has been developed which unlike the TVS-RAD code is fully the development of NRC KI and is considered as a substitute for this code.

In addition, a new program developed, which unlike the module is fully the development of the institute program.

A few years ago the constant-preparing code was not included in the package itself and had no graphic interface. Input data of TVS-M code consisted of a simple set of files having no connection with each other. When the number of various FA types involved in the design process becomes large, the risk of errors caused by human factor increases. To minimize the probability of human calculation error occurrence the special code SRBD was developed and is currently being put into use. The code SRBD is a database with a graphical user interface (see Figure 7) and provides:

- preparing the input data for the TVS-M code on the base of initial data (geometric sizes, material content and so on);
- storing in the database both the initial data and the calculation results (cross-sections needed for core calculations);
- tools for forming the documentation describing the cross-section libraries.

4. Conclusion

The paper gives a brief description of the current state of the KASKAD (KASKAD 2007) software package intended for VVERs neutronic calculations and presents short description of some improvements of the software package directed on improving the computation accuracy and expanding the application area as well as on improving the user interface and enhancing the level of computational automation.
Table 1. Estimated calculation errors for the KASKAD software package

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical concentration of boric acid at the beginning of fuel load operation</td>
<td>±0.3 g/kg</td>
</tr>
<tr>
<td>Fuel loading operating lifetime</td>
<td>±3%</td>
</tr>
<tr>
<td>Total efficiency of CPS rods</td>
<td>±10%</td>
</tr>
<tr>
<td>Efficiency of the control cluster of CPS rods</td>
<td>±10%</td>
</tr>
<tr>
<td>Total temperature reactivity factor (with account of water density and fuel temperature variations) at the beginning of fuel load operation</td>
<td>±3×10⁻⁵ 1/°C</td>
</tr>
<tr>
<td>Maximum relative FA power</td>
<td>±5%</td>
</tr>
<tr>
<td>Maximum relative power of FA layer</td>
<td>±10%</td>
</tr>
<tr>
<td>Maximum relative fuel rod power within FA layer</td>
<td>±4%</td>
</tr>
</tbody>
</table>

Table 2 – Estimated calculation errors for the KASKAD 2007 software package

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical concentration of boric acid at the beginning of fuel load operation</td>
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<tr>
<td>Total efficiency of CPS rods</td>
<td>±20%</td>
</tr>
<tr>
<td>Efficiency of the control cluster of CPS rods</td>
<td>±10%</td>
</tr>
<tr>
<td>Total temperature reactivity factor (with account of water density and fuel temperature variations) at the beginning of fuel load operation</td>
<td>±3×10⁻⁵ 1/°C</td>
</tr>
<tr>
<td>Relative FA power</td>
<td>±0.06*</td>
</tr>
<tr>
<td>Relative power of peripheral FAs</td>
<td>±0.09*</td>
</tr>
<tr>
<td>Relative power of FA layer</td>
<td>±0.10*</td>
</tr>
<tr>
<td>Maximum relative fuel rod power within FA layer</td>
<td>±4%</td>
</tr>
</tbody>
</table>

* values result from statistical processing of the comparison data and correspond to the confidence level of 95% (2σ²)

Figure 1. Comparison of calculated and measured value of critical boric acid (typical 18-month fuel cycle of VVER-1000)
Figure 2. Results of comparison of calculated and measured values of relative power FA layer (KV), VVER-1000, cycle 1

Figure 3. VVER-1200 calculation model (horizontal section)
Figure 4. VVER-1200 calculation model (vertical section)

Figure 5. Comparison of relative FA power (Kq) obtained with MCU-PD and BIPR-7A codes

\[
\delta = \frac{K_{\text{BIPR}} - K_{\text{MCU}}}{K_{\text{MCU}}} \times 100\%
\]

HZP
\[
\delta_{\text{max}} = 2.5\% \quad \sigma = 1.3\%
\]

HFP
\[
\delta_{\text{max}} = 2\% \quad \sigma = 1\%
\]

Figure 6. Comparison of fuel rod relative power (Kr) obtained with MCU-PD and PERMAK-A codes.
\[ \delta = \frac{K_{PERMAK} - K_{MCU}}{K_{MCU}} \times 100\% \]

\[ \sigma_{MCU} \approx 1\% \]

FA № 35
\[ \delta_{\text{max}} = 6.4\% \]
\[ \sigma = 2.5\% \]

FA № 61
\[ \delta_{\text{max}} = 6.9\% \]
\[ \sigma = 2.6\% \]

Figure 6. Comparison of fuel rod relative power (Kr) obtained with MCU-PD and PERMAK-A codes

Table 3. Comparison of Keff value obtained with MCU-PD and BIPR-7A codes

<table>
<thead>
<tr>
<th>Power, MWt</th>
<th>Inlet coolant temperature, °C</th>
<th>(^{135})Xe poisoning</th>
<th>(K_{\text{eff}}^{\text{BIPR}} - K_{\text{eff}}^{\text{MCU}}, % )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>27</td>
<td>–</td>
<td>-0.15</td>
</tr>
<tr>
<td>0</td>
<td>120</td>
<td>–</td>
<td>-0.12</td>
</tr>
<tr>
<td>0</td>
<td>200</td>
<td>–</td>
<td>-0.11</td>
</tr>
<tr>
<td>0</td>
<td>280</td>
<td>–</td>
<td>-0.04</td>
</tr>
<tr>
<td>1600</td>
<td>289</td>
<td>–</td>
<td>-0.16</td>
</tr>
<tr>
<td>3200</td>
<td>298</td>
<td>–</td>
<td>-0.08</td>
</tr>
<tr>
<td>3200</td>
<td>298</td>
<td>+</td>
<td>-0.01</td>
</tr>
</tbody>
</table>

Table 4. Comparison of some reactivity effects obtained with MCU-PD and BIPR-7A codes

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Deviation BIPR-7A from MCU, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coolant temperature coefficient of reactivity</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>Fuel temperature coefficient of reactivity</td>
<td>&lt; 9</td>
</tr>
<tr>
<td>Boric acid reactivity coefficient</td>
<td>~ 4</td>
</tr>
<tr>
<td>Efficiency of single RCCA</td>
<td>&lt; 7</td>
</tr>
<tr>
<td>Efficiency of RCCA control group</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>Efficiency of emergency protection system</td>
<td>2</td>
</tr>
</tbody>
</table>
Figure 7. User interface of neutronic constant software

List of nomenclature
FA - Fuel Assembly
MOX - Mixed Oxide
NRC KI - National Research Center "Kurchatov Institute"
RCCA - rod control cluster assembly
VVER - Russian Type of Pressurized Water Reactor
Kq - relative FA power
Kr - fuel rod relative power
KV - relative FA layer power

References