Development and using computer codes for improvement of defect assembly detection on Russian WWER NPPs

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Abstract: Diagnosis methods of fuel failure detection are currently in development to improve radiation safety and shortening of fuel reload time at Russian WWERs. The works include creation new computer means for increase of effectiveness of fuel monitoring and reliability of leakage tests. Reliability of failure detection can be noticeably improved when we apply an integrated approach. The integrated approach to diagnosis of fuel failures at WWERs includes the following methods.

The first is fuel failure analysis under operating conditions. Analysis is performed with the pilot version of the expert system, which has been developed on the basis of the mechanistic code RTOP-CA. The second stage of failure monitoring is ‘sipping’ tests in the mast of the refueling machine. The leakage tests are the final stage of failure monitoring. A new technique with pressure cycling in the specialized casks was introduced to meet the requirements of higher reliability in detection/confirmation of the leakages. Measurements of the activity release kinetics during the pressure cycling and handling of the acquired data with the RTOP-LT code enable to evaluate a defect size in leaking fuel assembly. The mechanistic codes RTOP-CA and RTOP-LT were verified on a base of specialized experimental data and currently the code were certified by Russian authorities ROSTECHNADZOR. Now the pressure cycling method in the specialized casks has official status and is utilized at the all Russian WWER units.

Some results of application of the integrated approach to fuel failure monitoring at several Russian NPPs with WWER units are reported in the present paper. Predictions of the current version of the expert system are compared with the results of the leakage tests and with the estimations of the defect size by the pressure cycling technique. Using the RTOP-CA code the level of activity is assessed for the following fuel campaign if the leaking fuel assembly was decided to be reloaded into the core. A project of the automated computer system on the basis of the RTOP-CA code for the ‘on-line’ fuel monitoring in the core during WWER-1000 operation is also presented.

Key words: RTOP-CA code, RTOP-LT code, ‘sipping’ test, leakage test, pressure cycling method for defect detection, integrated approach to WWER fuel failure monitoring.
1. INTRODUCTION

An integrated approach to fuel failure diagnosis is under development for nuclear power plants (NPPs) with WWER-type reactors. The integrated approach comprises the following three stages.

At stage I, the level of core defectiveness is assessed during reactor operation. It gives the on-line information on the parameters of failed fuel: burnup and the number of leaking fuel rods, defect sizes. The core contamination with tramp uranium is also estimated. The fuel failure analysis during reactor operation is carried out with the current version of the expert system elaborated on the basis of the certified mechanistic code RTOP-CA [1]. The RTOP-CA code is designed to predict the primary coolant activity and to model the degradation of defective fuel properties. In the current version of the expert system core-average characteristics of reactor operation are used in the analysis (history of total reactor power).

Preliminary assessments of the core defectiveness during reactor operation reduce the uncertainty of failed fuel parameters as well as the risk to miss the defective fuel assembly (FA) at subsequent procedures of leakage testing. It also gives the opportunity to find beforehand a suitable substitution for the failed FA, so saving the outage time.

Stage II of fuel failure diagnosis is the so-called ‘sipping leakage testing’ in the mast of refueling machine [2]. The sipping tests are carried out during refueling outage when the fuel cycle is over. At present, equipment for the sipping tests is not mandatory for WWERs and may be absent at some units. The sipping technique allows detecting the leaking fuel assemblies. However, the defectiveness of the FAs specified as ‘leaking’ is supposed to be proved by additional leakage tests in the specialized casks of the spent fuel pool. The severity of the failure is also determined in the cask leakage tests. If sipping equipment is not installed at an NPP unit, the fuel failure analysis during reactor operation is the only means to reduce time and optimize the expenses for the cask leakage tests.

The leakage tests in the casks of the spent fuel pool are the last stage (stage III) of fuel failure diagnosis. To meet the up-to-date stringent requirements for reliable detection and evaluation of fuel failures, a new technique was developed with pressure cycling in the casks for leakage testing. The technique is of high sensitivity in detection of the failures. The RTOP-LT code [3] was developed for evaluation of an effective hydraulic defect diameter for leaking FAs. The assessment of defect size is taken into account in making a decision whether it is possible to reload the failed FA with a ‘small’ leak. If the leaking FA is decided to be reloaded into the core, a prediction can be computed with the RTOP-CA code concerning the level of coolant activity for the next fuel cycle. After the next cycle is over, an analysis of the reloaded leaking FA is repeated by the pressure cycling technique to assess the degree of defect degradation.

Taking the current version of the expert system for fuel failure analysis under operation conditions as a basis, the project of an advanced computer system to monitor the in-core state of nuclear fuel is developed. The fuel monitoring in the advanced computer system will be performed using the data from the in-core instrumentation system (ICIS) at operating NPP units. The on-line data on evolution in time of axial power profiles in particular FAs in the core are presumed to improve the reliability of predictions concerning fuel failures.

The advanced computer system will combine the capabilities to assess the current state of nuclear fuel in the core and to make predictions for the case of scheduled changes in fuel operation regimes (e.g. load-follow modes). The main block of the system is going to implement the fuel failure analysis and predictions of leaking fuel behavior under operation conditions. Additional block will involve rod-to-rod monitoring of the intact fuel (estimation of fission gas release, mechanical stresses in claddings).

The present paper provides some examples of applying the integrated approach to fuel failure diagnosis at Russian NPPs with WWER-1000 units. A comparison is given between the predictions of the current version of the expert system made during reactor operation and the results of the leakage tests after reactor shutdown (including the results of the cask leakage tests
with the pressure cycling technique). The project of the advanced computer system to monitor the fuel state in the core is also briefly described.

2. **THE RTOP-LT CODE. NEW METHOD DEVELOPMENT FOR IMPROVE SENSITIVITY OF LEAKAGE TESTS IN CASKS AT WWER**

For reliable detection and evaluation of fuel failures, a new technique at Russian WWERs was developed with pressure cycling in the casks for leakage testing. The technique is of high sensitivity in detection of the failures. By measuring a nuclide activity kinetics during pressure cycling and by processing the obtained data the RTOP-LT code is used [3].

The pressure cycling method for detection and evaluation of fuel failures consist in the following procedure. Testing FA is located in a specialized cask with circulating coolant in loop of the system. Pressure inside the cask is changed according to scenario shown in Fig.1.

The RTOP-LT code includes a lot of physical models for description of activity release in the coolant through defect in the cladding. The main goal of the code consisted in sensitivity improvement of the cask method at WWER NPPs. The second task was evaluation of effective hydraulic defect diameters in cladding of WWER fuel rods by use of cycling pressure dependence. Activity release kinetics depends on parameters of defective fuel rod before testing procedure. For this reason, parameters of defect fuel rods were determined against of burnup, operational period and time of fuel rod depressurization. Parameters of defective fuel rod, which are determinative for kinetics of activity release, are following: FP distribution inside the rod, volume of nondensables, size of fuel pellets, defect location and defect size, geometry of fuel-cladding gaps and fuel cracks.

These values are calculated by the RTOP-CA code and the RTOP-LT code with taking into account of pressure changing during transportation of FAs from reactor core to the cask. Phenomenology of processes in defective rods at testing in the cask is following. Water enters inside the rod when external coolant pressure exceeds internal one. Fresh coolant in the rod enriches by soluble nuclides due to digestion effect. Diffusion of soluble FPs from regions of high concentration to regions of low concentration takes place during digestion period. Then when external pressure diminishes lower than internal pressure, the soluble nuclides and fuel fragments release from the defective rod. Kinetics of activity release depends on scenario of pressure changing, defect and gaps parameters. Following physical processes are realized in the RTOP-LT code:

- Coolant transfer inside a rod and coolant release through defect.
- Coolant digestion inside the defective fuel rod (diffusion of nuclides inside the rod).
- Convective transport of soluble FPs.
- Transport and release of insoluble FPs and fuel fragments.

The RTOP-LT code includes two computer modules. The first is responsible for coolant transport inside the rod and release through defect. The second module calculates a transfer of soluble FPs and fuel fragments. Hydraulic equations are used to model coolant transport inside the defective rod. The equations takes into account of geometry of gaps, cracks parameters,
effective size of defect and its position. An effective hydraulic resistance of the defect has nonlinear dependence of coolant velocity due to turbulence effects. These hydraulic equations are very similar to equations which are used for description of electrical currents (equivalent of coolant flows) and difference of electrical potentials (equivalent of pressure differences).

Equivalent electrical schemes for defective rods including pellets with and without central hole are different, Figs. 2.

![Equivalent electrical schemes](image)

**Fig.2.** Equivalent electrical schemes corresponding to coolant hydraulic transport in defective rods.

A – fuel rod including pellets with central hole, B – fuel rod including solid pellets.

Measurements of the activity release kinetics during the pressure cycling and handling of the acquired data with the RTOP-LT code enable to evaluate a defect size in leaking fuel assembly. The mechanistic RTOP-LT code was verified on the base of specialized experimental data and currently the RTOP-LT code was certified by Russian authorities ROSTECHNADZOR [4]. The evaluations of effective hydraulic diameters are taken into account to make a decision whether the leaking fuel may be reloaded for the next fuel campaign or not. After the campaign is over the reloaded leaking assemblies are tested again with the technique of the pressure cycling to estimate the degradation of the defect size. Now the pressure cycling method in the specialized casks has official status and is utilized at all Russian WWER units.

### 3. THE RTOP-CA CODE. MODELLING OF PRIMARY COOLANT ACTIVITY AND DEFECTIVE FUEL ROD BEHAVIOUR UNDER OPERATIONAL CONDITIONS

The mechanistic code RTOP-CA was developed to model a behavior of failed fuel rods and release of radioactive fission products into primary coolant under WWER operation conditions. The RTOP-CA code incorporates self-consistent models for the following physical processes in a failed fuel rod: fuel thermomechanical behavior; radial burnup and Pu profiles; radiolysis-assisted fuel oxidation; thermal conductivity degradation with burnup; changes in FP diffusivity in oxidizing fuel under irradiation; FP release out of fuel; mass transfer inside failed rod; release and behavior of radioactive FPs in primary circuit. In detail the code is described elsewhere [5]. Physical models of the RTOP-CA code were separately verified using a wide database of in-pile and out-of-pile, full- and small-scale experiments. Database for integral verification of the code included:
The experiments in research reactors were carried out under well-defined conditions and provide the most reliable dataset.

NPP data on failed fuel characteristics is less detailed; information was obtained in leakage tests during outages. Number of defective fuel rods in calculations was chosen according to the number of detected failed fuel assemblies (1 or 2 defective rods per assembly, 1.3 in average). It was presumed that failed fuel characteristics were constant during the operation period. Verification was performed for various operation periods at different power units with WWER-440 and WWER-1000 reactors.

Activity kinetics of a wide spectrum of radioactive FPs was measured in experiments at research reactors and at NPPs: nuclides of iodine \((^{131}\text{I}-^{135}\text{I})\), xenon \(^{133}\text{Xe},^{135}\text{Xe},^{135m}\text{Xe},^{137}\text{Xe},^{138}\text{Xe},^{139}\text{Xe}\) and krypton \(^{85m}\text{Kr},^{87}\text{Kr},^{88}\text{Kr},^{89}\text{Kr}\). Results of the verification were compared with data on defective FA testing by use of pressure cycling method. The RTOP-CA calculations are in good agreement with the data in the whole range of experimental conditions.

Recently the RTOP-CA code was certified by Russian supervision authorities ROSTECHNADZOR [6]. The RTOP-CA code is capable to predict the primary coolant activity and degradation of failed fuel properties.

**4. THE EXPERT SYSTEM FOR FUEL FAILURE ANALYSIS – EXAMPLES OF APPLICATION**

The basic version of the expert system for fuel failure analysis under operation conditions and methods to process the data on primary coolant activity have been described in detail recently[1,4]. Data on activity are analyzed with the expert system in the following steps. First, general analysis is performed to estimate the amount of tramp uranium in the core, to detect the occurrence of failures and to assess the burnup of leaking FAs. In case of severe failures the rate of fuel washout into coolant is determined. Failures are detected by spikes in activity of the long-lived radionuclides of iodine, caesium and xenon. Defective fuel burnup is evaluated by correlation on the ratio of \(^{134}\text{Cs}\) and \(^{137}\text{Cs}\) activities in spikes. Additional burnup evaluations are made using the ratios between activities of gaseous fission products (FPs) at reactor operation at a steady power level. Finally, the number of leaking fuel rods in the core and defect sizes are estimated.

Below, some examples are discussed illustrating the application of the integrated approach to fuel failure diagnosis at WWER units, including failure analysis during reactor operation.

**4.A. Fuel failure diagnosis – example I**

The operation parameters of unit N1 for one of the fuel cycles are shown in Fig.3. Spikes in \(^{131}\text{I}\) and \(^{134,137}\text{Cs}\) activities at power scrams unambiguously demonstrate the appearance of failed fuel in the core. The mass of tramp uranium \(M_{\text{TU}}\) assessed by \(^{131}\text{I}\) and \(^{134}\text{I}\) activities is different. A relatively high ratio \(M_{\text{TU}}(^{131}\text{I})/M_{\text{TU}}(^{134}\text{I})\approx 20\) supports the conclusion[1] that leaking fuel is present in the core and indicates that defects in fuel rods are not too small. Steady level of \(^{134}\text{I}\) activity during the fuel cycle shows that no fuel washout took place, so the failures were not severe.
According to the results of $^{134,137}$Cs spike analysis, the burnup of defective FAs correspond to 3 or 4 years of operation (see Figs.4,5). The estimation of defective fuel burnup can be refined using the data on activity of gaseous FPs [1,7]. The analysis in Figs.6,7 shows that the failed FA is of the 3rd year of operation.
Fig. 5. Estimation of defective fuel burnup by Cs spiking: I – approximate ranges of activity ratios $^{134}\text{Cs}/^{137}\text{Cs}$ and corresponding burnup ranges for FAs with different operation time; – the range of $^{134}\text{Cs}/^{137}\text{Cs}$ activity ratios measured in spike at the end of the fuel cycle, unit N1.

The number of leaking fuel rods in the core and defect size (small or coarse defect) is assessed taking into account the estimated burnup. The technique is similar to the analysis of defective fuel burnup using gaseous FP activities. For the fixed fuel burnup the ‘chart’ of $^{131,133,135}\text{I}$ activities is calculated with the RTOP-CA code. It resembles the ‘chart’ for gaseous FPs in Fig. 6. But in contrast to Fig. 6, the iodine activity ‘chart’ is three-dimensional and different colors mark the points which correspond to different number of defective fuel rods, $N_F$, in calculations. The 3-D range of experimental data is plotted in the ‘chart’ after activity data have been processed and confidence intervals have been chosen. Then the relative amounts of points with different colors are counted in the range of the data scattering (for the given confidence level). Finally, we come to a sort of a histogram showing the ‘probability’ to find different numbers of defective fuel rods in the core.

The results of the analysis for the fuel cycle at unit N1 are provided in Figs. 8, 9. The estimations show a high probability to find one leaking fuel rod with a coarse defect in the core.

Fig. 6. Average ratio of $^{85m}\text{Kr}/^{135}\text{Xe}$ and $^{88}\text{Kr}/^{135}\text{Xe}$ activities – the RTOP-CA calculations: ○ – defective fuel of the 1st year of operation, □ – 2nd year, ◇ – 3rd year, ▲ – 4th year of operation. Colored areas show the ranges of experimental data scattering for the fuel cycle at unit N1: – area corresponding to 100% confidence level of experimental data; – area corresponding to 80% confidence level.
Fig. 7. Estimation of defective fuel burnup by gaseous FP activities for the fuel cycle at unit N1: probability to detect a defective FA with different operation time: – estimation with 100% confidence level of experimental data; – estimation with 80% confidence level.

Fig. 8. ($^{131}$I, $^{133}$I) plane projection of the 3-D ‘chart’ of iodine activities (Bq) to estimate the number of failures. “Clouds” of different colors correspond to calculations with different number of defective fuel rods, $N_F$, in the core: from $N_F = 1$ in the left-hand lower corner to $N_F = 10$ in the right-hand upper corner. Experimental data range – for the fuel cycle at unit N1.

Fig. 9. The number of failures estimated for the fuel cycle at unit N1: – estimation with 80% confidence level; – estimation with confidence level of 70%.
The predictions by the current version of the expert system agree well with the results of the cask leakage tests performed after reactor shutdown. One leaking FA after 3 years of operation was detected. The cask leakage test with the pressure cycling technique to estimate the defect size was not performed. However, the presence of \( ^{133}\text{Xe} \) and \( ^{136}\text{Cs} \) in water sample from the cask circuit as well as high activities of \( ^{134,137}\text{Cs} \) (\( \sim 50 \) times higher the ‘3\( \sigma \) criterion’) indicated a coarse defect.

4.B. Fuel failure diagnosis – example 2

As a fuel cycle at unit N2 was over, a defective FA after 1 year of operation was detected with the burnup of \( \sim 11.5 \text{ MW-days/kgU} \). The cask leakage test with the pressure cycling technique proved its defectiveness and the effective defect size was assessed to be \( \sim 80 \mu\text{m} \). It was decided to reload this FA into the core for the next fuel cycle.

The coolant activity level for the upcoming fuel cycle was preliminarily predicted with the RTOP-CA code. The prediction was made for the first 4 months of the fuel cycle assuming the unit would be operated under normal conditions at 100\% power and the coolant flow rate to cleaning filters would be 20 t/hr. The planned position for the reloaded defective FA in the core and its power factor were known and were taken into account in calculations. The defect was assumed to be located in the lower part of the fuel rod – up to 50 cm from the fuel stack bottom. It is a typical axial range for debris defects in WWER fuel rods.

The predictive calculations are shown in Fig.10. Fig.10 also presents the post-test activity calculations with accounting for the actual power history and the actual coolant flow rate to the cleaning system.

A minor difference in the level of activity for the predictive and the post-test calculations is explained by the fact that the actual flow rate to filters was somewhat lower than the nominal value.

The last two months of the fuel cycle were marked with a noticeable increase of \( ^{131}\text{I} \) and gaseous FP activities (see Fig.11b,c). The question was whether we had a new failure or it was a secondary defect in the reloaded leaking FA. To answer this question the data on coolant activity were analyzed with the expert system.
The ratios of $^{134}$Cs and $^{137}$Cs activities in two observed spikes in the middle of the fuel cycle correspond to defective fuel of the 2$^{nd}$ year of operation (Figs.11,12). The analysis of gaseous FP activities leads to the same result (Fig.13).

The analysis of $^{131}$,$^{133}$,$^{135}$I activities has shown that until the middle of the fuel cycle there was only one fuel rod in the core with a relatively large defect. Thus, until the middle of the fuel cycle these were no new failures and the only leaking FA was that reloaded for its 2$^{nd}$ year of operation.

Coolant activity level increased in the last quarter of the fuel cycle after an evident spike of $^{131}$I activity which took place under operation at constant power. It is important that $^{131}$I spike was not accompanied with spiking of Cs activity (see Fig.11b).

The assessment of defective fuel burnup by gaseous FP activities at the end of the fuel cycle confirms the supposition that additional failure of fresh FA have occurred (Fig.14). The analysis of $^{131}$,$^{133}$,$^{135}$I activities has shown that the number of defective fuel rods has increased up to 2 or 3 (Fig.15).

**Fig.11.** a – Data on the fuel cycle at unit N2 with reloaded leaking FA: reactor thermal power (MW), coolant flow rate to cleaning filters (10$^{-7}$ t/hr). The hatched regions show two intervals used for failure analysis. b – $^{131}$,$^{134}$I and $^{134}$,$^{137}$Cs activities (Bq) in primary coolant. c – Gaseous FP activities (Bq).

![Figure 11](image1.png)

**Fig.12.** Estimation of defective fuel burnup by Cs spiking in the middle of the fuel cycle at unit N2: I –ranges of activity ratios $^{134}$Cs/$^{137}$Cs and corresponding burnup ranges for FAs with different operation time; – experimental data range.

The results obtained with the current version of the expert system agree with the data of the cask leakage tests after the fuel cycle at unit N2 was over. In addition to the defective FA initially reloaded into the core for its 2$^{nd}$ cycle, a fresh leaking FA was detected. The both assemblies were tested by the pressure cycling technique. Defect size in both cases was estimated to be about 100 µm.
Fig. 13. Estimation of defective fuel burnup at the middle of the fuel cycle at unit N2: 
\(a\) – calculated ratios of FP activities and experimental data scattering ranges at confidence levels of 80 and 70% (for legend see Fig.6); \(b\) – probability to detect leaking FAs with different operation time.

Fig. 14. Estimation of defective fuel burnup at the end of the fuel cycle at unit N2: 
\(a\) – calculated ratios of FP activities and experimental data scattering ranges at confidence levels of 80 and 70% (for legend see Fig.6); \(b\) – probability to detect leaking FAs with different operation time.

Fig. 15. The number of failures estimated at the end of the fuel cycle at unit N2: 
- estimation with 80% confidence level of experimental data; 
- estimation with confidence level of 70%.
Thus, no significant defect degradation was observed in the course of the fuel cycle for the reloaded defective FA. It is additionally evidenced by no fuel washout into coolant as assessed from the rather stable level of $^{134}$I activity.

4.C. Summary of applications at NPPs

The expert system and the RTOP-CA code have been used at NPPs with WWER-1000 units for several years for failure monitoring. The expert system is applied to assess the current level of the core defectiveness. The data obtained are taken into consideration by the NPP personnel in planning how many and what FAs should be checked in the cask leakage tests. The RTOP-CA code can be directly applied to predict activity levels when questions arise of reloading leaking FAs into the core.

Table 1 (column 2) gives the number of fuel cycles analyzed with the expert system at different NPPs with WWER-1000 units. For all the fuel cycles the burnup of defective fuel was assessed by the ratios of gaseous FP activities. In some cases there were no data on $^{134,137}$Cs activity spikes and, so, gaseous FPs provided the only source of information to estimate the burnup of defective fuel. For all the analyzed fuel cycles the predictions of the current version of the expert system agree with the results of the cask leakage tests.

Column 3 of Table 1 shows the number of fuel cycles for which activities of I, Xe, Kr radionuclides in primary coolant were calculated by the RTOP-CA code for operation conditions. In most cases these were the post-test calculations. The input number and parameters of leaking fuel rods in the calculations were taken in accordance with the results of the cask leakage tests after the fuel cycle was over. The calculated values of radionuclide activities are in agreement with the data on activity measurements at NPPs.

These calculations simultaneously expand the verification database of the RTOP-CA code and show its predictive capabilities.

Table 1. Application of the current version of the expert system and the RTOP-CA code at NPPs with WWER-1000 units

<table>
<thead>
<tr>
<th>NPP</th>
<th>Number of analyzed fuel cycles</th>
<th>Estimation of the core defectiveness level</th>
<th>Calculations of activity level using the data of the leakage tests</th>
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<td>1</td>
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<td>4</td>
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<td>Novovoronezh</td>
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<td>5</td>
<td></td>
</tr>
<tr>
<td>Total:</td>
<td>18</td>
<td>14</td>
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</tr>
</tbody>
</table>

5. COMPUTER SYSTEM FOR IN-CORE FUEL MONITORING – PROJECT

Until recently, the ideology of fuel monitoring under operation conditions was confined to integrated core indices, e.g. FA average heat generation rates and axial FA power profiles. However, development of new fuel cycle strategies and new kinds of fuel for WWER reactors has entailed the necessity to review the design criteria and safety margins. More detailed and reliable approaches to in-core fuel monitoring has also become important. First of all, it deals with the introduction of the rod-to-rod core control.

At present time the rod-to-rod approach to fuel monitoring is getting especially urgent since FAs of different designs with different fuel types and fabricated by different manufacturers can be loaded into the core concurrently. Under the same external conditions different fuels may show different behavior (e.g. may demonstrate different margins to heat transfer crisis). Higher
burnups aggravate PCI problems with power ramps being the most severe case. If the rate of mechanical loading is above the rate of the relaxation processes, PCI leads to cladding failure. To provide a safe and effective operation of power units with new fuel cycles and new fuel types it becomes important not only to monitor the neutronics and thermophysical characteristics of the core under varying operation conditions but also to have detailed information on the in-rod processes: fuel and cladding thermal mechanics, gaseous FP release, change of fuel microstructure (rim-structure formation).

The data on the rod-to-rod power distributions can also be used to increase the reliability of fuel failure analysis during reactor operation. Presently, the level of core defectiveness is assessed by most expert systems proceeding from the averaged reactor characteristics. For detected leaking fuel rods, along with control of activity release into coolant, it is necessary to estimate the extent of fuel degradation and possibilities of severe secondary failures.

These tasks can be solved by integrating the in-core instrumentation system (ICIS) and available fuel computer codes. On this basis an advanced fuel monitoring computer system can be created to control the state of both intact and defective fuel in the core. The main functions of the system will include the monitoring of the current fuel state in the core and predictive calculations for scheduled changes in operation regimes.

The up-to-date ICIS systems provide wide possibilities of rod-to-rod on-line fuel monitoring. The examples are the system for operator engineering support (‘SIPO’) installed at the Volgodonsk NPP; the ICIS system with external computer software ‘Khortitsa-M’; ‘KRUIZ’ program-technical complex for WWER reactors [8,9] and the BEACON system for PWRs [10]. The state-of-the-art ICIS is, as a rule, a multi-level system that comprises sets of interrelated computer programs. Each level of the system is responsible for performing a separate block of tasks. With the multi-level architecture the system may be adapted for needs of a particular user. A convenient graphical interface makes it easier for the personnel to comprehend the in-core processes, allows operative and substantiated solution-making.

The project of the computer fuel monitoring system assumes two subsystems for analysis of defective and intact fuel. The calculation of intact fuel parameters (prior to failure) is necessary for correct modeling of defective fuel behavior and activity release into coolant. The subsystem for intact fuel calculations is subsidiary for the tasks of fuel failure diagnosis.

Each subsystem will contain two levels: monitoring of the current state and the possibility of predictive estimations for the planned conditions of operation. The project structure of the whole system is as follows:

**Subsystem 1 – Defective fuel**
- Expert assessment of the core contamination and defectiveness level based on the data on coolant activity.
- Prediction of coolant activity and degradation of failed fuel properties.

**Subsystem 2 – Intact fuel**
- Monitoring and analysis of the current state of the intact fuel (control of design limits, PCI occurrence, mechanical stresses in cladding, etc.).
- Predictive calculations for behavior of intact fuel under the planned conditions of operation (scheduled power ramps, load-follow modes, etc.).

Mechanistic codes are preferably to be used in the fuel-monitoring computer system. Such codes can be easily adapted to fuel design changes without performing numerous expensive experiments (in contrast to the correlation-based codes). The subsystem responsible for fuel failure diagnosis will be developed on the basis of the RTOP-CA mechanistic code and the current version of the expert system for fuel failure analysis under operation conditions. A certified Russian integrated fuel code will be used for the analysis of the intact fuel.

The development of the fuel-monitoring computer system will be an additional support to NPP personnel in all regimes of normal reactor operation providing (if required) the detailed on-line information on the state of fuel in the core. Along with the available leakage test methods
used after reactor shut down, namely, the sipping-tests and the cask leakage tests (including the pressure cycling technique), the system will give the following benefits:

- improved reliability of fuel failure diagnosis with higher level of radiation safety at WWER power units;
- increased efficiency of fuel management at NPPs;
- shorter outages for refueling;
- decreased radiation doses for the personnel.

6. CONCLUSIONS

The expert system for fuel failure analysis under operation conditions in its current version makes it possible to assess the defectiveness level of the WWER core. The estimated parameters are as follows: mass of tramp uranium, number of leaking fuel rods, burnup of defective fuel and defect sizes; intensity of fuel washout into coolant from fuel rods with severe defects. Predictive calculations of coolant activity can be carried out with the RTOP-CA code if a decision has been taken to reload a ‘small leak’ FA into the core.

The current version of the expert system and the RTOP-CA code were the foundation to develop the project of the on-line fuel-monitoring computer system. To enhance the reliability of predictions the fuel analysis in the advanced computer system will be performed with taking into account the ICIS data. The fuel-monitoring computer system is designed to support the NPP personnel, first, making possible the on-line assessments of the core defectiveness level and, second, giving possibility to predict the transient performance of intact fuel (e.g. for load-follow modes).

ACKNOWLEDGEMENTS

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