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EXPERIMENTS AT REACTOR MIR TO JUSTIFY SAFE OPERATION OF VVER FUEL OF IMPROVED DESIGN

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ABSTRACT: *The paper is focused on specific aspects of test methods and some representative experimental data regarding the irradiation tests conducted in the MIR reactor. The irradiation tests were performed using the VVER-1000 shortened fuel rods with a burnup of 44.4 MWd/kgU (irradiation tests ##1 and 2) after their refabrication and fuel rods with artificially applied defects on fuel claddings. Provided here is also some information about the RTOP-CA code verification based on the available experimental data. The RTOP-CA (Ref. 1) code is intended for calculation modeling of defect fuel behavior and fission products propagation in the primary circuit of water-cooled reactors.*

KEYWORDS: *MIR reactor, reactor experiment, refabricated fuel rods, artificial cladding defects, RTOP-SA code, fission gas activity.*

I. INTRODUCTION

At present JSC "TVEL" is making efforts to improve the VVER fuel. This work is targeted at improving fuel economic performance and increasing its performance reliability both for Russian and foreign nuclear power plants operating the VVER type reactors. It is expected that nuclear fuel of improved performance will be used in the TVS-K fuel assemblies including its possible operation in PWR reactors. Research and development work is under way to demonstrate safe operation of new nuclear fuel in case of fuel failure. In particular, irradiation tests are conducted in research reactor MIR to investigate release of radionuclides from fuel rods with artificially applied defects in fuel claddings. These experimental data are used to verify computer codes intended for calculation modeling of fuel and fuel rod behavior both before failure and after origination of through-wall-thickness defects in the fuel cladding. The models of physical processes under development can be applied to predict activity of the primary coolant for both VVER and PWR in case of Russian fuel failure.

II. EQUIPMENT AND IRRADIATION TESTING CONCEPT

JSC "SSC RIAR" developed special equipment and test methods for the PV-1 loop facility of the MIR reactor to conduct irradiation testing of fuel rods with artificial through-wall thickness defects applied in claddings under the conditions simulating the design basis operating conditions typical for a power reactor with provision for regular and continuous measurements of the loop coolant activity (Ref. 2).

With regard to irradiation parameters of fuel under irradiation and layout of test channels, the PV-1 loop facility has performance capabilities similar to other water-cooled facilities in the MIR reactor but it has the smallest primary circuit volume and thus it becomes the most suitable for in-pile measurements and required minor modification of its instrumentation and measuring equipment as it was originally designed for recording thermal and physical parameters (irradiation test parameters were recorded to guarantee the irradiation test safety). It was equipped with a special coolant sampling equipment and gamma spectrometry equipment to perform on-line measurements of fission products activity which propagate into the loop coolant (Fig. 1, 2).

The on-line measurement system that operates continuously makes it possible to obtain comprehensive data for specific activity of highly radioactive short-lived fission products with short half-life periods (from 5 to 10 minutes).

The sampling method is primarily intended for obtaining quantitative data on long-lived fission products with rather low activity.

The prevalence of these methods could be different as it is governed by objectives of irradiation tests. The on-line measurement method prevails over the sampling method when short-term irradiation tests are conducted and followed by rapid changes in the coolant activity. The sampling method could be of great importance when long-term irradiation tests in static conditions are conducted.

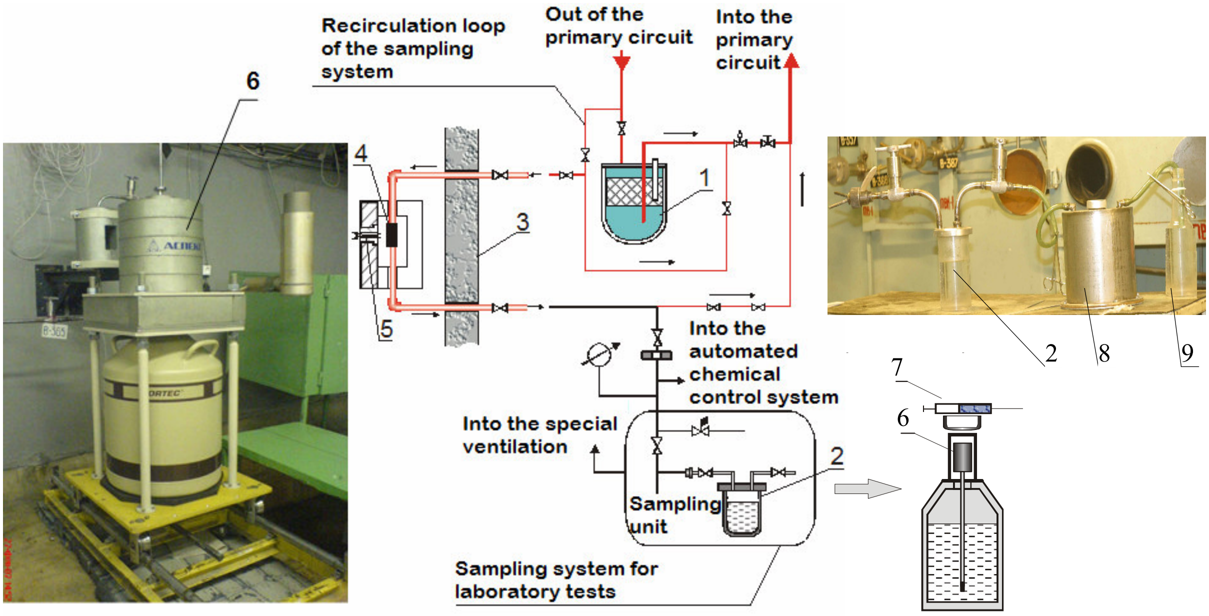


Fig. 1. Outfitting scheme of the PV-1 loop facility primary circuit at the MIR reactor and its completion with measuring equipment: 1 – ion-exchange filter; 2 – displaceable sampling tank; 3 – wall of the PV-1 loop facility shielded chamber; 4 – measuring tank; 5 – collimator; 6 – detector; 7 – syringe with a sample; 8 – gas delay tank; 9 – water tank.

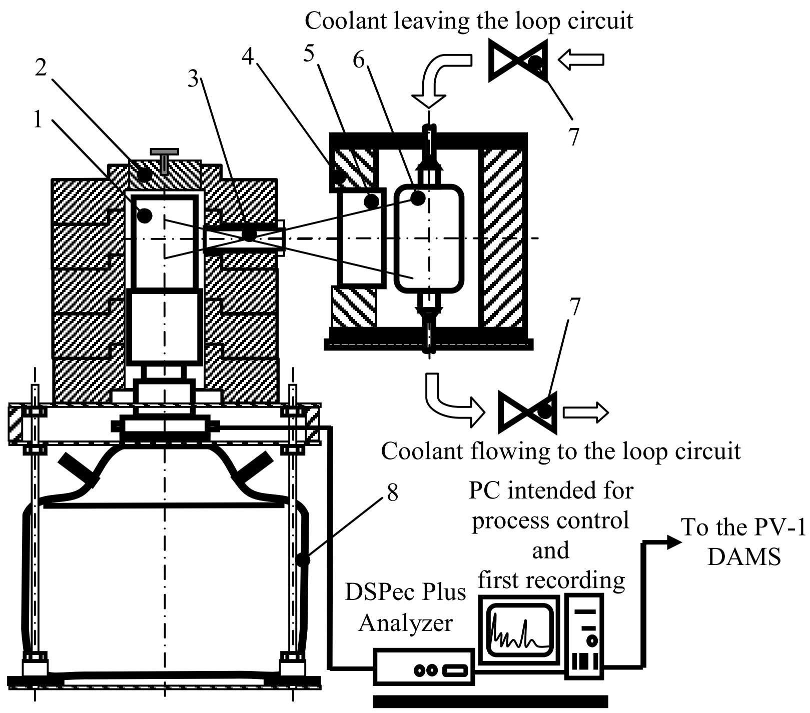


Fig. 2. Layout of the PV-1 loop facility coolant gamma spectra measurement area at the MIR reactor:
1 – gamma-ray detector; 2 – radiation (background) shielding of the gamma-ray detector; 3 - collimator;
4 – radiation shielding of the metering tank; 5 – shielding window of the metering tank; 6 – metering tank;
7 – cutoff valves of the metering tank; 8 – Dewar's flask.

III. TEST RIG AND EXPERIMENTAL FUEL RODS

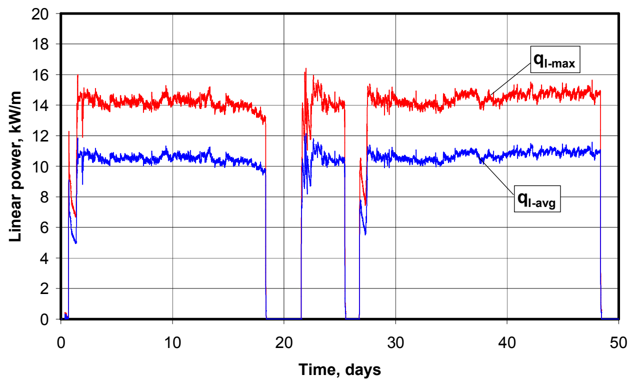
The fuel test rig (FTR) was designed in such a manner as to achieve specified thermal and physical parameters as well as coolant velocities around the fuel rods under irradiation which were comparable to their standard operating conditions in the VVER-1000 fuel assembly.

There was an experimental fuel assembly comprising seven fuel rods in the fuel test rig. It was the same as the VVER-1000 fuel assembly at its cross-section. The experimental fuel rod with the artificially applied defect was inserted into the central position and was surrounded by six fresh fuel rods. The fuel stack was ~ 1000 mm long that is equivalent to the MIR reactor core height. The design of experimental fuel rod was chosen with the aim to ensure its similarity to the VVER-1000 full-size fuel rod as to the fuel column length and gas plenum.

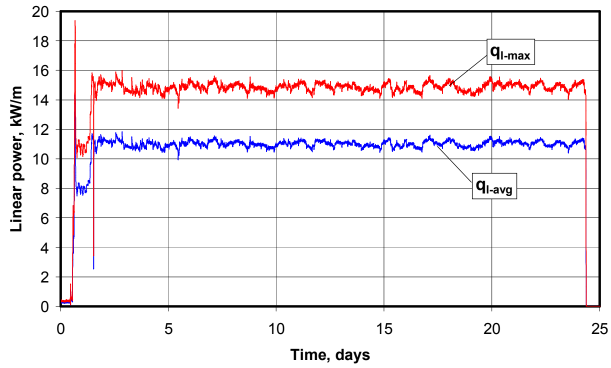
As to irradiation test #1, the artificial through-wall thickness defect was applied in the region of the gas plenum. An artificial defect of longitudinal groove type was applied on the cladding at a distance of 150 mm from the lower end plug of fuel rod to conduct irradiation test #2.

IV. RESULTS OF IRRADIATION TESTS ##1 AND 2 AND SIMULATION OF NUCLIDE RELEASE FROM FUEL RODS WITH ARTIFICIALLY APPLIED DEFECTS

Irradiation test # 1 was carried out during two reactor operation cycles for about 20 days each. An average linear heat rate was maintained at a level of about 11 kW/m along the length of fuel rods under irradiation during the reactor operation cycles (Fig. 3). Scenarios of irradiation testing as to changes in heat generation rate and the reactor coolant parameters (temperature and pressure) closely reflected the operating procedures adopted at nuclear power plants operating the VVER type reactors. These experiments made it possible to simulate release of nuclides resulted from "spike-effect" that is an abrupt increase of activity due to changes in the linear power or the coolant pressure.



a)



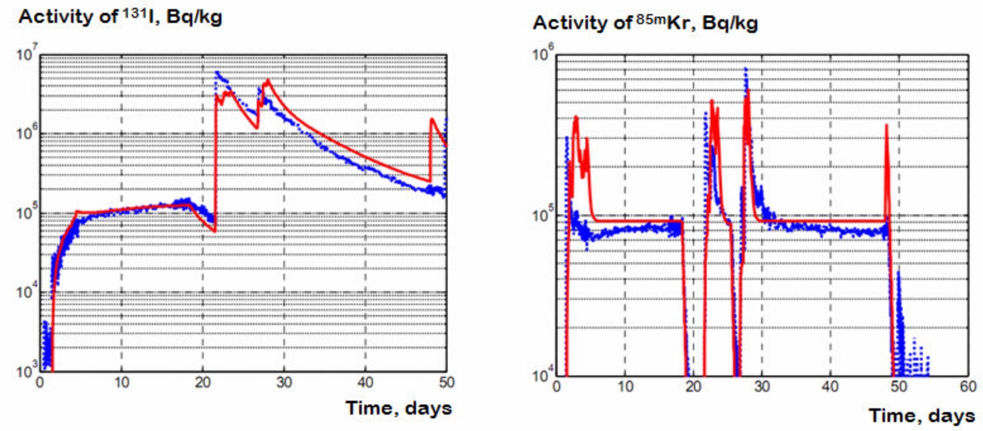
b)

Fig. 3. Peak and average linear power of fuel rod with artificially applied defect during irradiation test # 1 (a) and # 2 (b).

As evidenced by the results of the on-line measurement data processing, an increase of activity during the first reactor operation cycle was caused by release of fission products due to fission of nuclear fuel that was deposited on the surfaces of structural components in the loop test facility. Such a conclusion could be made based on the release to birth rate of fission products (it is normalized to the generation rate of nuclides in fuel rod under irradiation) as a function of decay rate. The release to birth rate of nuclides due to fission of nuclear fuel that is present in the circuit does not depend on the decay rate. Kinetics of ^{131}I activity increase in the loop test facility during the first reactor operation cycle as well as the rate of ^{131}I activity decrease due to release of nuclides resulted from "spike-effect" were used as a basis to choose a rate of nuclide escape from the circuit because of efficient coolant purification. Sorption/desorption of nuclides in the test channel of the loop test facility needs to be taken into account to describe activity of nuclides during irradiation test # 1 in the MIR reactor. Rates of sorption and desorption were chosen with due consideration for nuclides activity in the coolant during the first reactor operation cycle. As an example Figure 4 demonstrates the comparison of calculated and measured kinetics values for ^{131}I and ^{85m}Kr activities (measurements were performed during the irradiation test # 1). As it follows from the Figure 4, the observed abrupt increases of activity are attributable to release of nuclides from the defect fuel rods due to the "spike-effect". As it can be seen, both the areas exposed to irradiation under steady state conditions and in case of activity release from the fuel rod into the coolant have much in common.

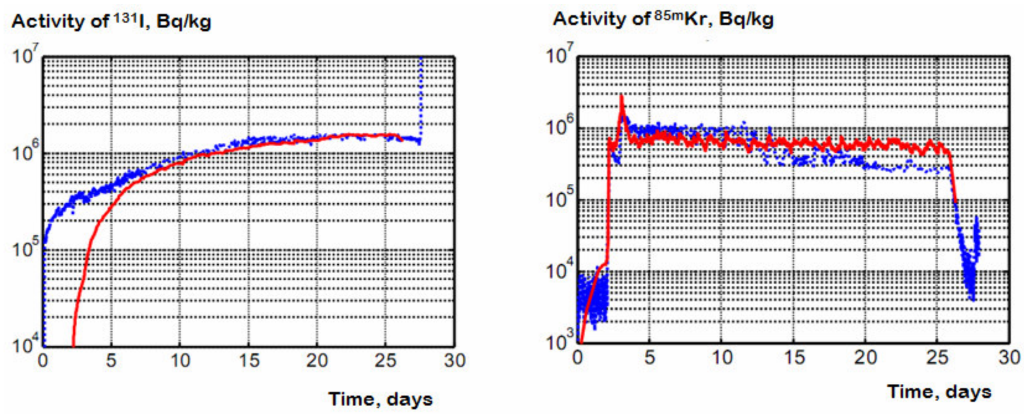
According to the irradiation test scenario, irradiation test # 2 was carried out during one reactor operation cycle for about 25 days (Fig. 3) at a constant linear heat rate of fuel rod (linear power was ~ 11 kW/m), constant temperature and pressure of the coolant. A level of fission products activity in the loop coolant was much higher during the irradiation test # 2 as compared to the activity level achieved during the first reactor operation cycle of irradiation test # 1. Thus, it was exceeded 2.5 times as to short-lived ^{134}I and almost 10 times as to long-lived ^{131}I. Difference in activity incremental rate that was observed during irradiation test # 2 for iodine with different life time as opposed to irradiation test # 1 is indicative of significant release of activity from the defect fuel rod during the irradiation test # 2 as compared with the activity release from the deposits.

Fig. 5 shows comparison of calculated and measured activity values for irradiation test # 2. Fluctuation of the average linear heat rate in fuel rod was the main mechanism governing release of nuclides into the coolant during the irradiation test # 2. Spikes in nuclides activity correlate well with increases of linear power. When increasing the heat rate, the temperature of fuel rod becomes higher and as a result water can evaporate inside the fuel rod. The resultant excess pressure of steam gas mixture under the fuel cladding causes propagation of nuclides into the coolant. The RTOP-CA code provides for mass transfer between the defect fuel rod and the coolant.



a) b)

Fig. 4. Dynamics of ^{131}I (a) and ^{85m}Kr (b) activities in the coolant of the PV-1 loop facility in the MIR reactor during irradiation test # 1. (—) – calculated data with the use of RTOP-CA, (·····) – measurement data.



a) b)

Fig. 5. Dynamics of ^{131}I (a) and ^{85m}Kr (b) activities in the coolant of the PV-1 loop facility in the MIR reactor during irradiation test #2. (—) – calculated data with the use of RTOP-CA, (·····) – measurement data.

The RTOP-CA code (Ref. 1) was improved with due consideration for mass transfer in fuel rod without a central hole. A specific feature of hole-free fuel rod is a reduced gas plenum under the cladding and increased hydraulic resistance. This feature affects activity propagation into the coolant in case of fuel failure. An updated version of the RTOP-CA code is used for calculation data analysis in support of hole-free fuel irradiation tests conducted in the MIR reactor.

In case of hole-free fuel, parameters of cracks are very important when mass transfer is calculated for failed fuel rod. The RTOP-CA was completed with finite-element module RTOP-3D to perform calculation modeling of dimensional changes for fractured fuel pellet.

V. CONCLUSIONS

Two irradiation tests were conducted in the PV-1 loop facility of the MIR reactor with the use of special equipment and test methods to investigate release of fission products from failed fuel rods of improved design which attained a burnup of 44.4 MWd/kgU. The artificial through-wall thickness defect was applied in the region of the gas plenum to conduct irradiation test # 1. An artificial defect of longitudinal groove type was applied on the cladding at a distance of 150 mm from the lower end plug of fuel rod to conduct irradiation test # 2. Thermal parameters of the PV-1 loop facility coolant parameters were measured during irradiation testing. Performed were also on-line measurements of fission products activity in the PV-1 loop facility coolant of the MIR reactor. The obtained irradiation test data were used to verify improved RTOP-CA.

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