INVESTIGATION OF THE VVER-1000 FUEL RODS BEHAVIOR UNDER LOCA CONDITIONS. IN-REACTOR EXPERIMENTS MIR-LOCA/45 AND MIR-LOCA/63

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ABSTRACT: *In the loop channel of the MIR reactor were performed experiments MIR-LOCA/45 u MIR-LOCA/63 with refabricated fuel rods (RFRs) made from TVSA VVER-1000 full-size fuel rods spent at the 1st unit of the Kalinin NPP up to a maximum burnup of 45 MWd/kgU and 63 MWd/kgU respectively. The purpose of the experiments was to obtain data on the behavior of fuel rods under the loss of coolant accident, including cladding deformation, leakage parameters, fragmentation, displacement and dispersion of fuel.*

KEYWORDS: *MIR reactor, reactor experiment, refabricated fuel rods, loss of coolant accident, cladding deformation, leakage parameters, fragmentation.*

I. EXPERIMENTAL EQUIPMENT

In each experiment was tested one fuel rod, located along the central axis of the test rig (TR) to avoid the heat rate and temperature non-uniformity over the cladding perimeter. The fuel rod was mounted in the spacer grids located 200 mm from each other (Fig. 1).

Two electric heaters allow modeling the thermal effect of surrounding fuel rods in the VVER-1000 fuel assembly (FA) and achieve initial water steam circulation. In the TR were used spacer grids that allowed to mount the thermoelectric transducer of the cladding temperature measurements in such a way that the hot junction were pressed to the fuel rod cladding. The mounting was carried out remotely. The coolant temperature, the fuel rod cladding temperature at three points along the height, the heat rate, the gas pressure into the FR were measured during the test. The test was carried out in a steam-argon atmosphere.

The RFRs contained fuel pellets without a central hole with an outer diameter of 7.8 mm into the cladding with an outer diameter 9.1 mm and a wall thickness 0.585 mm. In both fuel rods there was no initial fuel-cladding gap. An oxide layer with thickness (10-15) μm was formed on the inner surface of the cladding. The thickness of the layer on the outer surface of the cladding did not exceed 10 μm.

The difference in the fuel structure of the tested fuel rods is the incompletely formed structure of high burnup in the MIR-LOCA/45 fuel rod and the more pronounced gas swelling of the fuel in the MIR-LOCA/63 fuel rod.

The RFR scheme is shown in Figure 2. The existence of a free gas volume in the fuel rod lower part is due to the pressure transducer mount.

Before the sealing, the RFR was filled with helium to a certain pressure, which after filling the RFR was controlled by a pressure transducer.

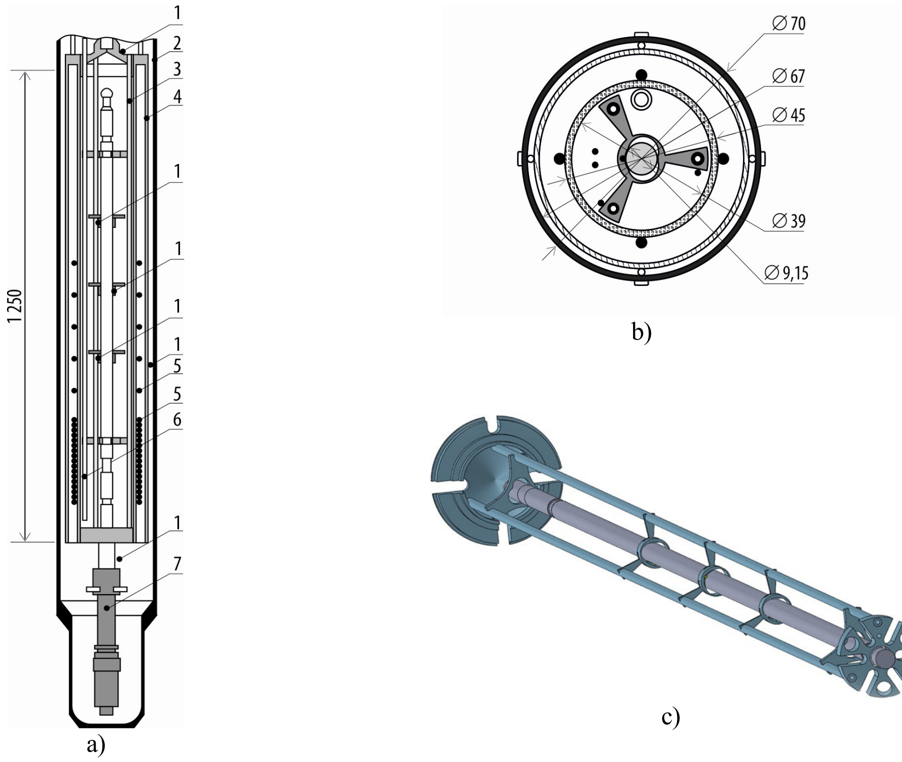


Fig. 1. The constructive scheme (a), the cross section (b) and the fuel rod mount (c) of the TR:
1 - thermoelectric converter; 2 – TR jacket; 3 - basket; 4 - insulator; 5 - heater; 6 - water supply tube; 7 - pressure transducer.

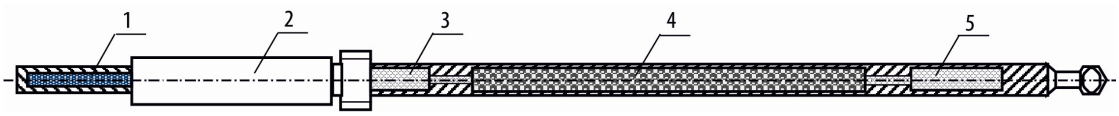


Fig. 2. Design of the tested RFR:
1 - ferromagnetic rod; 2 – pressure transducer; 3 - the bottom free volume; 4 - fuel core; 5 - upper free volume.

II. ALGORITHM OF THE EXPERIMENTS

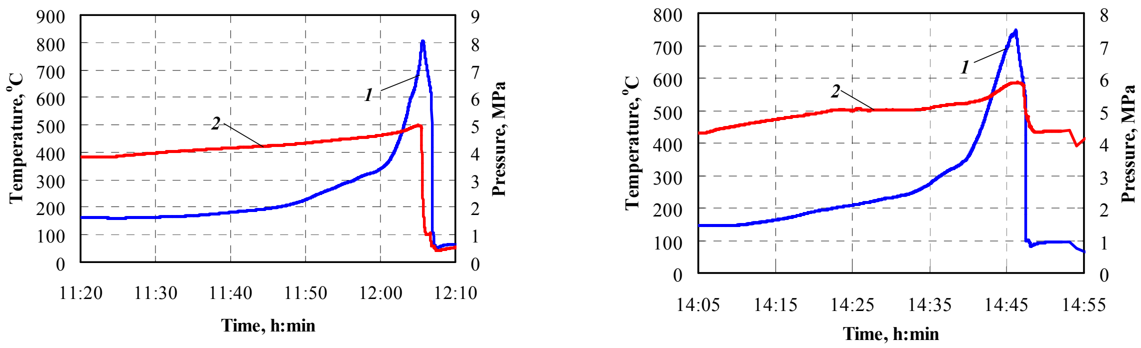
The electric heaters, installed in the TR, create an initial steam flow before the reactor is brought to power. The cladding temperature increases to (250-270) ^{o}C. Further, the fuel rod is heated at a given rate (2-3) K/s by increasing the reactor power. When the cladding temperature reaches a certain value, the reactor is shut down to subcritical conditions by the emergency protection rods, after which the RFR is rapidly cooled by (400-450)°C with increase in the water level in the TR. The last stage is the long cooling of the fuel rod.

III. RESULTS OF IN-REACTOR EXPERIMENTS AND POST-TEST EXAMINATIONS

In the MIR-LOCA/45 experiment (Ref. 1), the heating of the fuel cladding was carried out at a rate of (3.0-3.5) °C/s until evidence of a cladding leakage as indicated by the pressure transducer readings and completed shortly after the cladding leakage by shutting down the reactor and increasing the water level in the TR at a rate of (0.1-0.3) m/s. The maximal cladding temperature was 807°C. According to the gas pressure transducer readings (Fig. 3a), the fuel rod leakage occurred at a cladding temperature of (770-780)°C and a pressure difference on the cladding equal to 5 MPa. The pressure drop is extended in time that indicates a significant hydraulic resistance of the fuel core.

In the MIR-LOCA/63 experiment (Ref. 1) the fuel cladding was heated at a rate of (3.0-3.5) °C/s to a temperature of 750°C (Fig. 3b), after which the experiment was completed by shutting down the reactor with followed increasing the water level in the TR at a rate of (0.1-0.3) m/s. The maximal cladding temperature was 750 °C under pressure drop on the cladding of 5.8 MPa. According to the pressure transducer, the fuel rod retained its integrity that was confirmed in the PIE.

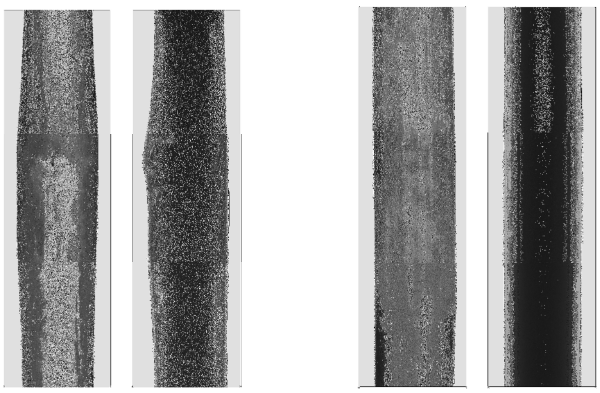
The fuel rod leakage in the MIR-LOCA/45 experiment and the maximal cladding diameter change in the MIR-LOCA/63 experiments occurred at the areas of the maximal calculated cladding temperature. Photos of these areas are shown in Figure 4.



a) b)

Fig. 3. Time variation of the cladding temperature (1) by (10-20) mm above the central spacer grid and the gas pressure (2) in the lower free volume of the fuel rod in the in-reactor experiments MIR-LOCA/45 (a) and MIR-LOCA/63 (b).

The change in the diameter of the cladding along the length of the tested fuel rods has shown a significant effect to the cladding deformation by the spacer grids, it is formation of local minima in the MIR-LOCA/63 fuel rod profilogram and the curve bend of the cladding diameter change in the fuel rod profilogram MIR-LOCA/45 (Fig. 5).



a) b)

Fig. 4. Appearance of the cladding and X-ray radiogram in the area of cladding destruction in the MIR-LOCA/45 experiment (a) and maximum deformation in the MIR-LOCA/63 experiment (b).
Note: * - X-ray radiogram MIR-LOCA/45 rotated 90º relative to the photo of appearance.

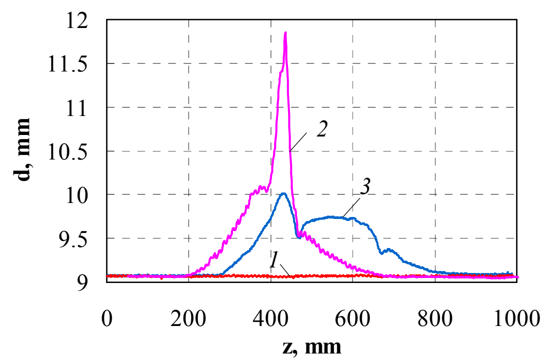


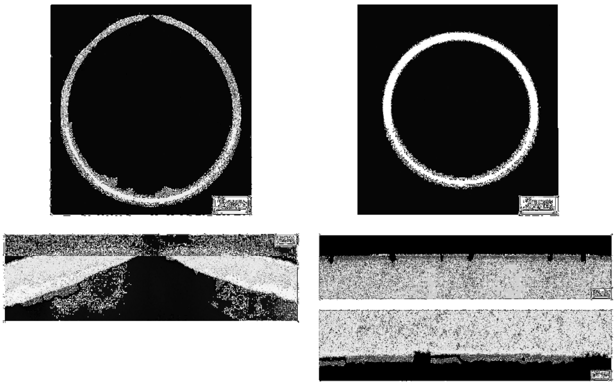
Fig. 5. Profilogram of the fuel rod cladding before the test (1) and MIR-LOCA/45 (2), MIR-LOCA/63 (3) fuel rod cladding after the test.

The cladding rupture in the MIR-LOCA/45 experiment occurred below the central spacer grid at a coordinate of 435 mm from the beginning of the fuel core of the fuel rod. The length of the formed rupture was 1.6 mm, the opening - 0.4 mm. The cladding rupture had a plastic character with a 100% thinning of the cladding before the rupture. Oxide layers on the outer and inner cladding surface, as well as the fragments of fuel that were on it, did not have a significant effect to its deformation

(Fig. 6). However, the storage of fuel fragments on the surface of the cladding more pronounced in the MIR-LOCA/45 fuel rod shows that deformation of the cladding can have an effect on the fragmentation of the outer layers of fuel.

Gamma scanning and X-ray radiography resulted there was no significant axial transfer of fuel. Redistribution of fuel fragments occurred only in the radial direction in areas of increased cladding deformation.

After the fuel rods were cut in the area of maximum cladding deformation, fuel was extracted from them. The extracted fragments with a size of less than 2.5 mm were scattered into fractions (Fig. 7). In both cases, the fraction of fines with a particle size comparable to the maximum opening of the MIR-LOCA/45 fuel cladding is small in the fuel composition.



a) b)

Fig. 6. Structure of the fuel cladding envelope MIR-LOCA/45 (a) in the section of strain rupture and MIR-LOCA/63 (b) in the cross section of its maximum deformation.

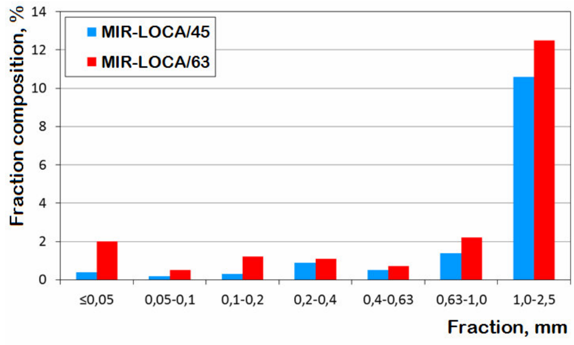


Fig. 7. Fractional composition of extracted fuel.

Based on the results of certification of the initial and refabricated fuel rods, as well as the results of post-test studies, factors that can influence the deformation of the cladding under LOCA conditions are determined:

- the high hydraulic resistance of the fuel rod column with pellets without a central hole at a burnup sufficient to close the fuel-cladding gap can significantly limit the flow of gas to the heated section of the fuel rod, retarding the deformation of the cladding by the pressure of the filling gas;

- tight adhesion of the cladding to the fuel core, which is manifested in the preservation of fuel fragments on the inner surface of a substantially deformed cladding, can hinder the separation of the cladding from the fuel;

- the presence of an oxide layer on the outer and inner surfaces of the cladding has a deterrent effect on the deformation of the surface layers of the cladding. The localization of the surface deformation of the cladding on the sections of the cracks in the oxide layers can accelerate the onset of the formation of a concentrated deformation of the cladding, accelerating its rupture.

IV. CONCLUSIONS

In the loop channel of the MIR reactor were performed experiments MIR-LOCA/45 и MIR-LOCA/63. The purpose of the experiments was to obtain data on the behavior of fuel rods under the loss of coolant accident, including cladding deformation, leakage parameters, fragmentation, displacement and dispersion of fuel.

The maximal cladding temperature achieved in the MIR-LOCA/45 experiment made up 807°C and the one achieved in the MIR-LOCA/69 made up 750°C. According to the gas pressure gage readings in the MIR-LOCA/45 experiment, the RFR lost its integrity at (770-780)°C and pressure drop 5 MPa while in the experiment MIR-LOCA/69 it remained leak-tight.

REFERENCES

1. A. V. ALEKSEEV, A. V. GORYACHEV, O. I. DREGANOV, A. L IZHUTOV, L. V. KIREEVA, I. V. KISELEVA, V. N. SHULIMOV, V. I. KUZNETSOV, V. V. NOVIKOV, A. V. SALATOV, P. V. FEDOTOV, "Investigation of VVER-1000 Fuel Rods Behavior under LOCA. MIR-LOCA/45 and MIR- LOCA/69 Experiments," *Proceedings of JSC "TVEL" Scientific Conference "New Generation Nuclear Fuel for NPPs"*, Moscow, Russia, November 16-17, 2016.