# State of the VVER-1000 Spent U-Gd Fuel Rods Based on the Results of Post-Irradiation Examinations

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**Key words**: the VVER-1000 reactor, U-Gd fuel rod, fuel rod, dimensions, fuel

The present paper is devoted to post-irradiation examinations (PIE) of U-Gd fuel rods with different geometry of the fuel pellets irradiated as part of the VVER-1000 fuel assembly. As evidenced by their PIE data, they did not exhaust their service life based on the main parameters (geometrical dimensions, corrosion state, and release of fission product gases).

## 1. Introduction

Nowadays fuel rods with embedded in fuel matrix absorber (gadolinium) are used to compensate the excess reactivity in addition to boron concentration control in the reactor coolant and adjustment of heat generation rate over the cross-section of the reactor core.

JSC “SSC RIAR” performed post-irradiation examinations of Gd-contained fuel rods with different geometry of the fuel pellets (the pellet with an outer diameter of 7.57mm and 7.60mm) ranging in burnup 1365 MW·d/kgU and 30–60 MW·d/kgU, respectively.

## 2. Results of Post-Irradiation Examinations

### 2.1. Geometrical Dimensions

Fuel rods exhibit changes in their geometry (a change in diameter and length) during their operation in the reactor. This process can be divided into two stages. The fuel cladding diameter tends to decrease while its length increases due to radiation-thermal creep and radiation –induced growth at the first stage from the very beginning of irradiation and until the fuel-to-cladding gap becomes closed. At the second stage ridges are formed on the cladding after the fuel comes in contact with the cladding (local changes of the cladding diameter whose period is equal to the fuel pellet height) and further increase of fuel burnup originates the stage of reverse cladding strain (the cladding diameter increase due to fuel swelling). In this case, amplitude of the cladding length change reducers and depends on fuel swelling to a great extent.

The use of pellets with increased diameter and, as consequence, smaller fuel-to-cladding gap in the initial condition provokes the interaction between the fuel pellet stack and the cladding at earlier stage. By way of illustration Fig.1 provides profile diagrams of Gd-contained fuel rods with different geometry of the fuel pellets at different burnup. The analysis of data on the cladding diameter change within the examined burnup range (Fig. 2a, b) revealed that the formation of ridges on the claddings of Gd-contained fuel rods with the fuel pellet with an outer diameter of 7.60mm starts at a burnup of 30 MW·d/kgU while the Gd-contained fuel rods with the pellet with an outer diameter of 7.57mm showed the evidence for their formation at a burnup of 40 MW·d/kgU. However, differences in the height of these ridges are insignificant with increased burn-up. The reverse cladding strain can be observed at a fuel burnup of 35 MW·d/kgU in the Gd-contained fuel rods with the pellets of increased diameter and it can reach 46μm at a burnup of 61 MW·d/kgU. However, the Gd-contained fuel rods with the pellets of standard design show evidence of reverse cladding strain at higher burnups (50 MW·d/kgU) and it can be 27μm at a burnup of 65 MW·d/kgU.

Figure 2 (c,d) demonstrates the height of ridges and reverse cladding strain in relation to fuel burnup [1]. The comparison of experimental data on fuel rods and Gd-contained fuel rods revealed that the trend of the ridges height increase with increased burnup was almost the same and it did not depend on the size of the pellet. The reverse cladding strain is higher for the Gd-contained fuel rods compared to the fuel rods at equitable burnups (provided that the pellets are of the same size).

Elongation of the Gd-contained fuel rods with an outer diameter of fuel pellets 7.57mm and 7.60mm averaged over the fuel assembly reach 20mm and 18mm, respectively (Fig. 3). Shown here are also elongation data of the fuel rods for comparison purposes [1].

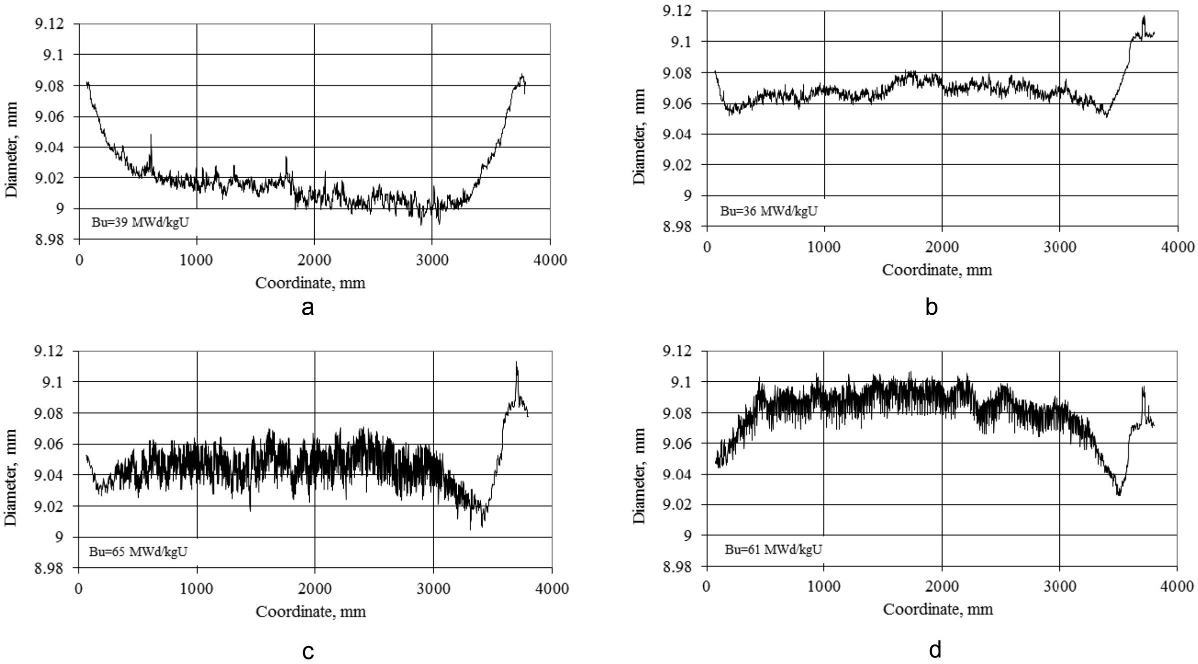


**Figure 1. Profile diagrams of Gd-contained fuel rods with different geometry of the fuel pellets a, c – pellet with outer diameter 7.57 mm; b, d –pellet with outer diameter 7.60 mm**

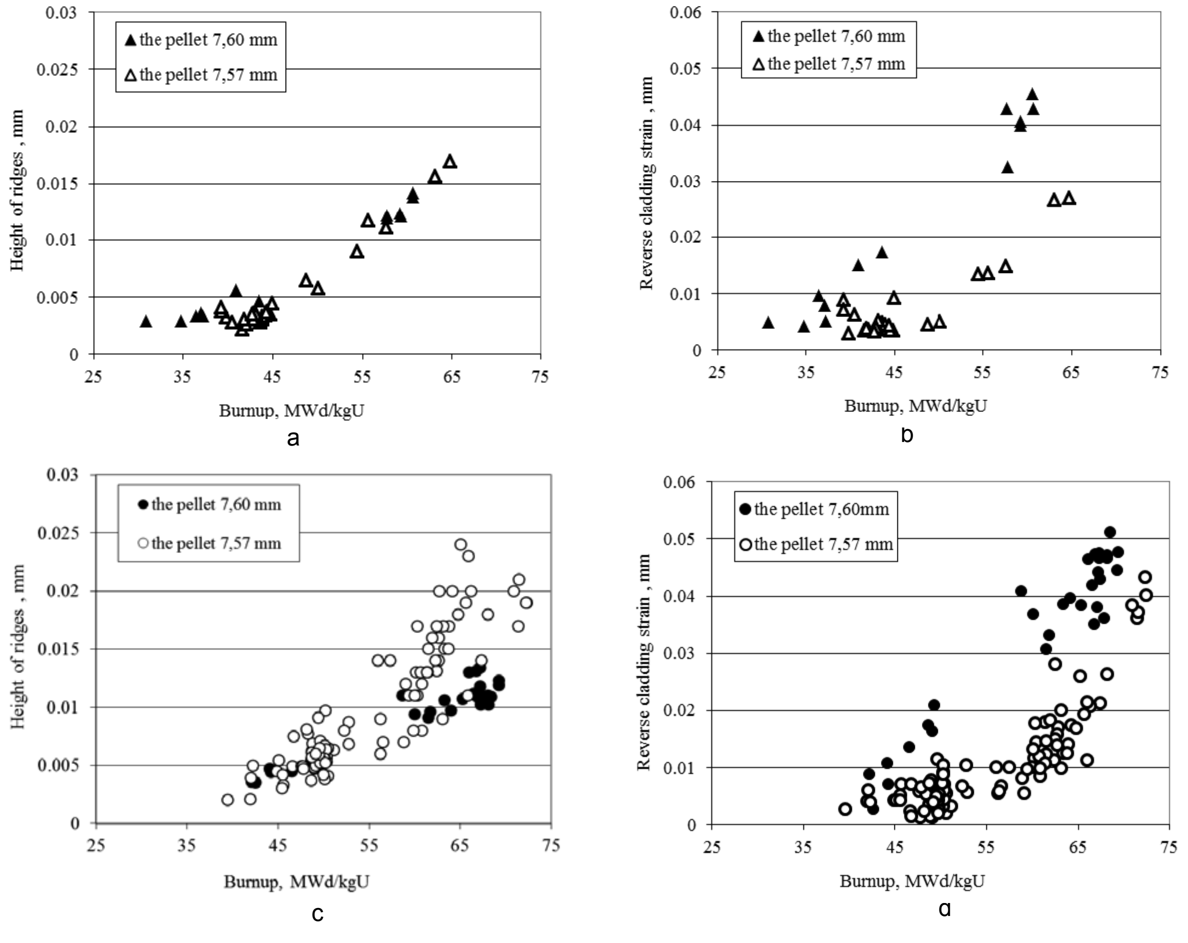


**Figure 2. Average height of ridges (a, c) and average reverse cladding strain (b, d) of Gd-contained fuel rods (a, b) and fuel rods (c, d)**

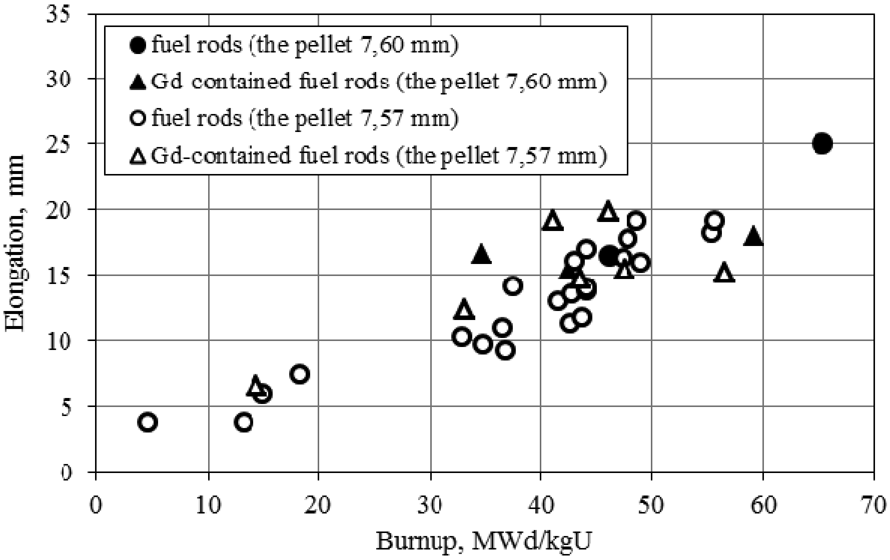
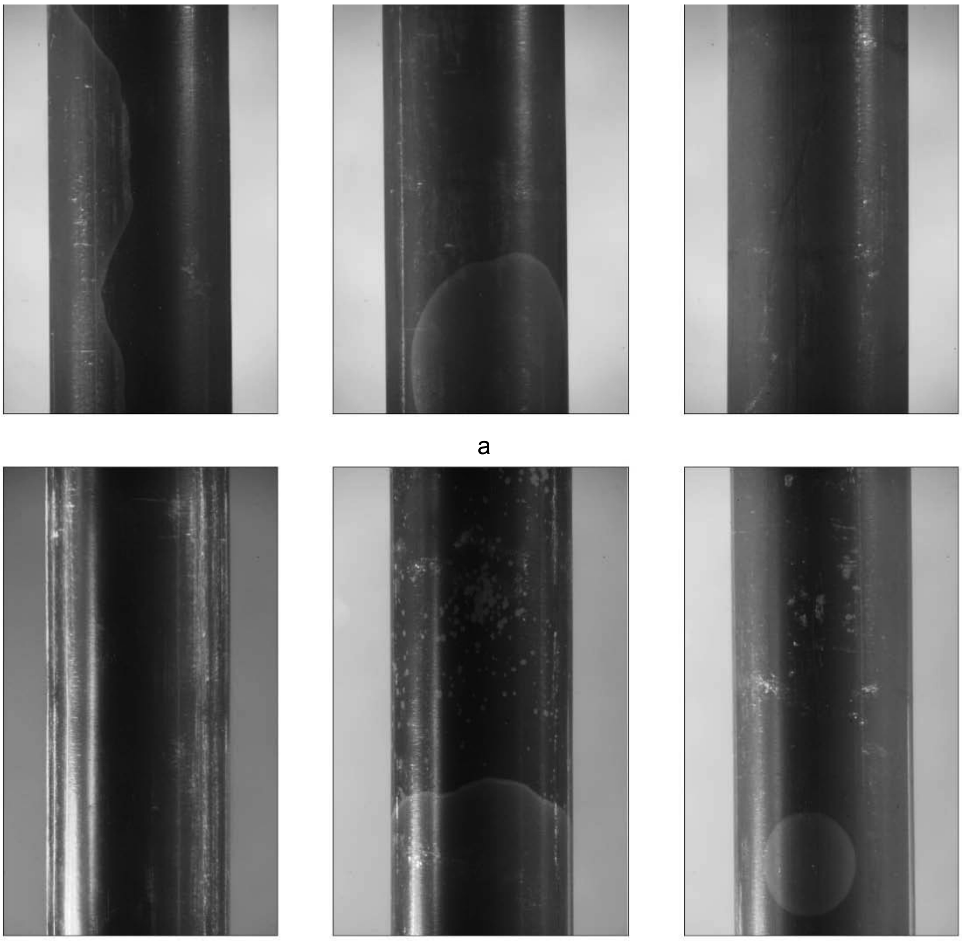


**Figure 3. Elongation of Gd-contained fuel rods and fuel rods with different geometry of the fuel pellets**



b

**Figure 4. Cladding outer appearance of the Gd-contained fuel rods with different geometry of the fuel pellets**
**a –pellet with outer diameter 7.57mm,**
**burnup 65 MW·d/kgU,**
**b –pellet with outer diameter 7.60mm,**
**burnup 61 MW·d/kgU**

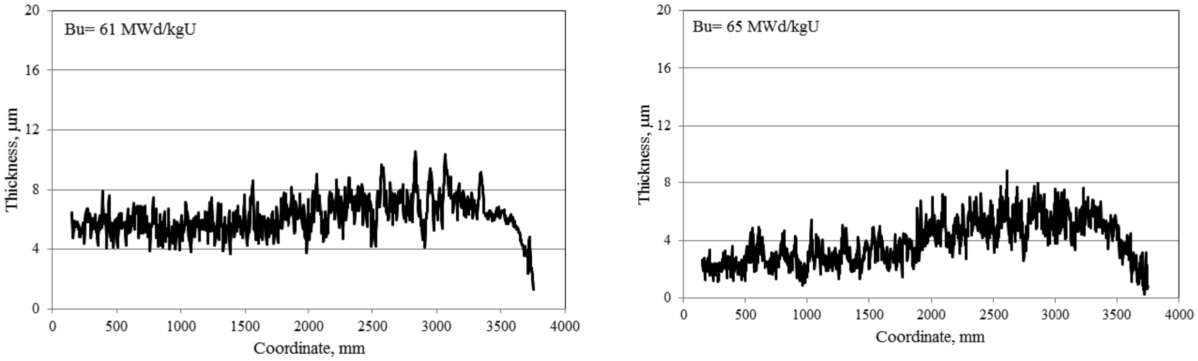
## 2.2. Cladding Condition

No differences were found in the condition of the claddings of the Gd-contained fuel rods with different geometry of the fuel pellets as well as compared with fuel rods [1]. The outer surface was dark grey with faint oxide places (Fig. 4). The oxide film becomes thicker with the higher elevation and attains its highest value at Z=3000-3200mm (Fig. 5). Further the oxidation degree becomes lower. According to the eddy current measurement data, the maximum thickness of the oxide layer does not exceed 14µm. As to the metallographic examination, this value is equal to 8µm (Fig.6).

When there was a tight contact between fuel and the cladding, the oxide film was continuous on the inner surface over the entire perimeter and its thickness did not exceed 12µm (Fig. 6). Hydrogen content in the cladding was no higher than 0.01% within the examined burnup range.

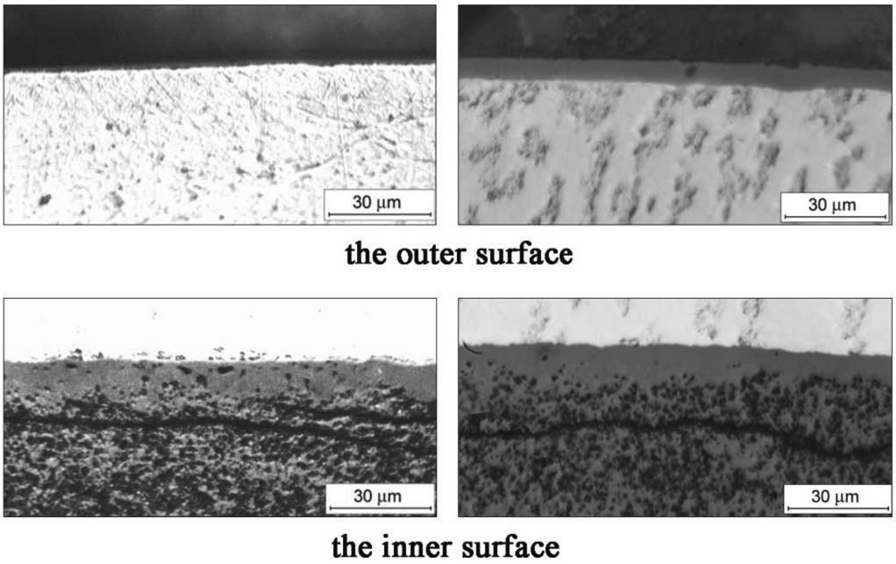
## 2.3. Fuel Condition and Fission Gas Release

Shown in Fig. 7 is the fuel microstructure at the cross-section of the Gd-contained fuel rods with different geometry of the fuel pellets. The pellets were pre-



a b

**Figure 5. Profiles of the oxide thickness change along the length of the Gd-contained fuel with different geometry of the fuel pellets**
**a – pellet with outer diameter 7.57mm, b – pellet with outer diameter 7.60 mm**

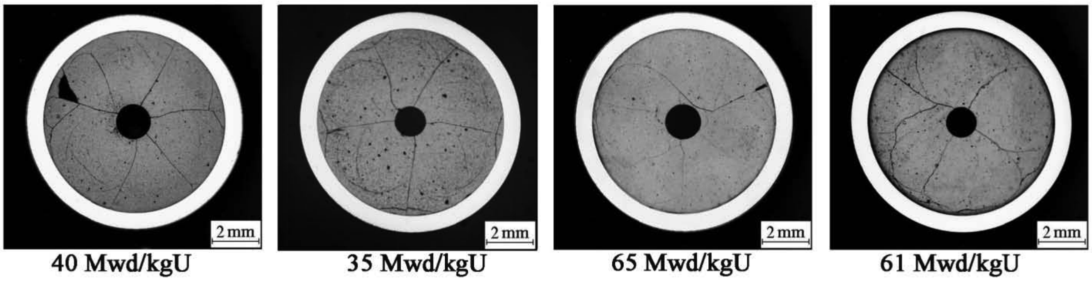


a b

**Figure 6. Oxide film appearance on the inner and outer surfaces of the Gd-contained fuel rods with different geometry of the fuel pellets**
**a – pellet with outer diameter 7.57 mm, burnup 65 MW·d/kgU, Z=2680 mm;**
**b – pellet with outer diameter 7.60 mm, burnup 61 MW·d/kgU, Z=3150 mm**

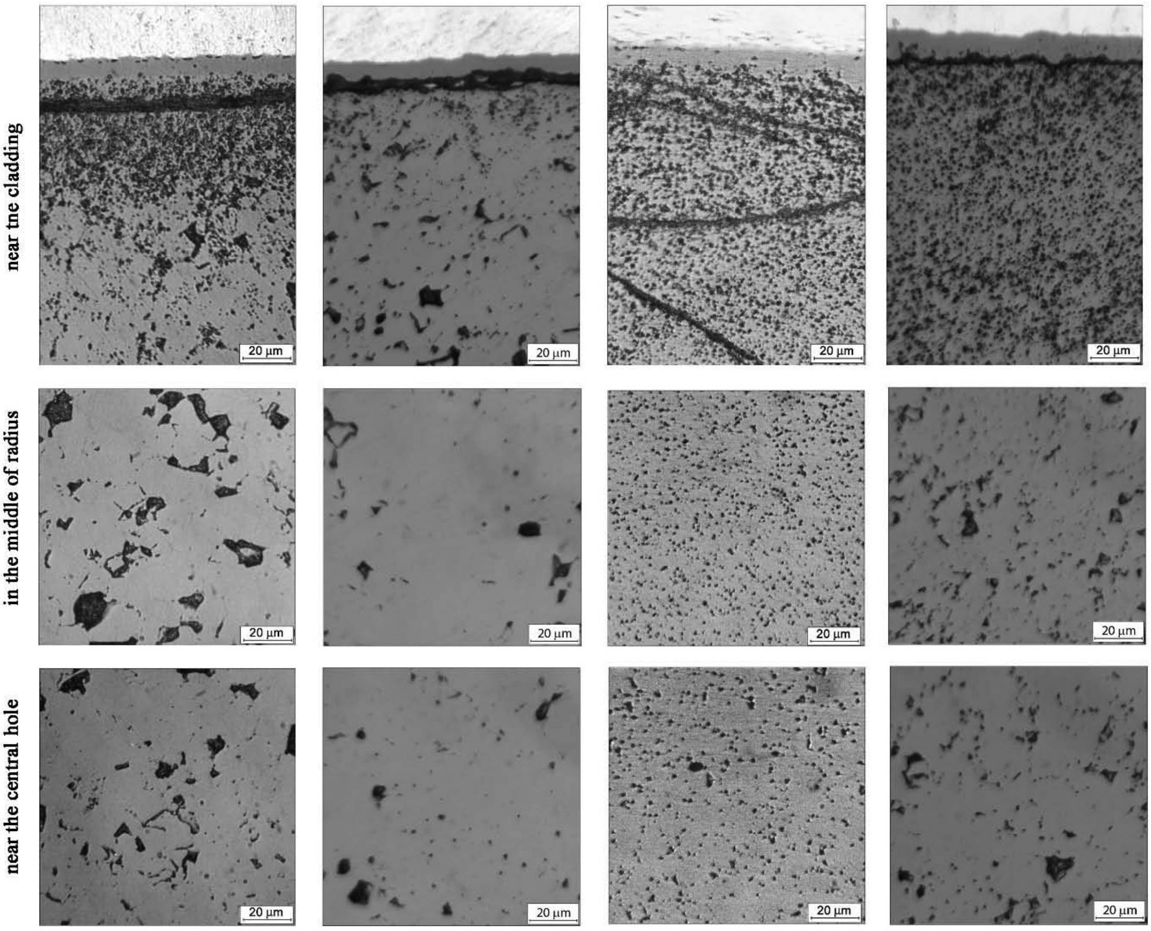
dominately fractured into fragments by radial cracks with the exception of peripheral layer that both the radial and tangential cracks were visible (Fig. 7). Displacements of pellet fragments and changes in the diameter of the central hole were not observed.

Figure 8 demonstrates fuel microstructure. Noticeable changes in the structure, which manifested themselves as increased porosity, were observed in the peripheral layer at a burnup of 40 MW·d/kgU. There was no evidence of changes in concentration of pores along the radius. The distribution of pores is inhomogeneous within the burnup range of 60-65 MW·d/kgU. The concentration of pores is the highest close to the cladding but it



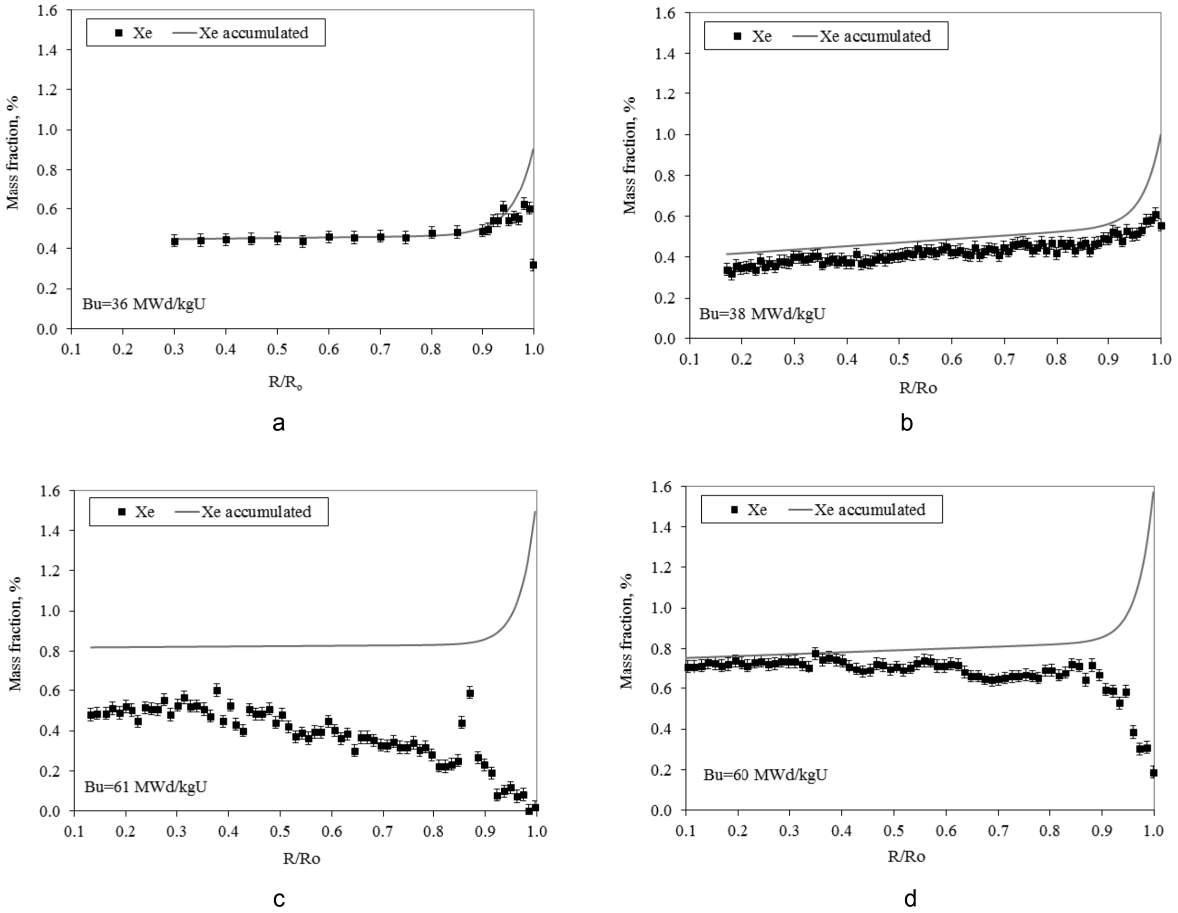
a b c d

**Figure 7. Fuel macrostructure in the Gd-contained fuel rods**
**a, c – pellet with outer diameter 7.57mm, b, d – pellet with outer diameter 7.60mm,**



a b c d

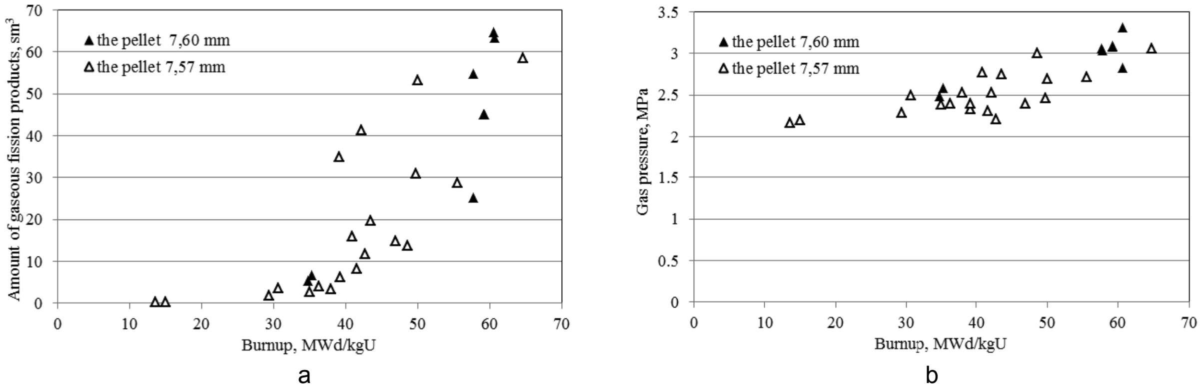
**Figure 8. Fuel microstructure at the cross section of the Gd-contained fuel rods with different geometry of the fuel pellets**
**a, c - pellet with outer diameter 7.57mm; b, d - pellet with outer diameter 7.60mm**



a b

c d

**Figure 9. Distribution of xenon accumulated and measured (in the fuel matrix) along the fuel pellet radius in the Gd-contained fuel rods with different geometry of the fuel pellets a, c - pellet with outer diameter 7.57mm; b, d - pellet with outer diameter 7.60mm**



a b

**Figure 10. Quantitative profile of gaseous fission products (a) and gas pressure (b) under the cladding of Gd-contained fuel rods**

tends to decrease as approaching the central hole. The metallographic examination data correlate with the EPMA data. Shown in Fig. 9 is the xenon profile along the pellet radius (it was measured in the fuel matrix and estimated with due account for neodymium accumulation). Its concentration in the matrix tends to decrease from the central hole towards the cladding. The obtained experimental data show evidence for propagation of restructured area from the pellet edge towards the center.

The differences in release of gaseous fission products from fuel under the cladding for the Gd-contained fuel rods with different geometry of the fuel pellets are not significant. Xenon and krypton were accumulated in the amount of 65cm$^3$ (the pellet with an outer diameter of 7.60mm, burnup 61 MW·d/kgU) and 59cm$^3$ (pellet with an outer diameter of 7.57mm, burnup 65 MW·d/kgU) (Fig. 10a). The gas pressure did not exceed 3.3 and 3.1MPa (Fig. 10b).

## 3. Conclusion

As evidenced by the PIE data, the Gd-contained fuel rods with different geometry of the fuel pellets did not exhaust their service life based on their main performance parameters (geometrical dimensions, corrosion state, and release of fission product gases).

The use of pellet with increased diameter caused fuel-cladding interaction at earlier stages in the Gd-contained fuel rods pellet with outer diameter 7.57mm as opposed to the Gd-contained fuel rods pellet with outer diameter 7.60mm. However, the cladding diameter change did not reveal any exceed in deformation criterion.

## References:

[1] Strozhuk A.V., Zvir E.A., Zhitelev V.A., Polenok V.S., Sidorenko J.G., Shevlyakov G.V., Kobylyansky G.P., and Volkova I.N.. Results of Post-Irradiation Examinations of the VVER-1000 Fuel Assembly with Higher Uranium Content. International Scientific Workshop Meeting “Operating Experience of the Russian Nuclear Fuel in the VVER-1000 Reactor”, October 20-24, 2014, Kolontaevo