Specific features of the determination of the pellet-cladding gap of the fuel rods by non-destructive method

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Abstract. This report describes the specific features of determining the pellet-cladding gap of the irradiated WWER-1000 fuel rods by nondestructive method. The method is based on the elastic radial deformation of the cladding up to its contact with the fuel. The value of deformation of cladding till its contacting fuel when radial force changes from F_{max} to 0 is proposed as a measuring parameter for determination of the diametrical gap. Because of the features of compression method, the obtained gap value is not analog of the gap measured on micrograph of the fuel rod cross-section. Results of metallography can provide only qualitative evaluation of its method efficiency. Comparison of the values determined by non-destructive method and metallography for WWER-1000 fuel rods with burnup from 25 to 55 MWd/kg U testified that the results of compression method can be used as a low estimate of the pellet-cladding gap value.

1. GAP MEASUREMENT SYSTEM

The principle of the gap measurement is described in the paper by R. Manzel [1]. This so-called "compression method has been known for more than 20 years and is used in many research laboratories, including RIAR [2] Fig.1 presents the scheme of the facility of the fuel-cladding gap measurement by the compression method.

The system of a loading fuel rod is pneumatic. The piezoelectric force transducer with high rigidity (~ 2000 N/μm) is used as an immovable support for the fuel rod. The length of the loading zone is 20 mm that covers two or three fuel pellets. The diametrical gap value from 0 to 110 μm is measurable. The maximum force appled to the cladding does not exceed 1200 N.

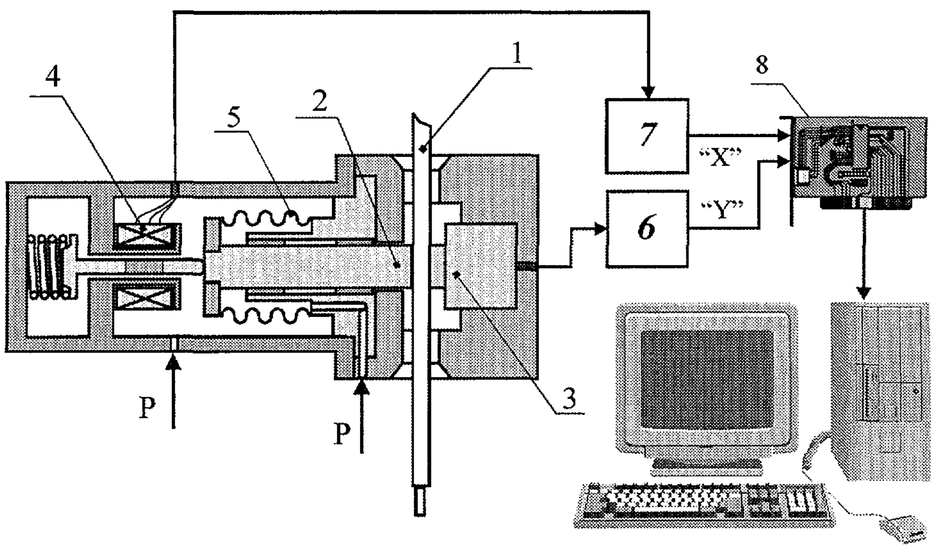


FIG.1. Schematic representation of the gap measurement facility: 1-fuel rod; 2-loader rod; 3-piezoelectric force transducer; 4-LVDT; 5-silphon; 6-charge amplifier; 7-normalizing amplifier; 8-analog/digital converter (ADC).

More than 150 fuel rods have been examined at the facility to date. Based on the gained data and the operating experience it's possible to indicate some advantages of this method:

- high efficiency (measurement of the fuel-cladding gap with step 50–100 mm along the length of the WWER-1000 fuel rod takes no more than 1.5 h);
- possibility of obtaining statistically reliable data on distribution of the gap along the fuel rod length. In this case, the number of the measurement points compensates the possibly low accuracy of the gap measurement in one point;
- possibility of performing the measurements before and after irradiation of the fuel rods in the reactor, and comparison of their results. It provides qualitatively new data on fuel behavior under various operating conditions.

But for the correct application of the results of the compression method the most important is a question of the measurement accuracy, and how these results correlate with the gap values measured by the traditional methods of optical metallography. The investigation of the facility characteristics using special rod test samples is not sufficient for the estimation of the gap determination accuracy for the irradiated fuel rods. Reasons of appearance of an additional error can be (Fig.2):

- misalignment of the fuel pellets relation to each other and to the cladding;
- nonuniform distribution of the gap both in limits of one cross-section, and on the height of the pellets;
- fragmentation of the fuel pellets;
- formation of oxides and deposits on the cladding surface, change of the fuel porosity etc., causing the rigidity change of the fuel-to-cladding system.

Because of the enumerated factors, the diagram of the loading irradiated fuel rod considerably differs from the diagrams obtained on the test samples.

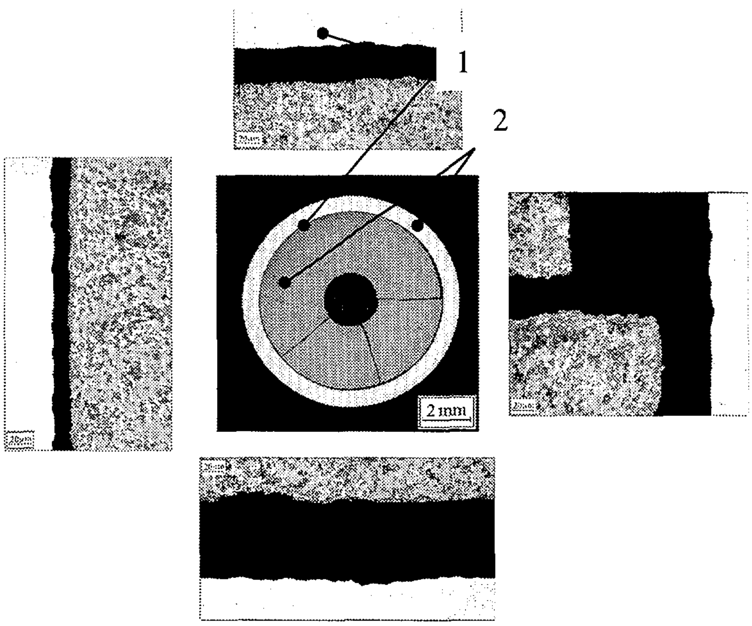


FIG. 2. Micrograph of cross-section of the WWER-1000 fuel rod: 1-cladding, 2-fuel.

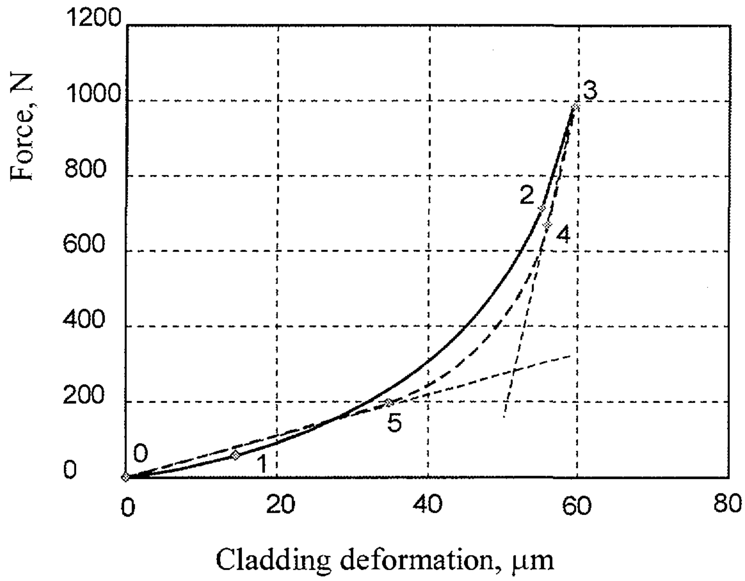


FIG .3. Typical „force-deformation" diagram of the rod loading of the WWER fuel rod: increase loading force, decrease loading force.

2. DETERMINING OF THE PELLET-CLADDING GAP ON THE „FORCE-DEFORMATION" DIAGRAM

Fig.3 presents a typical diagram of the WWER fuel rod loading pattern.

As a rule, the several linear parts can be distinguished on the loading diagram at the non-zero value of a cold gap.

The linear part 0-1 corresponds to the elastic deformation of the cladding before it's contact with the fuel. The length of the part 0-1 depends on a position of the fuel fragments relation to each other and to the cladding and can differ at one and the same diametrical gap value.

The part 2-3 corresponds to the cladding deformation when the pellet fragments are in a hard contact with the cladding.

The nonlinear cladding deformation dependence on the load for the part 1-2 is being explained by the displacement of the fuel fragments and the appearance of the local deformation of the cladding and fuel in the contact points.

As the displacement of the fuel fragments at the loading is irreversible, at decrease of load (curve 3-4-5-0) described above parts are clearly defined and width of the transient zone (part 4-5) decreases in comparison with the curve 0-1-2-3. The size of part 5-0 can be defined more exactly and the cladding rigidity, that determines the line slope on this part, can change slightly.

Therefore the deformation of cladding on the part 5-0 is used as a measuring parameter for determining of the pellet-cladding gap by compression method.

3. CORRELATION BETWEEN COMPRESSION METHOD AND METALLOGRAPHY

Let's consider the fuel rod segment *(a-b)*, which is deformed at measuring.
The diametrical gap values determined by the compression methods (δ_{ND}) and metallography (δ_{MG}) can be defined as:

$$\delta_{ND}(\varphi) = \min\{\delta_r(z,\varphi)\}_{(a,b)} + \min\{\delta_r(z,\varphi+\pi)\}_{(a,b)} \quad (1)$$

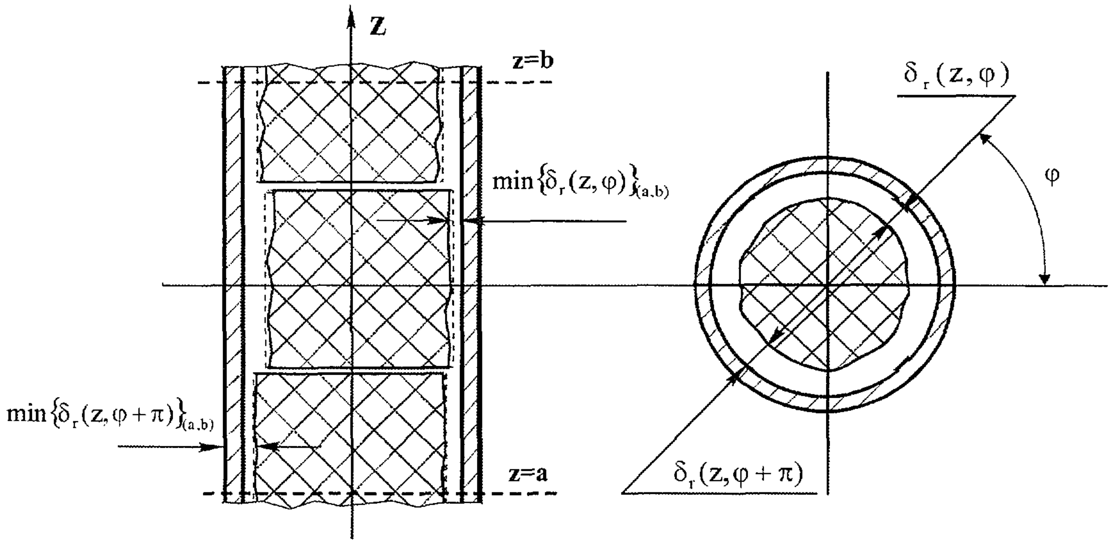
$$\delta_{MG}(z,\varphi) = \delta_r(z,\varphi) + \delta_r(z,\varphi+\pi) \; ; \quad (2)$$

$$\min\{\delta_{MG}(\varphi)\}_{(a,b)} = \min\{\delta_r(z,\varphi) + \delta_r(z,\varphi+\pi)\}_{(a,b)}; \quad (3)$$

where: $a \le z \le b$, $0 \le \varphi \le \pi$;

$\delta_r(z,\varphi)$, $\delta_r(z,\varphi+\pi)$ - radial gaps in section with the coordinate z in orientation φ ;

$min\{\delta_{MG}(\varphi)\}_{(a,b)}$ - minimum diametrical gap value determined by metallography for the segment *a-b* and orientation φ.



а б

FIG. 5. Schematic drawing of the fuel rod longitudinal (a) and cross-section (b): 1-cladding; 2-fuel pellets.

If the fuel fragments are immovable during the loading, the following equations should be true:

$$\delta_{ND}(\varphi) \;\le\; \min\{\delta_{MG}(\varphi)\}_{(a,b)} \;\le\; \delta_{MG}(z,\varphi), \quad (4)$$

In other words, for the orientation φ the gap value measured by the compression method should not exceed the value determined by metallography in the same orientation for any cross-section of the segment *a-b:*

$$\delta_{ND}(\varphi) \;\le\; \delta_{MG}(z,\varphi), \quad a \le z \le b \quad (5)$$

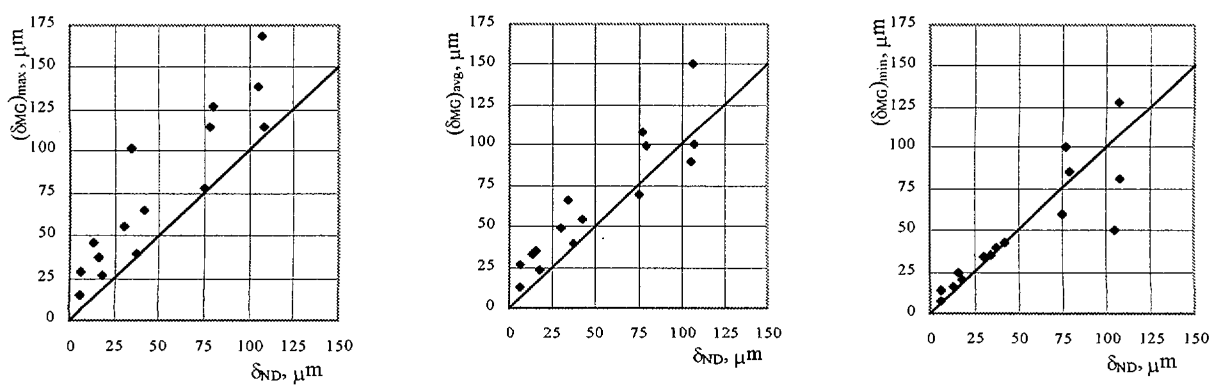
Due to the displacement of the pellets fragments during the loading, the value $\delta_{ND}(\varphi)$ should increase. In this case the equation (5) can be used for the experimental estimation of the effect of this factor on the measurement result.

Thus the compression method gives the value, which is an estimate of the minimum diametrical gap value for the segment *a-b* and orientation φ. Analysis of the accuracy of the compression method by the direct comparison with the results of the metallographic examination of one or several cross-sections, in view of different physical meaning of values, determined by these methods, is incorrect. Therefore only qualitative comparison of the metallography and the compression method results is possible. For this purpose fifteen cross-sections of the WWER-1000 fuel rods with burnup from 25 to 55 MWday/kgU were used — one for each segment of the rod, where the gap was determined by compression method in one arbitrary orientation. The diametrical gap on the micrograph was measured no less than in four orientations without considering the gaps between fuel fragments.

4. COMPARISON OF RESULTS OBTAINED BY COMPRESSION METHOD AND METALLOGRAPHY.

Fig.6 presents the comparison of the compression method results with the maximum, average and minimum gap values measured by metallography.

The comparison with the minimum gap value is most interesting (Fig. 6c). All the diagram points are split into two groups corresponding to the measured values of the gap δ_{ND} more or less than 50 μm. In spite of the fact that the compared data are not related to the azimuth coordinate, the points of the first group (δ_{ND} <50 μm) lie above the line of the equal values. For points of the second group (δ_{ND} >50 μm) the exceeding over the minimum values obtained on the cross-sections achieves 50 μm. This difference between the specimens of the first and second groups is explained by a different state of the fuel.



a) b) c)

FIG. 6. Comparison of the diametrical gap values determined by the compression method (δ_{ND}) with the maximum (a), average (b) and minimum (c) gap values measured by metallography: — line of equal values (δ_{ND}=δ_{MG}).

In the range of small values of the cold gap (the first group) the influence of the fuel fragmentation and initial non-uniform distribution of the gap is minimum. The difference between results of the methods does not exceed 10 μm for these specimens.

For the specimens of the second group the greater influence of fragmentation of fuel could be expected. At gap between the pellet fragments at 30–50 μm the value δ_{ND} should exceed $(\delta_{MG})_{avg}$ and should verge towards $(\delta_{MG})_{max}$. But this was not observed (Fig. 6 a,b). It seems the force of the loading (F_{max}=1200 N) was not sufficient in this case.
The described experimental data testify that the results of the compression method can be used as a low estimate of the pellet-cladding gap value at predicting the fuel rod performance.

5. APPLICATION OF THE COMPRESSION METHOD

As mentioned above, the advantages of the compression method is a high efficiency and the possibility obtaining statistically reliable data.

Fig.7 shows the cold diametrical gap values dependence on burnup. The data was obtained by the compression method on 67 WWER-1000 fuel rods with the maximum burnup from 22 to 57 MWday/kgU. The step of measurement along the fuel rod was 50–100 mm. The averaging of the diametrical gap values was performed in the range from 500 to 3000 mm. The average gap values determined by metallography for 20 cross-sections of the WWER-1000 fuel rods are presented in the same plot.

The line of least-squares trend for the compression method results crosses the vertical axis in the point $\delta_0 \approx 210\mu m$. This is in good agreement with the average value of the initial diametrical gap for the WWER-1000 fuel rods which equal to 225 μm [3].

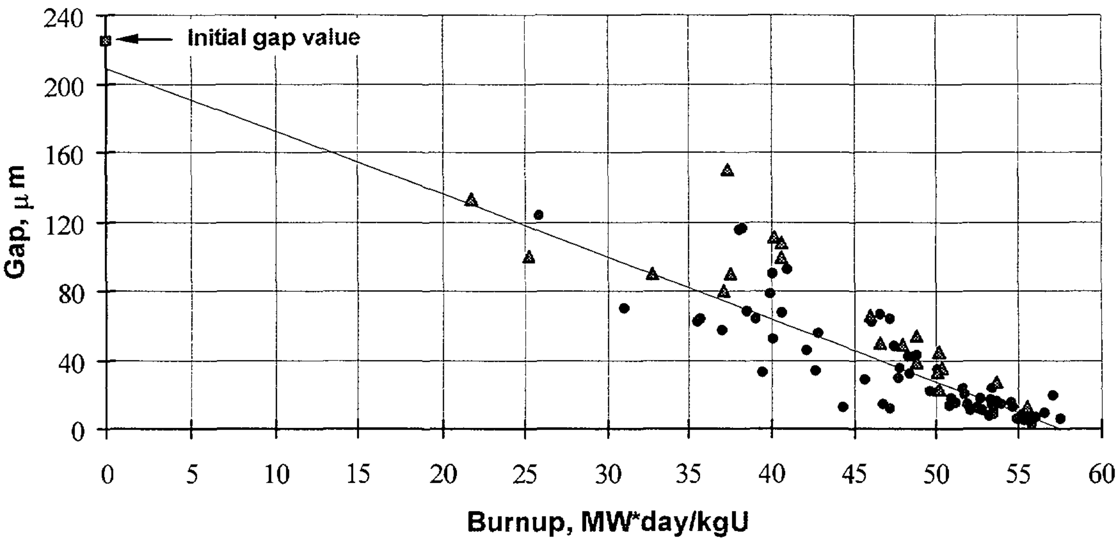


FIG. 7. The diametrical fuel-cladding gap dependence on burnup of the fuel rods:
- *gap values $(\delta_{ND})_{avg}$ determined by the compression method and averaged along the length of the WWER-1000 fuel rods;*

▲ *average values of the diametrical gap determined by metallography;*
the line of least-squares trend for the compression method results.

The gap values determined on the cross-sections, mainly, lie higher than trend line. It confirms the conclusion made before that the compression method provides a low estimate of the pellet-cladding gap value.

6. CONCLUSION

- Because of the features of the compression method, the obtained gap value is not analog of the gap measured on micrograph of the fuel rod cross-section. Therefore results of metallography can give only qualitative evaluation of the compression method efficiency.
- The comparison of the values determined by the compression method and metallography for the WWER-1000 fuel rods with burnup from 25 up to 55 MWday/kgU testifies that the results of the compression method can be used as a low estimate of the diametrical pellet-cladding gap value at predicting the fuel rod performance.

- In the range of the small gap values (<50 μm) the results of the compression method does not exceed the minimum diametrical gap values measured by metallograpfy. In the range of major gaps (> 50 μm) the compression method results approach to the average values of gap measured by metallography.

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