Change in Geometrical Parameters of WWER High Burnup Fuel Rods under Operation Conditions and Transient Testing

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1. Introduction

The degree of geometry variability of fuel rods (FR), cladding and fuel column is one of the most important characteristics of their serviceability. But on the other hand the geometrical parameters influence much on other FR characteristics such as fuel temperature, fission gas release, fuel-to-cladding interaction and cladding stress strained state as well as degree of interaction with the FA skeleton elements and skeleton rigidity.

The geometrical parameters of WWER-440 and WWER-1000 cladding and fuel column don't differ considerably as (they) delivered from the factory. The principal difference is the value of the central hole diameter. The central hole diameter for WWER-440 pellet is 1.2 mm and for WWER-1000 is 2.4 mm. More than that the outer diameter of the WWER-440 pellet is 7.59 mm at the initial state and as for the WWER-1000 pellet it is 7.55 mm [1]. At the same time the design operating conditions of WWER-440 and WWER-1000 fuel rods differ [2,3]: the average linear power is 129 and 167 W/cm^2, coolant temperature 312 and 335°C and coolant pressure 12.5 and 16 MPa for WWER-440 and WWER-1000, respectively. Coolant-fuel rod pressure difference is also higher for WWER-1000 core. So, the operation conditions for WWER-1000 fuel rods are severe.

Nevertheless, the post-irradiation examinations of WWER-440 and WWER-1000 fuel assemblies and fuel rods operated 3 fuel cycles under the design basis conditions don't reveal any considerable differences in the geometrical parameters changes in FR components. Rates of FR elongation, cladding diameter decrease, fuel column swelling are practically indistinguishable within the limits of statistical dispersion.

Differences in WWER-440 and WWER-1000 FR state become apparent at a burnup higher than 40 MWd/kgU that is the fourth year of operation. They were confirmed by the results of high burnup FR testing in the MIR reactor under transient conditions. The present report is dedicated to the peculiarities of geometrical parameters changes in WWER-440 and WWER-1000 claddings as well as fuel column at high burnups.

2. Operation Conditions

2.1. Subjects of Examination

The list of examined WWER-440 and WWER-1000 fuel assemblies those results were used as the base for conclusions is given in Tables 1 and 2. The grey colour is used for fuel assemblies, fuel rods of which were subjected to testing under transient conditions.

2.2. Change in Cladding Outer Diameter

It has been known that the outer diameter of WWER FR claddings decreases [4] because of coolant-fuel rod pressure difference and Zr-1%Nb alloy creep. The axial profile of the cladding outer diameter represents the axial distribution of neutron-flux density and temperature up to the moment of fuel-to-cladding contact. The maximum decrease of the cladding diameter was noticed in the central part of fuel rod. Difference (Δd_1) in the average diameters of the cladding in the region of gas plenum and maximum linear power one was taken to estimate the diameter decrease. Figure 1 demonstrates the change in difference according to the fuel burnup in WWER-440 and WWER-1000 fuel rods. As may be seen from the diagrams, the decrease in the cladding diameter for WWER-440 and WWER-1000 fuel rods follows nearly the same law up to burnups of 40-45 MWd/kgU. As for WWER-440 fuel rods, the cladding diameter stops decreasing at the burnups higher than 50 MWd/kgU. The data for this particular range of burnups are absent for WWER-1000 fuel.

The local changes in diameter of the cladding (so-called "ridgings") appear at a burnup of 40-45 MWd/kgU those spacing is a multiple of the fuel pellet length (that is an average of 11-12 mm). Such "ridgings" appear in the central part of fuel rod mainly. The height and number of "ridgings" noticed on the diagram of the outer diameter (Figure 2a) can be characterised by the periodogram peak amplitude (Figure 2b) that in its turn can be used as a qualitative characteristic of fuel-to-cladding interaction degree. Figure 2c shows the outer diameter profile for cladding in the central part of fuel rod provided with pellets having facets. The local changes in diameter are associated with the joints of fuel pellets. The minor decrease in the cladding diameter is noticed in the middle part of the pellet.

Figure 3 gives peak amplitude on the periodogram as a function of fuel burnup for WWER-440 and WWER-1000 fuel rods. All examined fuel rods are broken down into two groups: fuel rods equipped with the old type pellets (without facets) and fuel rods equipped with standard pellets (with facets). As may be seen from the diagrams, firstly, amplitude of peaks for WWER-440 fuel rods is 4 times more than for WWER-1000 fuel rods at the same fuel burnup. Secondly, the diagrams bear out the beneficial effect of facets on the mechanical fuel-to-cladding interaction for both types of fuel rods. According to the results of outer diameter analysis as well as results of metallographic study of WWER-1000 fuel rods operated under the design-basis conditions 4 fuel cycles show that the mechanical interaction between the fuel column and cladding is either at the initial stage or it is absent at all [5].

A change in stress sign in the cladding takes place in central part of WWER-440 fuel rods at higher burnups (>50 MWd/kgU) under the influence of swelling fuel column. The stresses gain the tensile character and the outer diameter of cladding begins increasing [3]. Thus for example, the number of fuel rods demonstrating the same effect is three times as much in WWER-440 fuel assembly operated 5 fuel cycles than in WWER-440 fuel assembly operated 4 fuel cycles under the same conditions. The maximum value of the reverse diametrical stress for fuel rods of this particular fuel assembly is no more than 30 μm.

Table 1. WWER-440 FA features

FA	NPP, Unit	Average burnup, [MWd/kgU]	Fuel pellet features	
			Initial enrichment on ^{235}U, [%]	Central hole diameter, [mm]
Д15687	NV NPP-4	24.2	3.6	1.2
Д52380	Kola NPP-2	27.62	3.6	1.4
Д11809	NV NPP -4	32.8	3.6	1.2
Д19159	NV NPP-4	34.1	3.6	1.2
Д11066	Rovno NPP-1	36.8	3.6	1.2
Д26135	NV NPP-4	38.1	3.6	1.2
E22198	Kola NPP-3	46.2	4.4	1.2
E22222	Kola NPP-3	48.2	4.4	1.2
Д35228	NV NPP-4	50.9	3.6	1.2

Table 2. WWER-1000 FA features

FA	NPP, Unit	Average burnup, [MWd/kgU]	Fuel pellet features	
			Initial enrichment on ^{235}U, [%]	Central hole diameter, [mm]
ЕД0623	Kalinin NPP-1	13.1	4.4; 3.6	2.4
ГВБ0068	NV NPP-5	21.7	2.4; 3.0; 3.3	1.4
Г0007	NV NPP-5	32.7	3.3	1.4
Г1562	Kalinin NPP-1	32.9	3.3	2.4
Г1565	Kalinin NPP-1	34.7	3.3	2.4
Г2149	Kalinin NPP-2	36.5	3.3	2.4
В0106	S-Ukrainian NPP-1	36.7	3	1.4
E1591	Balakovo NPP-3	41.4	4.4	2.4
ЕД1476	Balakovo NPP-2	42.5	4.4; 3.6	2.4
ЕД2077	Rovno NPP-3	43.6	4.4; 3.6	2.4
E0328	Zaporozhie NPP-1	44	4.4	2.4
E0329	Зап. АЭС-1	44	4.4	2.4
ЕД1114	NV NPP-5	44.7	4.4; 3.6	2.4
ЕД4108	NV NPP-5	46.2	4.4; 3.6	2.4
E0325	Зап. АЭС-1	48.9	4.4	2.4

2.3. Fuel Column Swelling

The change in volume swelling of the fuel column is studied adequately [3,5] up to fuel burnups of 63 MWd/kgU (WWER-440) and 50 MWd/kgU (WWER-1000). It is revealed that the rate of fuel swelling for WWER-440 and WWER-1000 fuel rods in the first linear approximation differs insignificantly. It is ~0.6% per 10 MWd/kgU. Based on fuel sintering through at the initial stage of operation (0.2-0.5% of the initial volume) this coefficient take on a value of 0.8% per 10 MWd/kgU over the range of 30 to 65 MWd/kgU (Figure 4).

2.4. Change in Fuel-to-Cladding Gap

The diametrical fuel-to-cladding gap was measured with the use of compression technique [6]. The gap measurement is in error of ±10 μm. The distinctive features of the technique didn't make it possible to measure the diametrical gap over 130 μm. The axial distribution of fuel-to-cladding gap demonstrates the largest decrease of the gap in the region 500 to 2000 mm for WWER-440 fuel rods. As for WWER-1000 fuel rods, the largest decrease is noticed in the region 500 to 3000 mm from the lower part of the fuel rod. Figure 5 demonstrates the simultaneous axial distribution of the outer diameter and fuel-to-cladding gap of WEER-440 and WWER-1000 fuel rods. The average gap was found for each fuel rod in the above-mentioned regions. The average fuel-to-cladding gap as a function of fuel burnup is given in Figure 6. The figure confirms the disappearance of fuel-to-cladding gap at a burnup of 42-45 MWd/kgU for WWER-440 fuel rods and 47-50 MWd/kgU for WWER-1000 fuel rods.

2.5. Fuel Rod Elongation

The cladding material creep in WWER fuel rods together with the radiation growth result in FR cladding elongation. Figure 7 gives the specific elongation of WWER-440 and WWER-1000 fuel rods as a function of average fuel burnup. All fuel rods are broken down into two groups: a) fuel rods, where fuel contact with cladding was absent during the whole period of operation; b) fuel rods, where fuel contact with cladding was noticed at the final stage of operation. Two techniques were used for contact finding that are the compression technique and deformation markings of local strain noticed on the outer diameter diagram. But it was assumed that if the average gap is less than 12 μm in the middle part of fuel rod in the cold state, such fuel rod had a tight fuel contact with cladding at the operating temperature. According to the comparison of pictures the elongation rate for WWER-440 fuel rods is slightly higher as of WWER-1000 fuel rods. So WWER-440 fuel rods elongate by 0.45% and WWER-1000 fuel rods by 0.4% at a burnup of 50 MWd/kgU. More than that the pictures demonstrate that fuel rods operated under the conditions of fuel contact with the cladding elongate to the greater degree than fuel rods, where the contact was absent. The only exception is the peripheral fuel rods in FA E22222, where the elongation was less in comparison with fuel rods in FA Д35228 in spite of the presence of fuel-cladding contact. The fuel burnup was the same. According to the analysis all fuel rods of this particular group were equipped with claddings making one lot and mechanical properties of claddings in this lot were

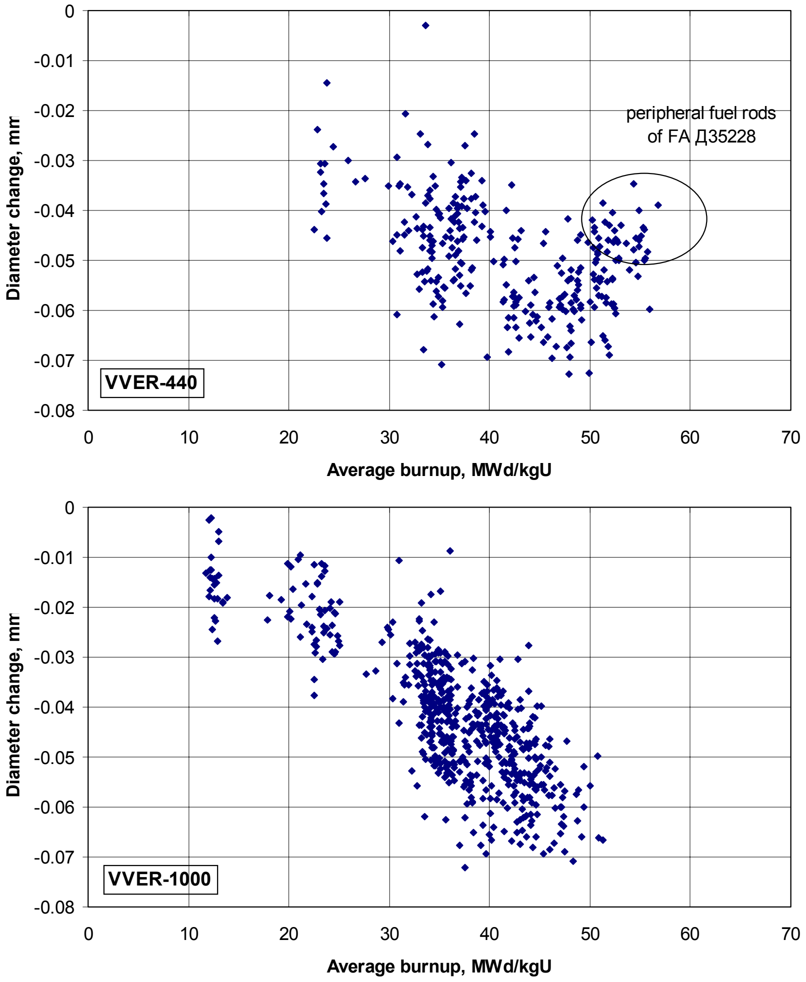


Figure 1. WWER cladding outer diameter change vs. fuel burnup

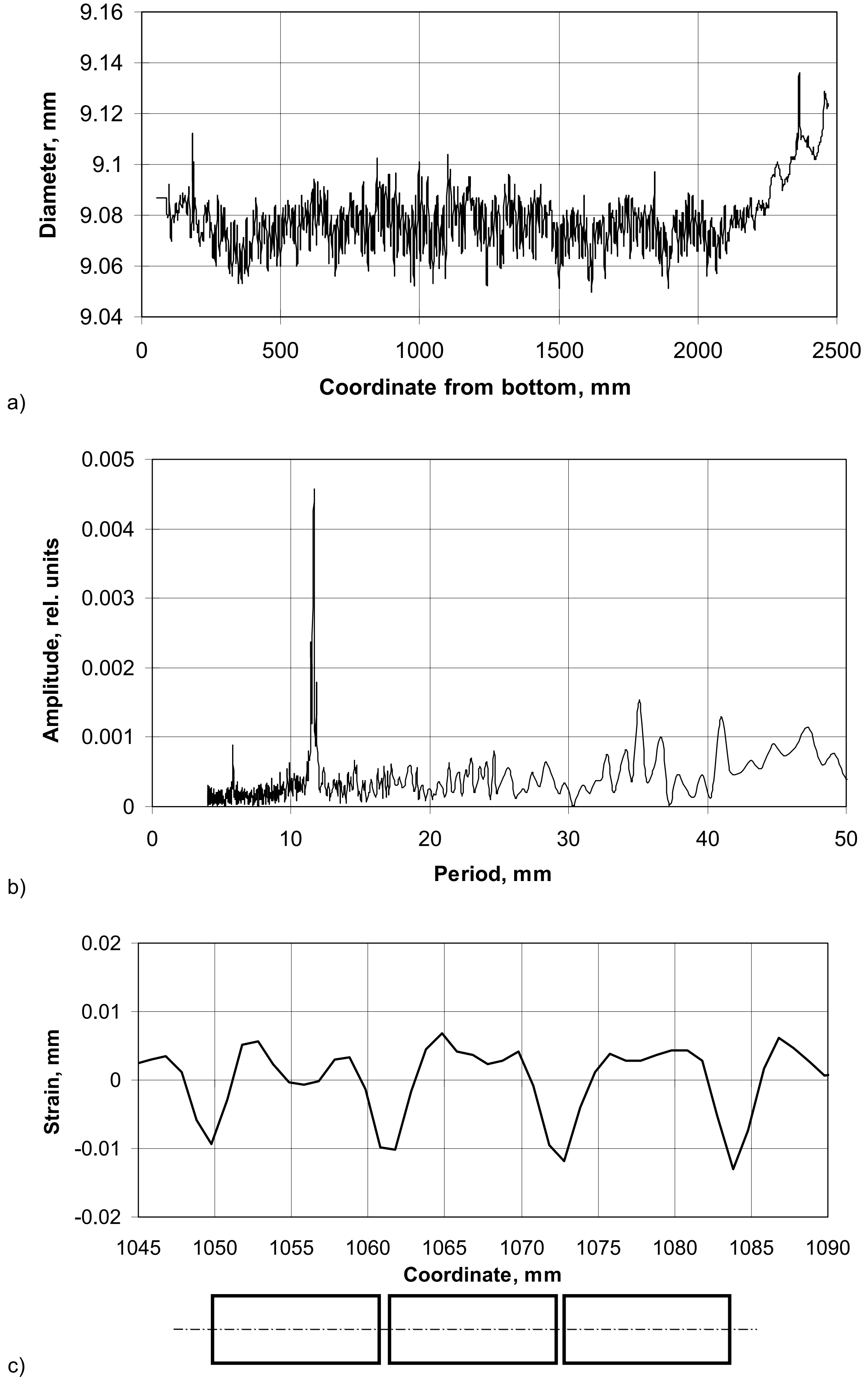


Figure 2. a) Cladding outer diameter profile of WWER-440 fuel rod after 4 fuel cycles; b) Cladding outer diameter periodogram of WWER-440 fuel rod after 4 fuel cycles; c) Cladding local strain of WWER-440 fuel rod at maximal linear power area after 4 fuel cycles

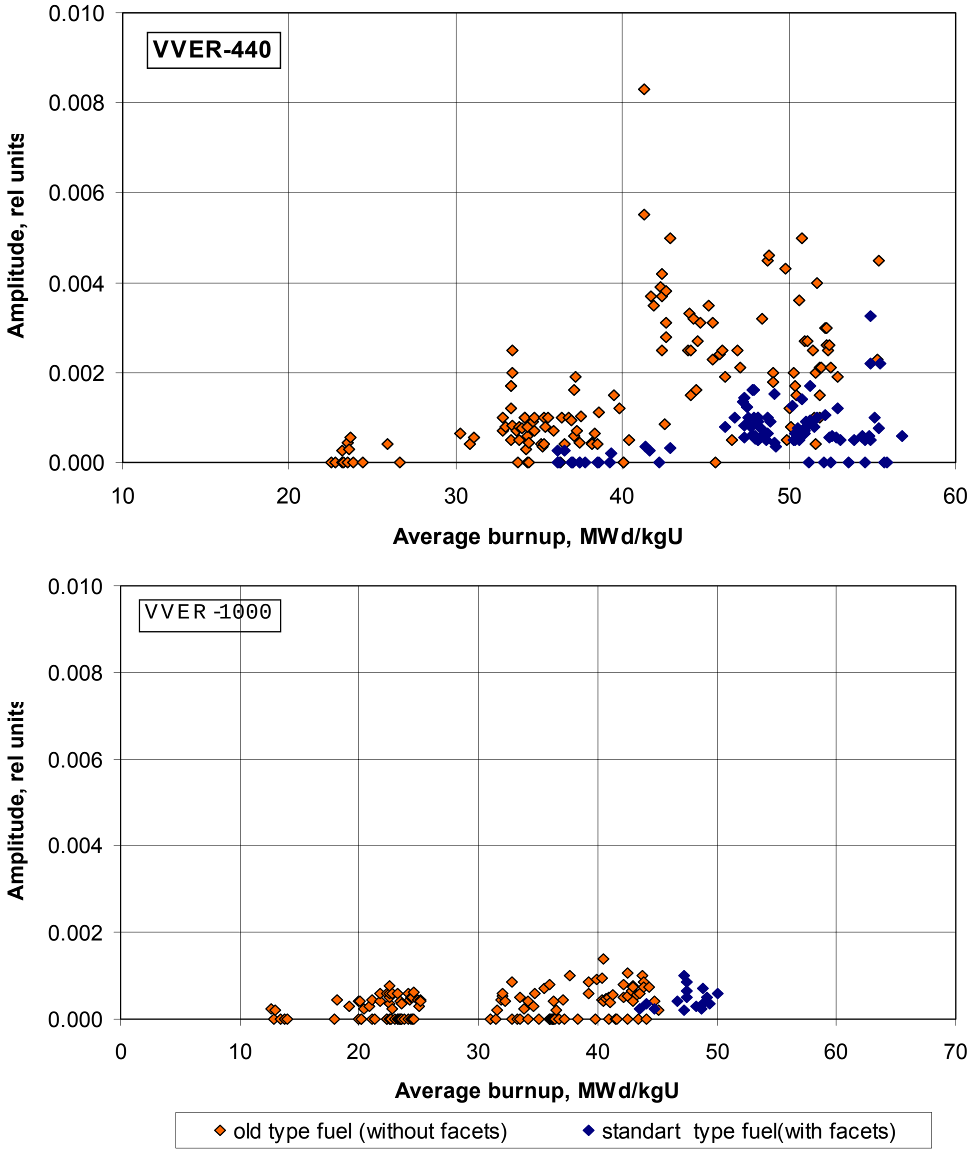


Figure 3. Peak amplitude (11 mm) at outer diameter periodogram of WWER fuel rods vs. average burnup

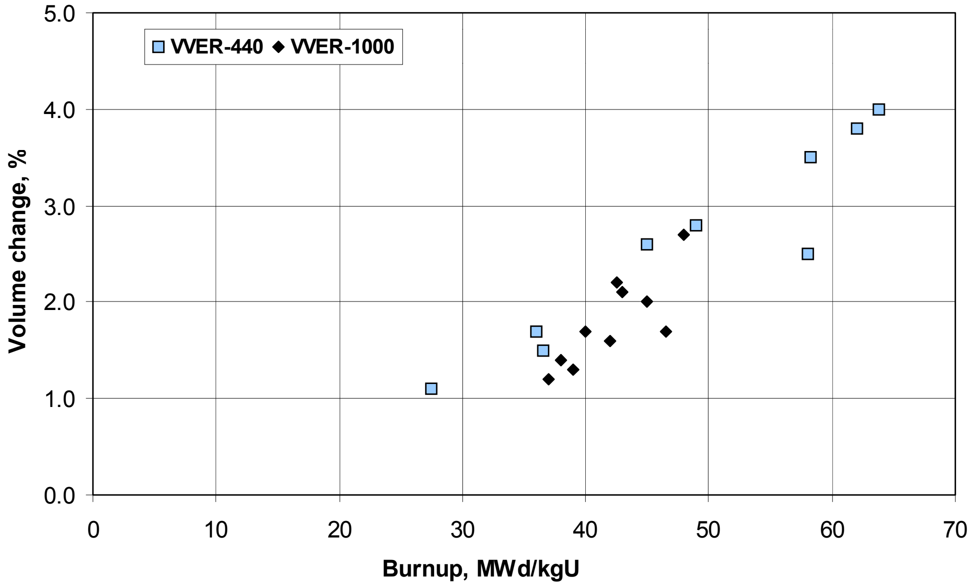
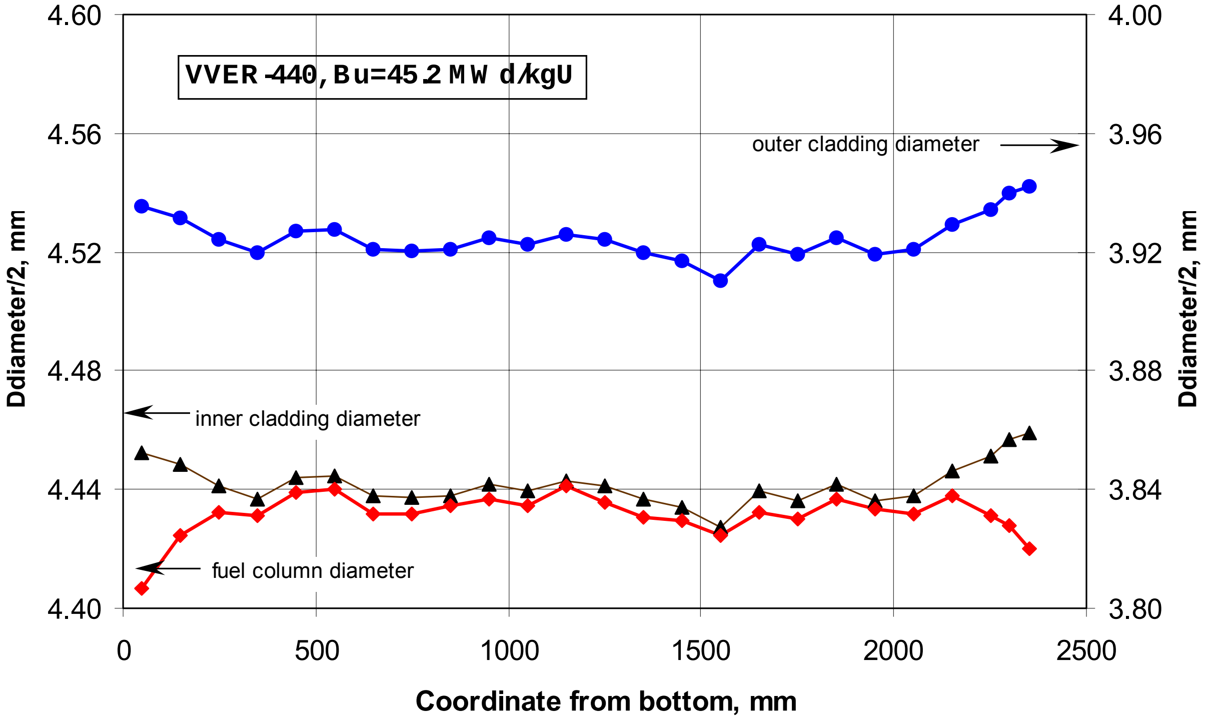


Figure 4. Dependence of WWER fuel swelling on local fuel burnup [5]



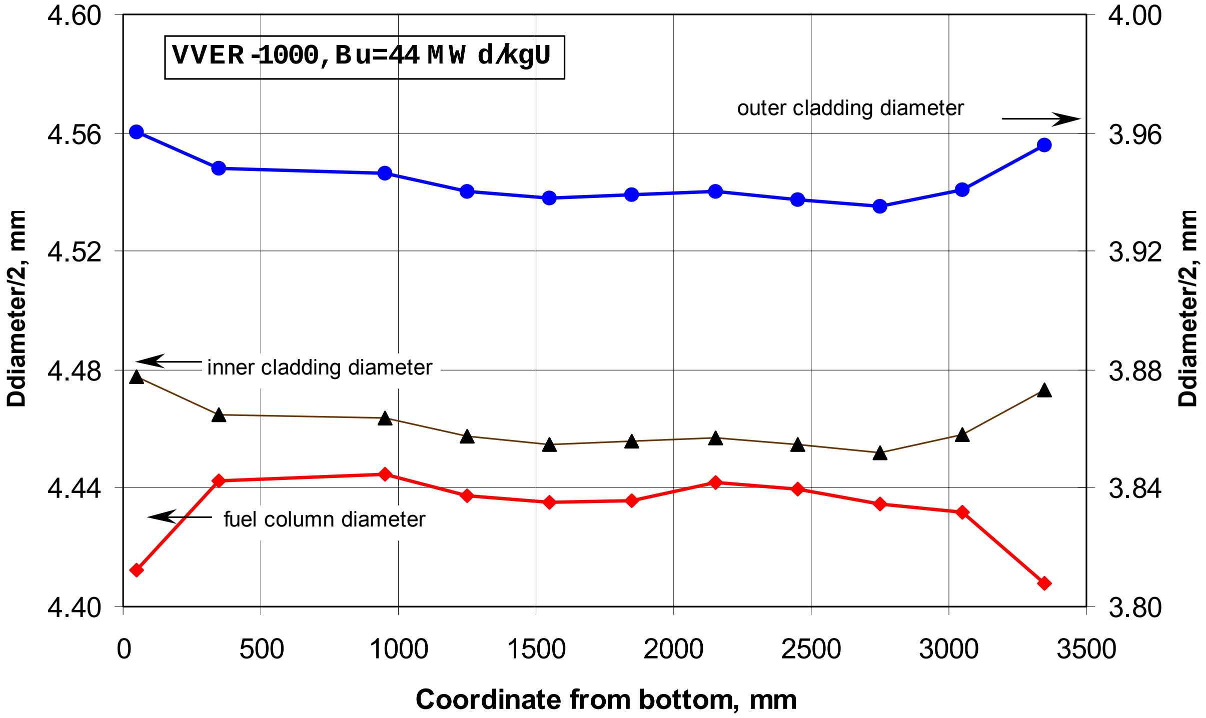
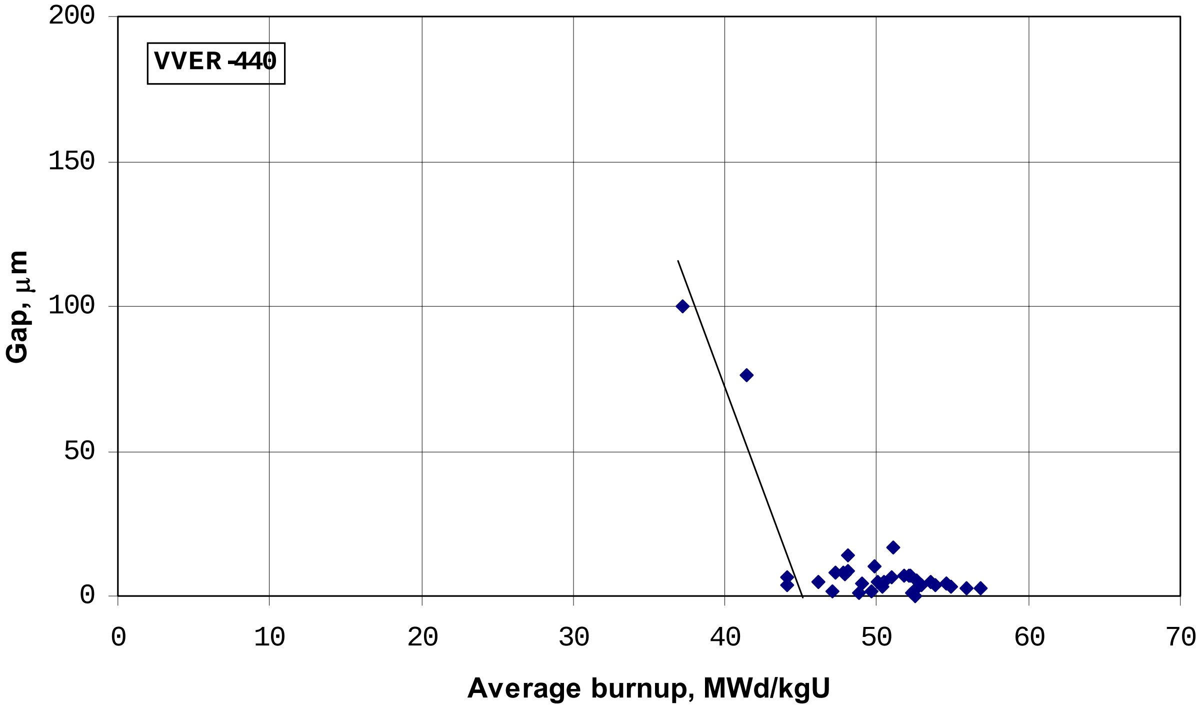


Figure 5. Axial profile of cladding outer and inner diameter and fuel column outer diameter for WWER fuel rods



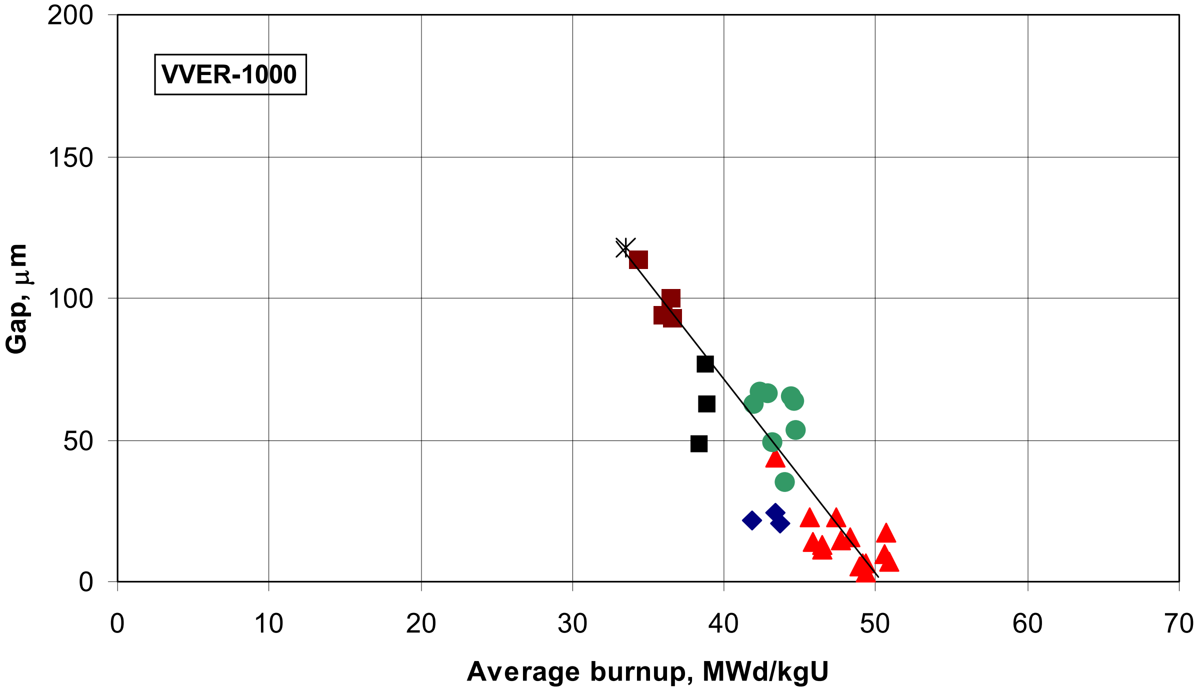


Figure 6. Dependence of WWER fuel-cladding gap on average burnup

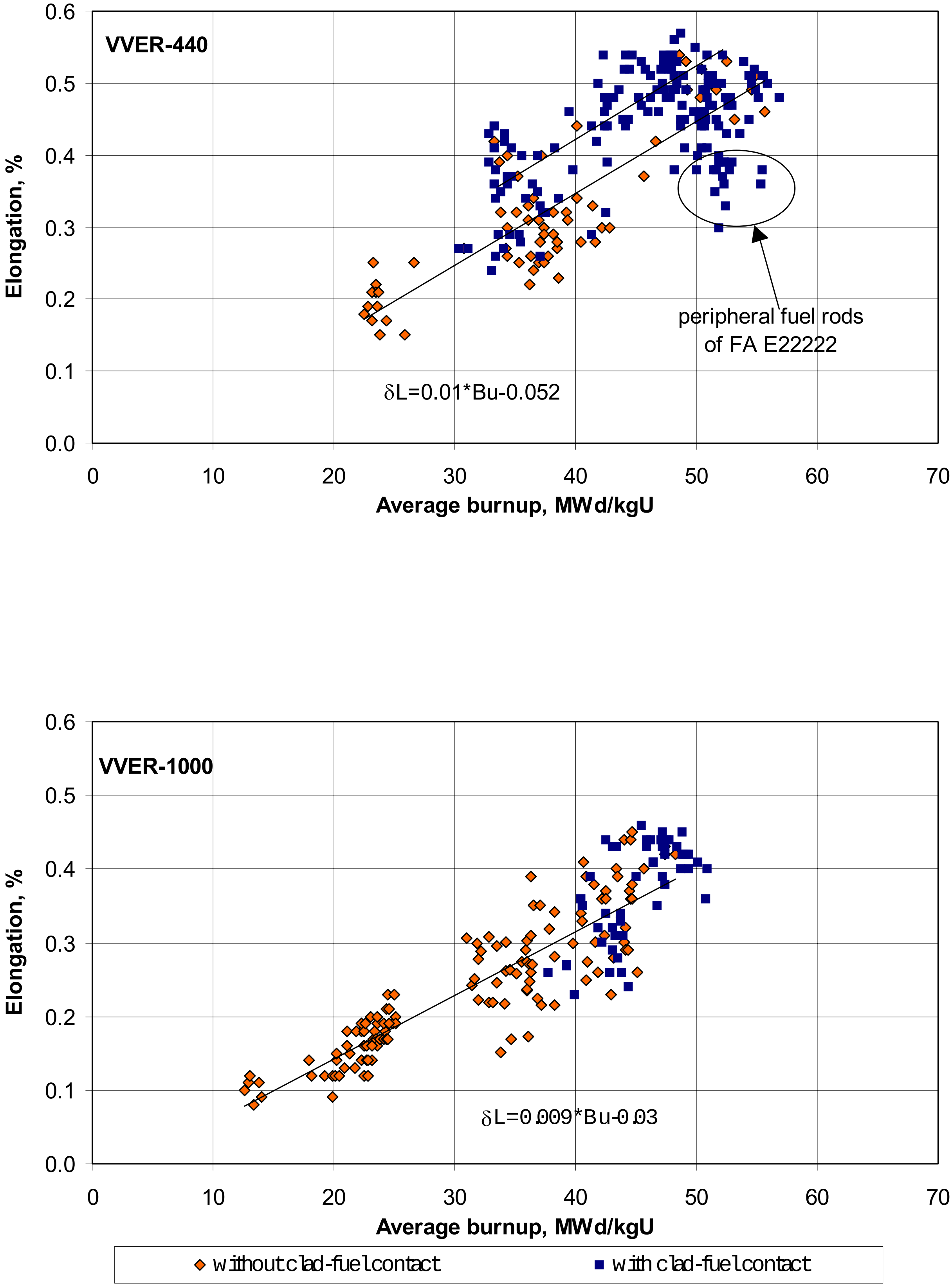


Figure 7. WWER fuel rod relative elongation vs. average burnup

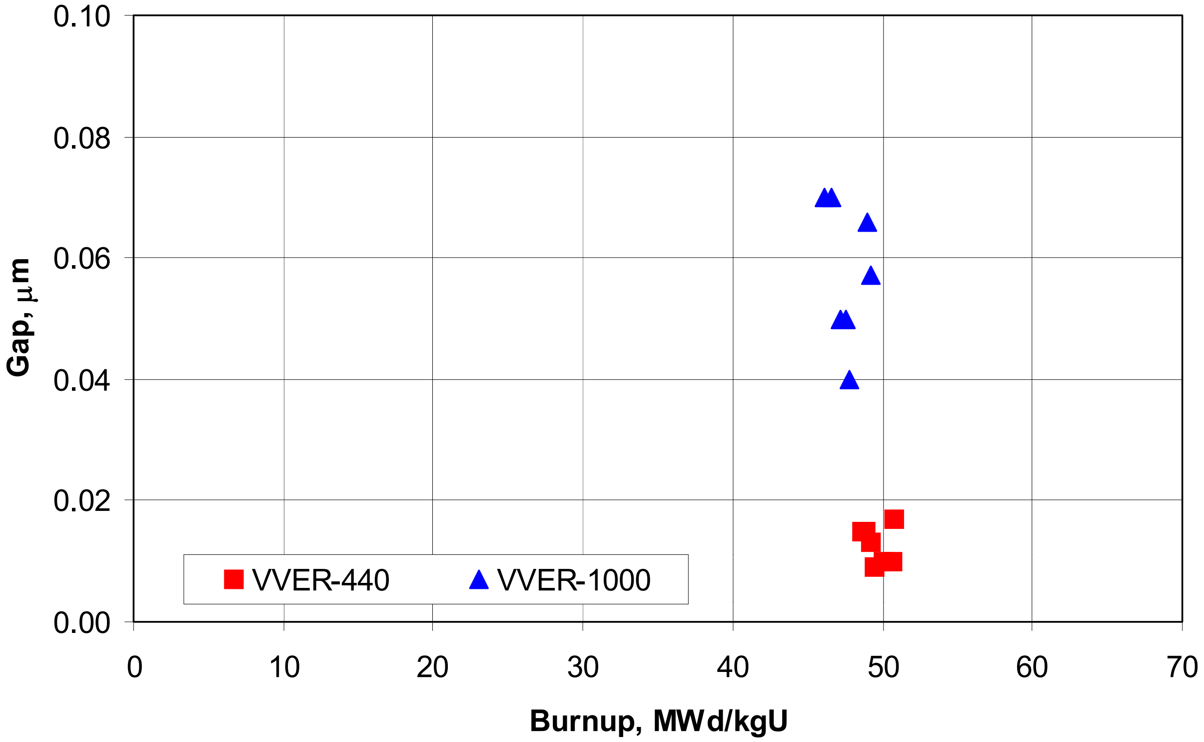


Figure 8. Fuel-cladding gap of WWER fuel rods before transient testing

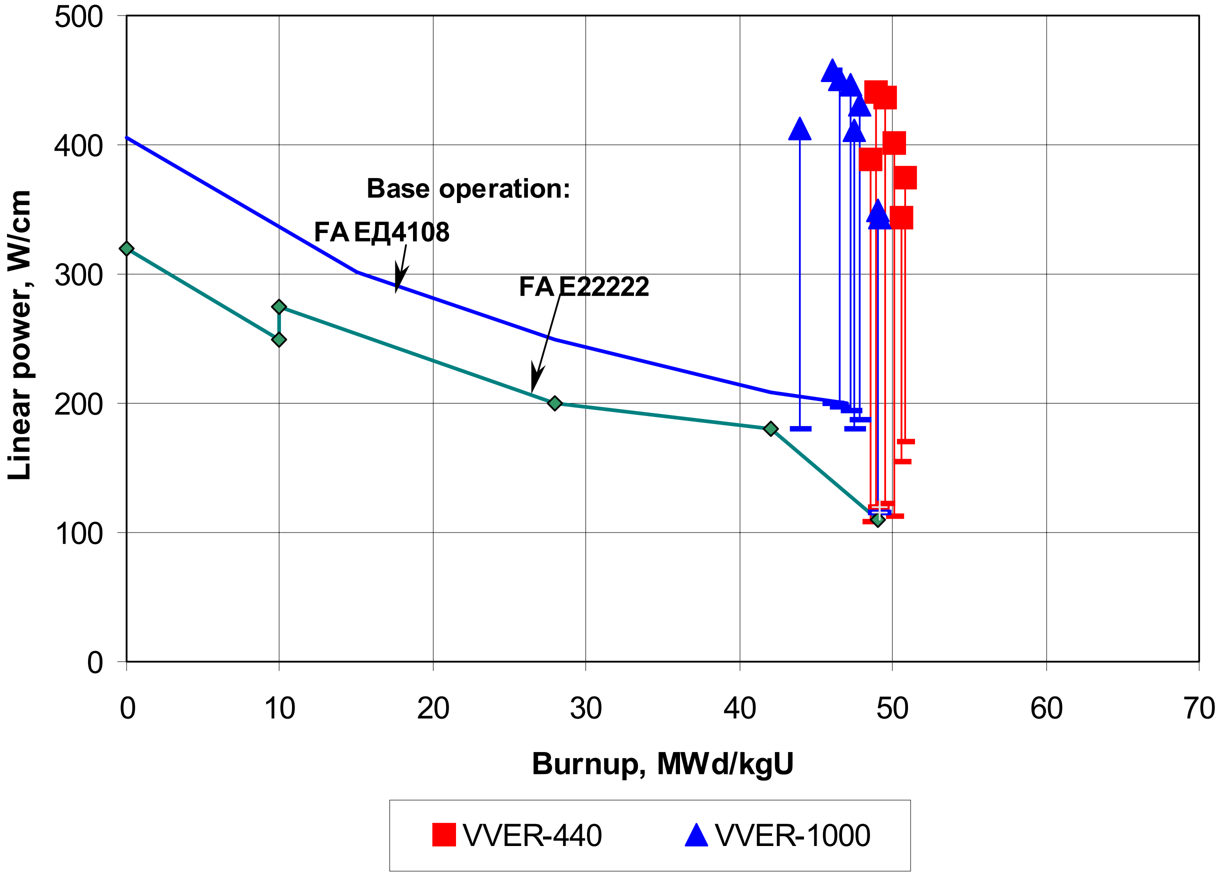


Figure 9. Transient test parameters for WWER fuel rods

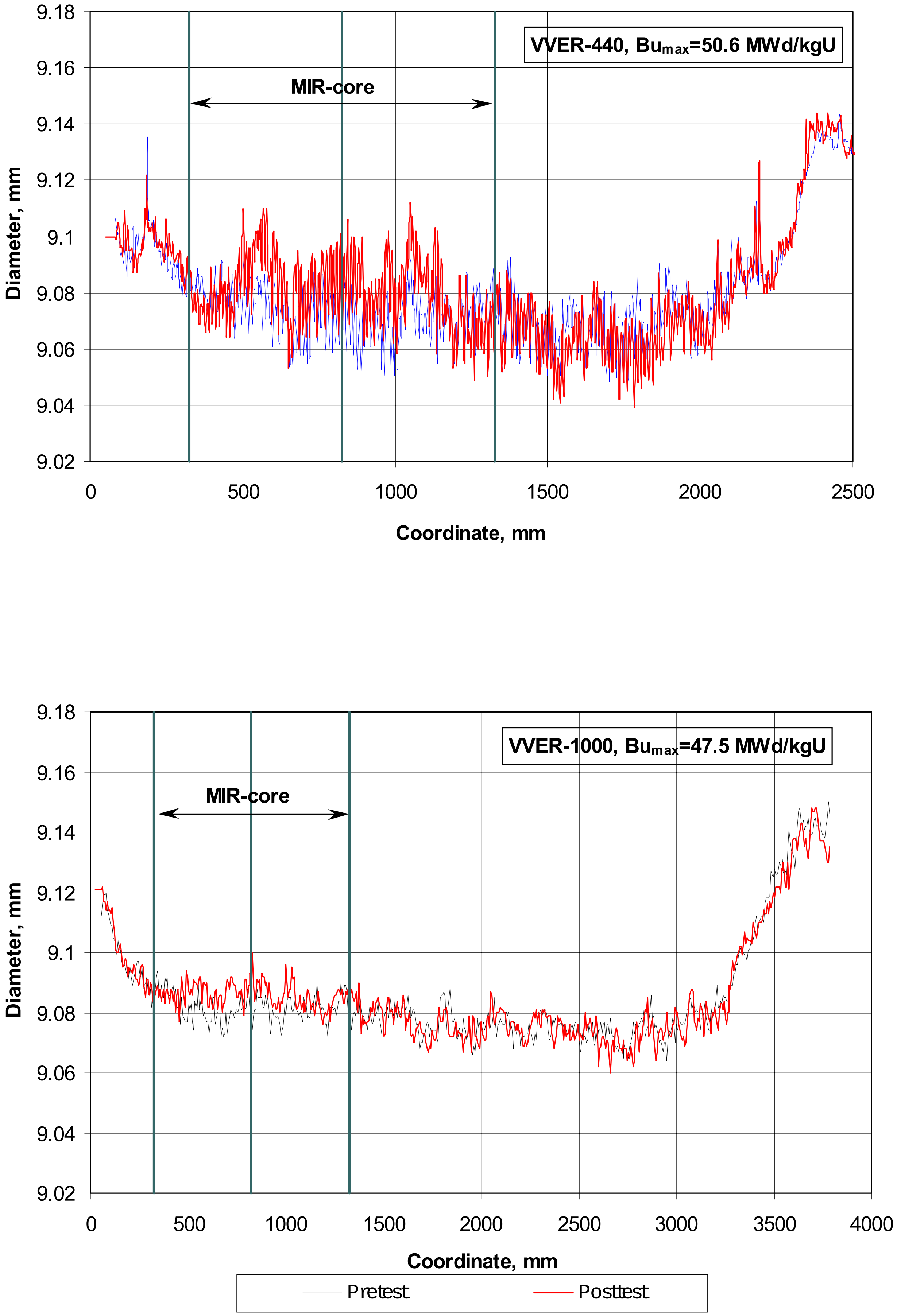


Figure 10. WWER cladding outer diameter profile before and after RAMP test

better than in other FR lots. The ultimate strength and yield stress in the cross direction were higher by 5-7% for claddings of this particular lot than for other claddings at a testing temperature of 380°C. But at the same time the yield stress in the axial direction doesn't differ from the yield stress of claddings taken from the other lots.

In this way the state of WWER-440 and WWER-1000 fuel rods differ as regards the change in geometrical parameters of the cladding and fuel column after operation under the design-basis conditions up to burnups more than 45-50 MWd/kgU differs. Thermo-mechanical interaction between fuel and cladding occurs to a greater degree in WWER-440 fuel rods than in WWER-1000 fuel rods, which reached the same fuel burnups. There are more fuel rods with the close fuel-cladding contact in WWER-440 fuel assembly. Nevertheless, the change in the cladding diameter because of hoop tensile strain is no more than 30 μm for WWER-440 fuel rods operated up to a burnup of 60 MWd/kgU. The material structure and mechanical properties of WWER-440 claddings are satisfactory and they don't differ from the material structure and cladding properties of WWER-1000. The specific elongation of WWER-440 fuel rods is greater by 10-12% in comparison with elongation of WWER-1000 fuel rods. As for volume swelling of the fuel column it doesn't differ considerably.

3. Transient Testing

3.1. Subjects of Examination and Testing Conditions

A set of transient tests for spent WWER-440 and WWER-1000 fuel rods was carried out in SSC RF RIAR in 1995-1999. The tests were run in transient conditions by single and gradual change in power [7,8,9]. The range of fuel burnup was 30-60 MWd/kgU for WWER-440 fuel rods and 27-50 MWd/kgU for WWER-1000 fuel rods. Fuel rods with the same ^{235}U enrichment (4.4%) and nearly the same fuel burnup of 46-51 MWd/kgU were chosen from the whole set of rods to analyse the differences in behavior of two types of fuel rods in the present paper. It has been already mentioned that the state of WWER-440 and WWER-1000 fuel rods reached the specified burnup was different. The main difference was the size of "cold" fuel-to-cladding gap. It was 10-20 μm for WWER-440 fuel rods (Figure 8). This leads to the close fuel-cladding contact when the starting linear power of ~100 W/cm was brought to. The "cold" fuel-to-cladding gap was 50-90 μm for the WWER-1000 fuel rods reached the same burnup. When the starting linear power of 180-200 W/cm was brought to, the fuel-to-cladding was different from zero. The second difference between the tested WWER-440 and WWER-1000 fuel rods consists in undergoing of initial stage of so-cold reverse strain by WWER-440 FR claddings by the time of test run beginning. WWER-1000 claddings were not subjected to this effect.

The range of linear power was chosen for the tested fuel rods (Figure 9) with due regard to starting level simulate the FR operating conditions at the final stage of their operation and the maximum linear power exceed the permissible level laid down in specifications. The picture also demonstrates that test conditions for WWER-440 and WWER-1000 fuel rods didn't differ significantly with regard to linear power. The coolant temperature and pressure simulate the operation conditions in the appropriate reactors.

3.2. Change in the Outer Diameter of Claddings

The typical diagrams made before and after the reactor tests show the outer diameter of claddings (Figure 10) for one WWER-440 and WWER-1000 full-size fuel rod reached a burnup of ~50 MWd/kgU. Their analysis revealed an insignificant increase in the outer diameter of the cladding in the area of the maximum linear power for WWER-440 fuel rods but the outer diameter of WWER-1000 fuel rods didn't change at all. The character of the local cladding strain was the same in both cases in other words there was no additional fuel-cladding interaction at the place of pellet junction.

Figure 11 gives the change in the outer diameter of claddings as a function maximum linear power. The picture confirms the difference in behaviour of WWER-440 and WWER-1000 fuel rods having a burnup of 50 MWd/kgU over the studied linear power range. The increase in the outer diameter of WWER-440 FR claddings was 22-33 μm. As for WWER-1000 fuel rods it was up to 10 μm.

The results presented in Figure 11 were obtained for the central area of fuel rods, where the linear power was the maximum one at the final stage of testing. There also the regions on the full-size fuel rods, where the linear power varies between zero to maximum values. This fact allows for establishing the relationship between the change in the outer diameter of claddings and linear power over the whole range of its variation practically when data for one fuel rod are available only. In order to exclude the influence of the "riddings" the length of region for averaging was taken equal to the length of several fuel pellets.

Figures 12a and 13a show the typical diagram of the outer diameter change together with the linear power profile along WWER-440 and WWER-1000 FR length. The outer diameter was in error of ±0.01mm. The relationship between the above-mentioned parameters is plotted in Figures 12b and 13b for each fuel rod.

Figure 12b demonstrates that a cladding strain for WWER-440 fuel rod begins at a level peculiar to the final fuel cycle under the operation conditions of power reactor (~100 W/cm). It should be noted that this particular fuel rod didn't have any essential fuel contact with cladding before the testing. The cladding strain is proportional to the linear power up to 250 W/cm in the first approximation. On the average, the outer diameter of WWER-440 FR claddings was constant over the thermal power range >300 W/cm. In its turn WWER-1000 FR diameter (Figure 13b) didn't change within the limits of measurement error.

3.3. Fuel-to-Cladding Gap

Figure 14 presents the values of average gaps measured in normal conditions after the reactor tests. The picture demonstrates the fuel-to-cladding gap in the region of maximum linear power is 40-65 μm after testing of WWER-440 fuel rods (the tight contact was noticed before testing). The gap decrease by no more than 20 μm was noticed for WWER-1000 fuel rods.

3.4. Change in the Outer Diameter of Fuel Column

Based on the available data on the outer diameter of the cladding, fuel-to-cladding gap for a separate sections of each fuel rod it is possible to define the axial distribution of the fuel column outer diameter and establish its relationship with the linear power.

Figures 15a and 15b show the profiles of the outer and inner diameter of the cladding as well as outer diameter of the fuel column for WWER-440 and WWER-1000 fuel rods after the testing. As indicated in these pictures, the region of the outer diameter averaging conforms to the pace of fuel-to-cladding gap measurement (50 mm). Figure 15a demonstrates that the outer diameter of the cladding increases insignificantly for WWER-440 fuel when a linear power of 343 W/cm has been reached. The maximum linear power region is characterized by a large fuel-to-cladding gap and the fuel column diameter is less in this region in comparison with the adjacent regions. The diameter of the fuel column increased in the WWER-1000 fuel rod over the region of the MIR reactor core, the cold gap became less and the cladding diameter increased insignificantly (Figure 15b). So the fuel column is touched to the cladding in the hot state.

The central hole diameter starts decreasing when the linear power is ~230-250 W/cm. When the linear power is 340-360 W/cm, the central hole disappears completely and a new central hole has appeared in one of the cross-sections of WWER-440 fuel rod when q_l=440 W/cm. Such behaviour of the central hole as compared with the decrease in the fuel column diameter draw to the conclusion that there is a certain relationship between them when the linear power is higher than 300 W/cm. The diameter of the fuel column was sensibly constant at the cross-sections that are free from the central hole. Correspondingly the change in cladding diameter was minimal (~25 μm) at these particular cross-sections. At the same time diameter of the fuel column increased at the cross-sections where the central hole diameter didn't change or changed insignificantly. The cladding diameter increased respectively.

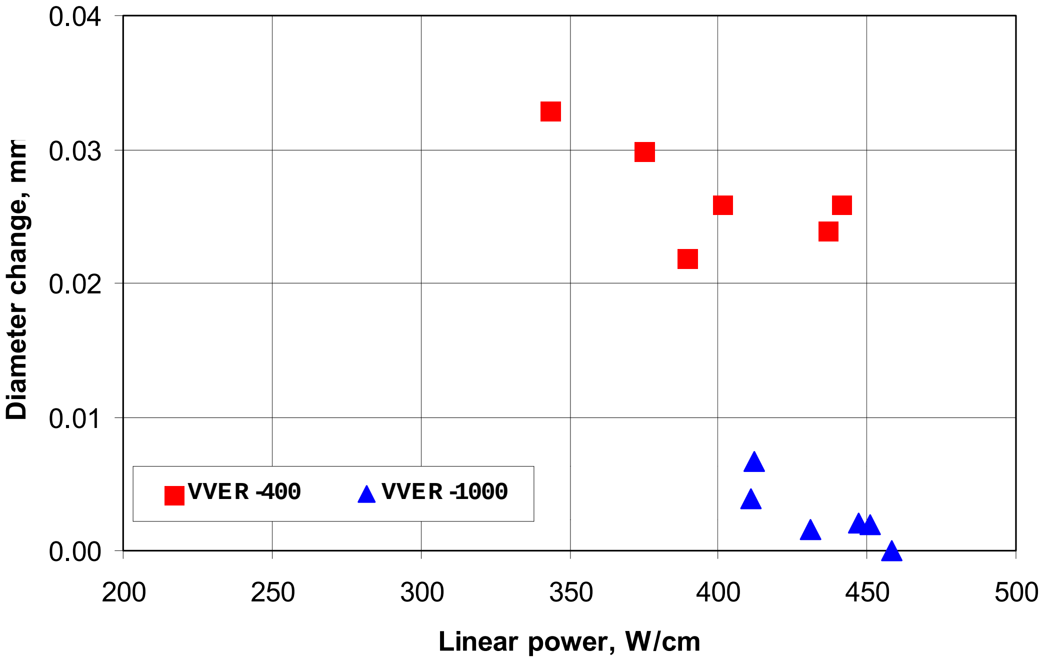
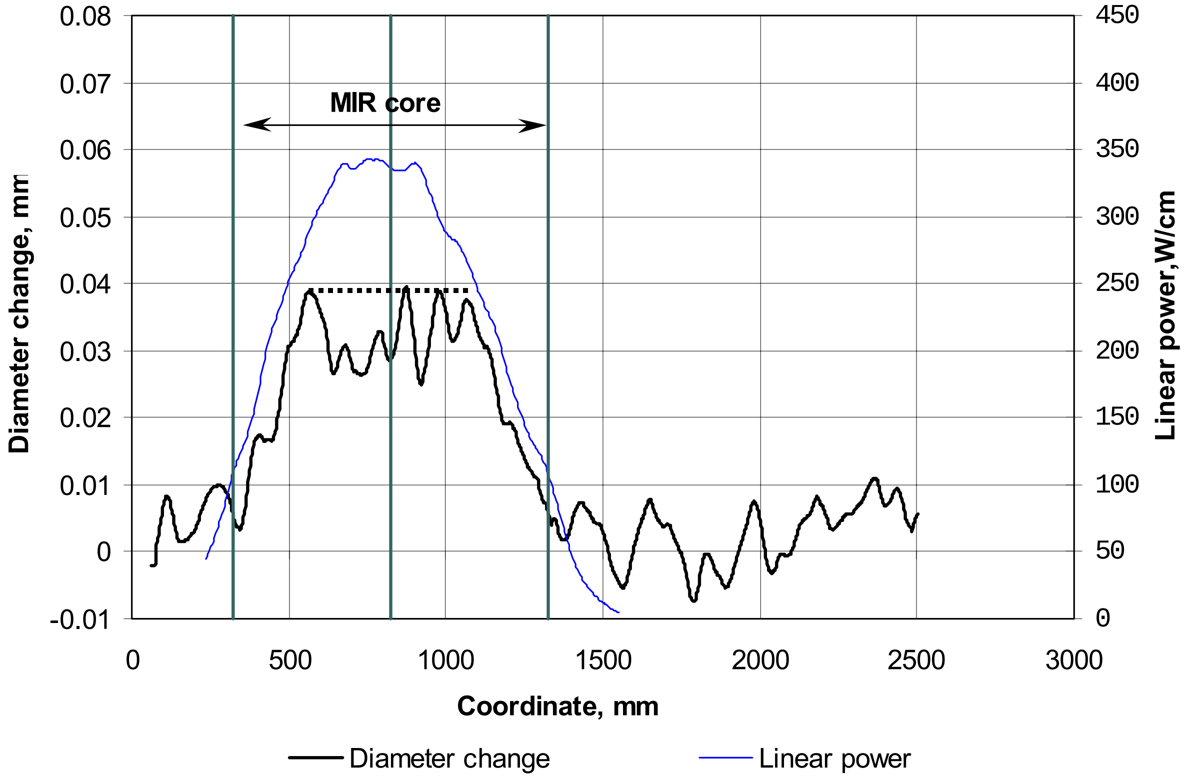


Figure 11. WWER cladding outer diameter change after transition test



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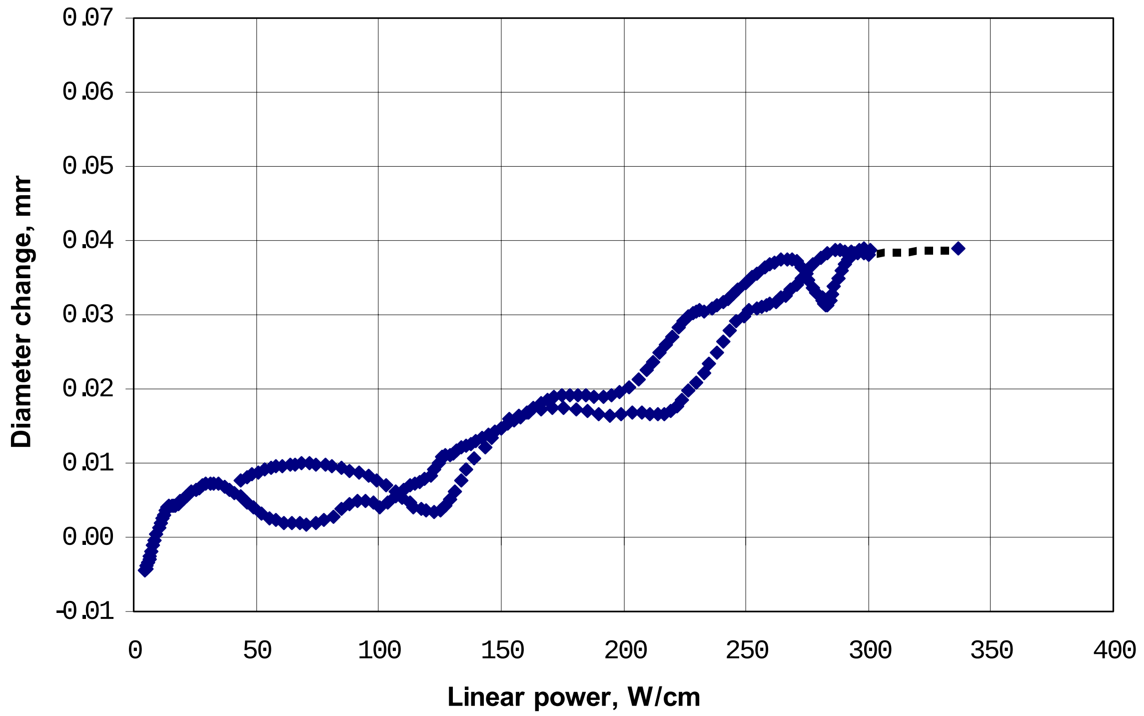
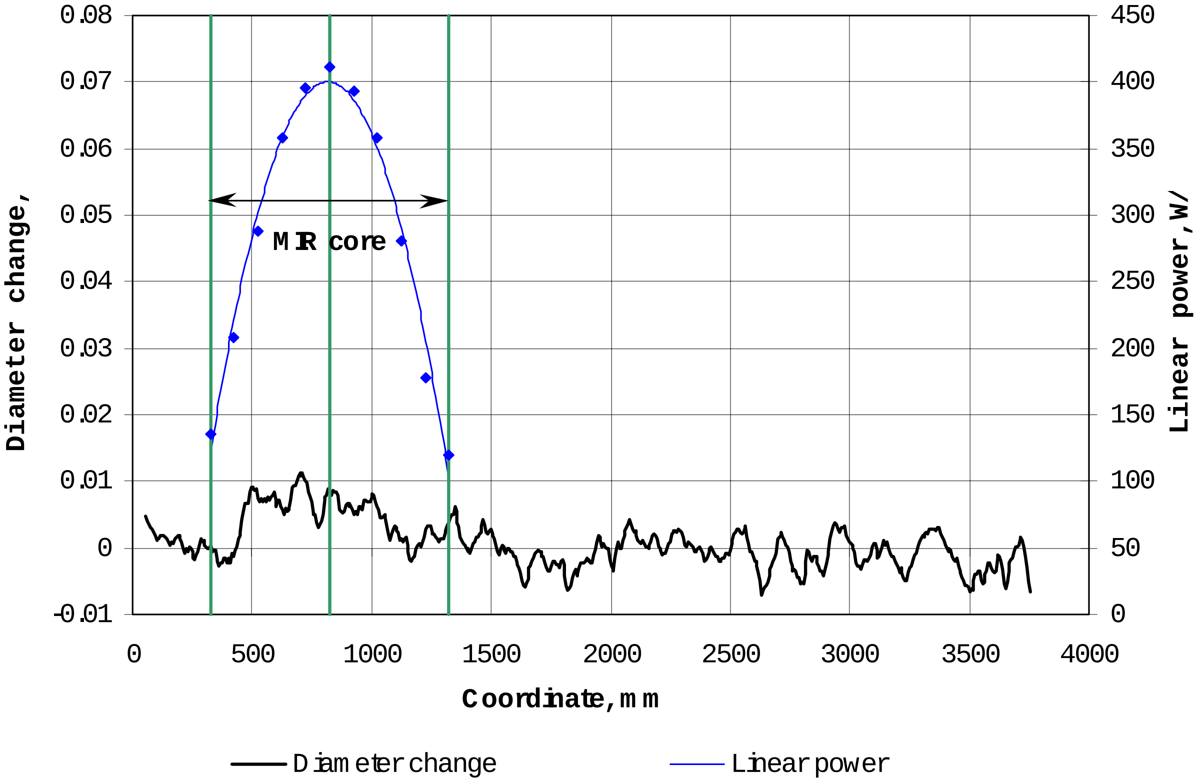


b)

Figure 12. **a) Cladding outer diameter and linear power distribution for WWER-440 fuel rod after transient test (*Bu*$_{max}$=50.6 MWd/kgU); b) Coupling between linear power and cladding diameter change for WWER-440 fuel rod after transient test**



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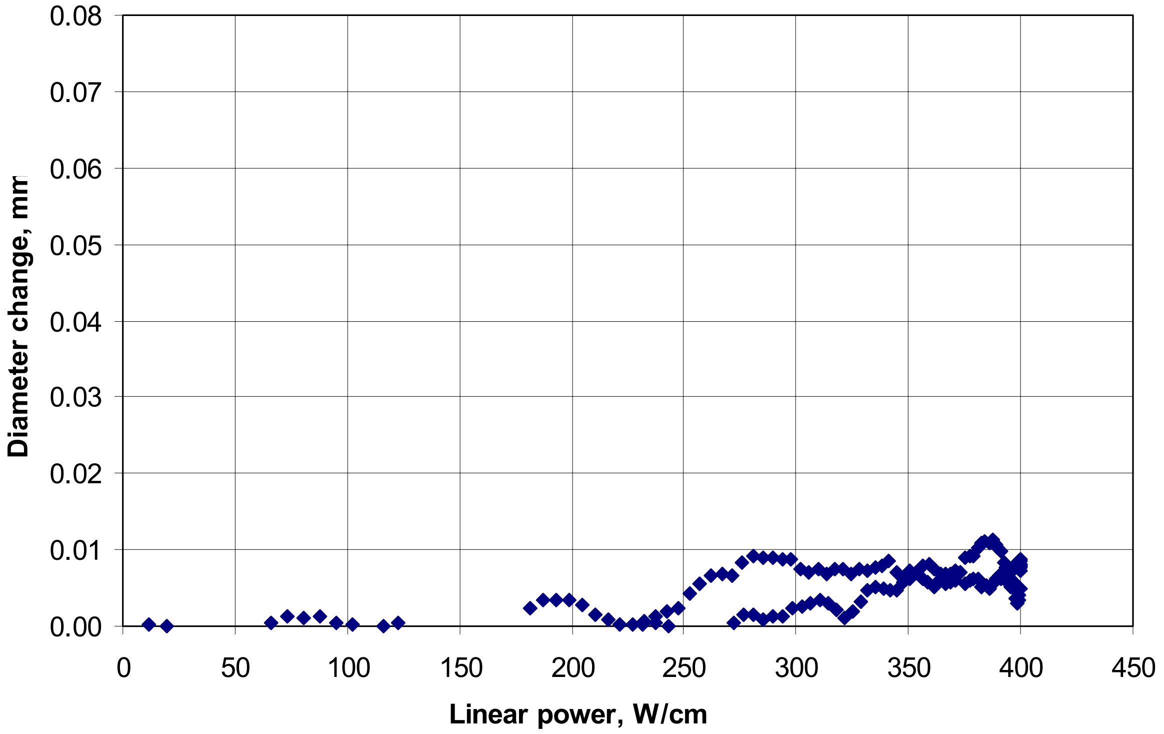

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Figure 13. a) Cladding outer diameter and linear power distribution for WWER-1000 fuel rod after transient test (Bu_{max}=47.5 MWd/kgU); b) Coupling between linear power and cladding diameter change for WWER-1000 fuel rod after transient test

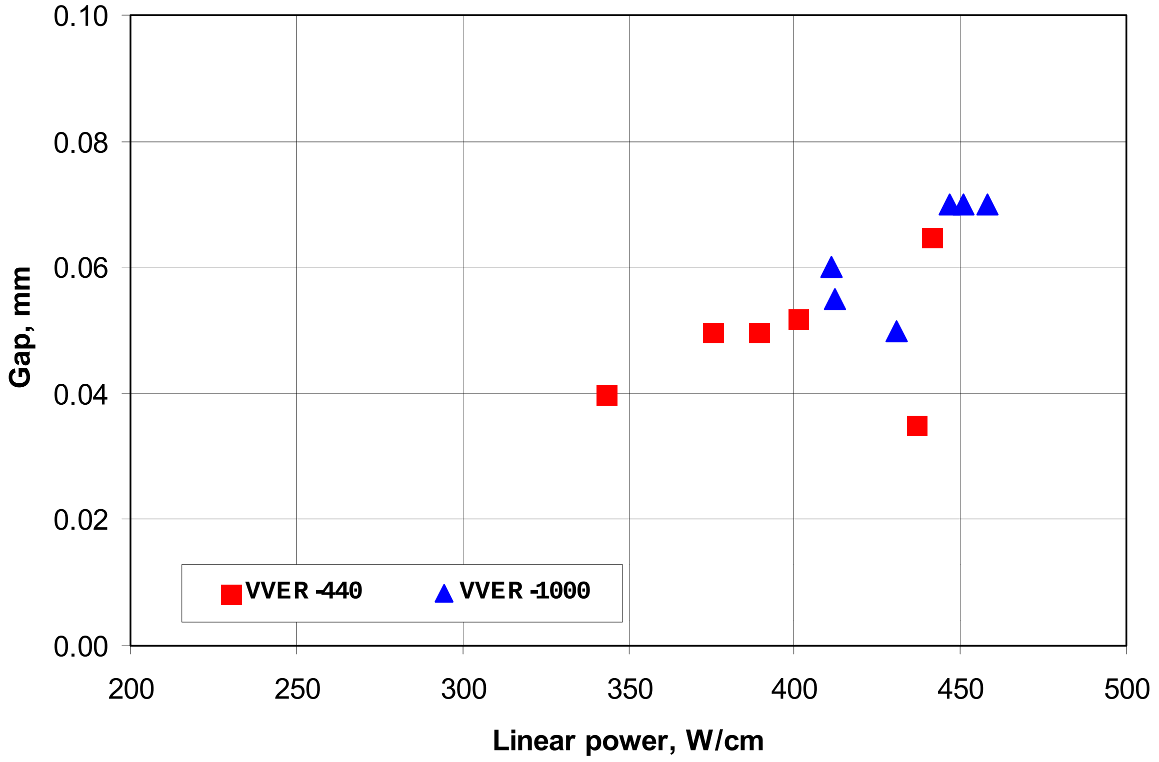

Figure 14. WWER fuel-cladding gap after transient test

4. Conclusions

The following conclusions can be drawn based on the study of geometric parameters changes of WWER-440 and WWER-1000 claddings and fuel column in operation conditions and transient testing:

- WWER-440 cladding is subject to tensile stress under the influence of fuel column at burnups of 42-45 MWd/kgU. However the value of hoop strain isn't high (Δd_2 is no more than 30 μm) and it doesn't lead to the mechanical properties of cladding;
- WWER-1000 fuel rods are characterized by the less degree of thermomechanical interaction after the operation conditions up to a burnups of 45-50 MWd/kgU in comparison with the WWER-440 fuel rods reached the same burnup. The close fuel-pellet contact in WWER-1000 fuel rods occur at higher burnups as opposed to WWER-440 fuel rods;
- Testing of high burnup WWER-1000 fuel rods in transient conditions over the linear power range of 180 to 400 W/cm demonstrates that the geometric parameters of WWER-1000 cladding are practically constant, fuel-to-cladding gap doesn't disappear, cladding strain is absent.

In their turn WWER-440 fuel rods having the same burnup and close fuel-cladding contact before the testing were subjected to considerable hoop cladding strain in testing up to 300 W/cm. But the hoop strain don't grow due to the structural changes in fuel column and decrease in central hole diameter occurred when the power is higher.

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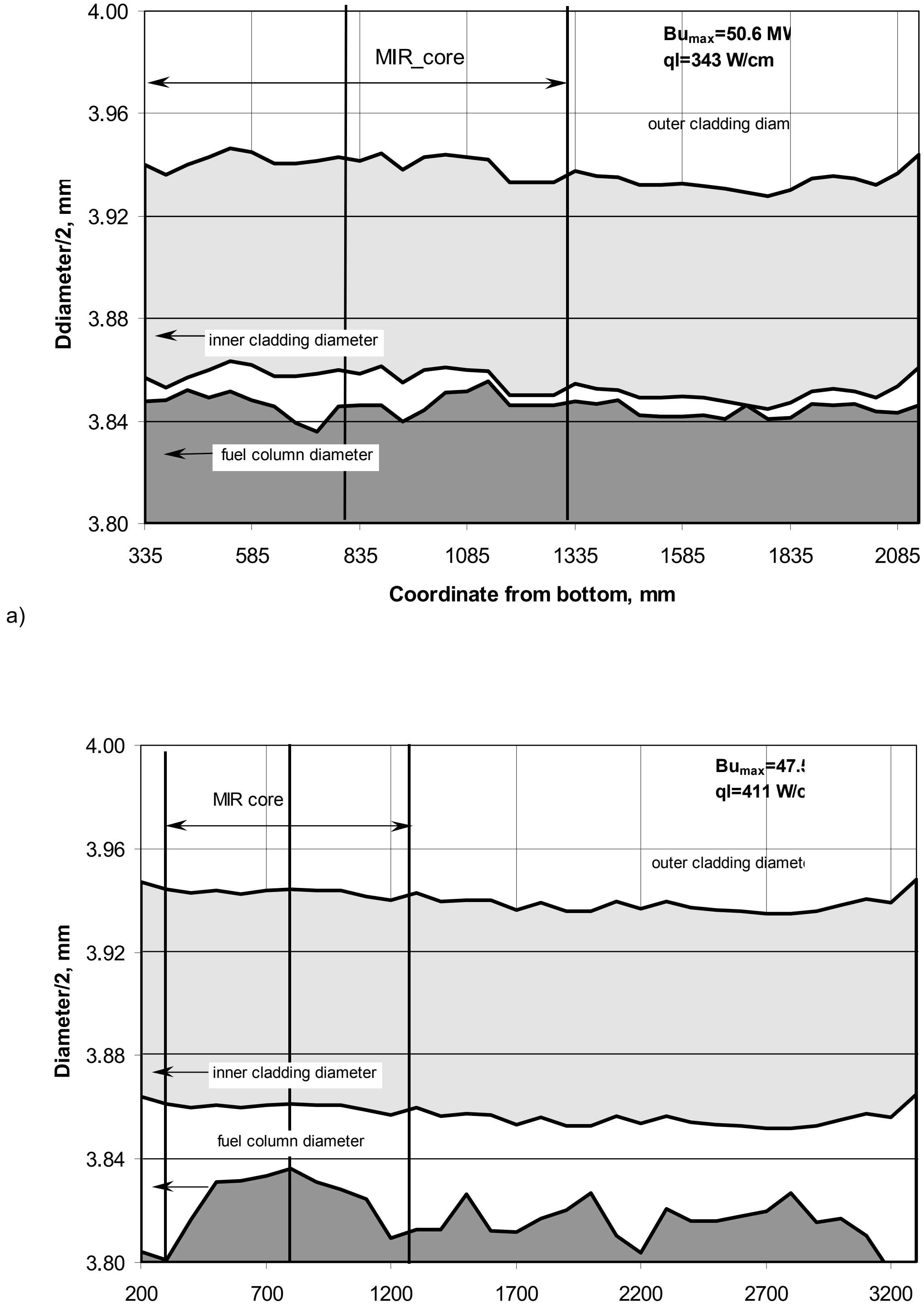

Figure 15. a) Axial profile of cladding outer and inner diameter and fuel column outer diameter for WWER-440 fuel rod after RAMP test; b) Axial profile of cladding outer and inner diameter and fuel column outer diameter for WWER-1000 fuel rod after RAMP test

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