RESULTS OF VVER FUEL RODS TESTS IN THE MIR.M1 REACTOR UNDER POWER CYCLING CONDITIONS

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Key words: fuel rod, VVER, reactor MIR.M1, loop facility, in-pile measurement gage, irradiation, burnup, linear heat rate, cycling, fission gas release, fuel temperature, fuel rod elongation, change of cladding diameter, post-irradiation examinations

The paper presents the main results of the 50…60 MWd/kgU burnup VVER fuel rods tests performed in the MIR.M1 reactor loop facilities under power cycling. The non-destructive PIE results are presented as well. A series of experiments was performed, including overall measurement of fuel rod parameters test, in one of which 300 cycles were done.

Irradiation under power cycling conditions and PIE of high-burnup VVER fuel rods showed the following:

- all fuel rods claddings preserved their integrity under irradiation at linear heat rate (LHR) higher than the NPP operating one;
- experimental data were obtained on the axial and radial cladding strain and fission gas release (FGR) from 50…60 MWd/kgU burnup VVER-440 and VVER-1000 fuel rods as well as on the kinetics of the change in these parameters and fuel temperature under the power cycling;
- non-destructive PIE results are in a satisfactory correlation with the data obtained by means of in-pile measurement gages during irradiation.

INTRODUCTION

The justification of the VVER fuel rods performance under power transient conditions goes along with the achievement of high fuel burnup in the VVER reactors [1]. In particular, power cycling occurred under the NPP maneuvering operation subjects fuel rods claddings to multiple thermo-mechanical loads and may affect their performance. These factors are taken into account when developing new-generation VVER fuel assemblies [2]. Both operating experience and calculation and experimental data on the fuel rods operation under power maneuvering show that pre-tests should be performed in the research reactors to implement the recommendation on the operating conditions and improve fuel.

It is evident that at least the most critical conditions determining the fuel rods performance under the power maneuvering should be simulated in these tests since a complete cycle of fuel rods operation in an NPP cannot be simulated. It allows the test results to be effectively used for developing the operating manuals, improving fuel and upgrading and verification of the calculation codes. The most important are experimental data on the behavior of VVER fuel rods with burnup more than ~ 50 MWd/kgU, when there is no pellet-to-cladding gap, under the power maneuvering.

The paper presents the key results of tests performed in the MIR.M1 reactor loop facility for 50…60 MWd/kgU burnup refabricated and full-size fuel rods removed from the spent VVER-440 and VVER-1000 fuel assemblies. The tests were performed under power cycling; non-destructive PIE results are presented as well. The results include experimental data on the FGR, fuel temperature and axial and radial cladding strain of high-burnup VVER fuel rods under the conditions is question. The tests and PIE programs were developed by RIAR specialists together with VNIINM and TVEL.

It should be mentioned that the state of fuel rods tested under the power cycling did not change significantly and corresponded to the one of the VVER fuel rods irradiated at the same LHR levels with no power cycling. More prominent fragmentation of fuel pellets and some increase in the FGR were observed. Therefore the destructive PIE results are not considered in the paper and described in detail in Ref. [3, 4, 5].

1. BASIC FUEL RODS CHARACTERISTICS AND IRRADIATION CONDITIONS

1.1 Experiments with VVER-440 fuel rods

Six fuel rods were subjected to overall parameters measurement test: three refabricated and three full-size fuel rods from spent VVER-440 FAs [6, 7, 8]. Refabricated fuel rods were done from fragments of the full-size fuel rods central parts. The basic condition to select fragments for their refabrication was the most uniform burnup distribution along the fuel column. The length, diameter and under-cladding gas pressure were measured at a time on one refabricated fuel rod. To evaluate the fuel temperature in this fuel rod, two other rods with the same burnup were equipped with thermocouples to measure temperature in the fuel column center.

The fuel rods characteristics were as follows:

- burnup after operation at NPP, MWd/kgU	-	51…61;
- refabricated fuel rod column length, m	-	0.4;
- cladding material	-	alloy E110.

Fuel rods were tested in the MIR.M1 reactor loop facility at an inlet coolant temperature of ~ 250°C and pressure of ~14 MPa. Three power cycles were done. The LHR in each cycle was increased by raising the power of MIR.M1 operational FAs surrounding the loop channel with the irradiation rig (IR). The parameters of the LHR change in the overall parameters measurement experiment were as follows:

- initial LHR, kW/m	-	15…19;
- LHR increment per cycle, kW/m	-	7.5…9.5;
- LHR increase rate, kW/m/min	-	0.25…0.30;
- exposure after LHR change in a cycle, h	-	6…7.

Another experiment was performed for four refabricated fuel rods made from fragments of full-size ones removed from spent VVER-440 FAs. Two refabricated fuel rods were equipped with thermocouples to measure temperature in the fuel column center [3].

The fuel rods characteristics were as follows:

- burnup after operation at NPP, MWd/kgU	-	52…61;
- fuel column length, m	-	0.4;
- cladding material	-	alloy E-110.

The test was performed in the MIR.M1 loop facility at a coolant inlet temperature of ~ 250°C and pressure ~ 13 MPa. There were two irradiation stages with ten LHR cyclings at each stage. The LHR increase in a cycle was provided by raising the power of MIR.M1 operational FAs surrounding the loop channel with the IR. It should be mentioned that during the test, slight LHR changes with an amplitude of 1…3% were recorded at the stationary power levels. They were caused by transient processes in the core and operation of control rods. The same power changes are typical for an NPP. The LHR change parameters in the experiment with VVER-440 fuel rods were as follows [8]:

- initial LHR, kW/m	-	17…21;
- LHR increment per a cycle, kW/m	-	8…11;
- LHR increase rate, kW/m/min	-	0.3…0.6;
- exposure after LHR change in a cycle, h	-	5…8.

1.2 Experiments with VVER-1000 fuel rods

In one of the experiments, four refabricated fuel rods were tested. They were done from fragments of full-size fuel rods from a spent VVER-1000 FA. One refabricated fuel rod was equipped with a pressure transducer (PF); another fuel rod was equipped with a thermocouple to measure temperature in the fuel column center. Two other fuel rods were equipped with the cladding extensometers (CE). A special IR was designed that had movable shielding made of hafnium (Fig. 1) [7].

The fuel rods characteristics were as follows:

- burnup after operation at NPP, MWd/kgU	-	49…50;
- fuel column length, m	-	0.4;
- cladding material	-	alloy E110.

The test was performed in the MIR.M1 loop facility at a coolant inlet temperature of ~ 280°C and pressure ~ 16 MPa. There were two irradiation stages with forty LHR cyclings at each stage. The power cycling was provided by moving the IR shielding from one couple of refabricated fuel rods to the other one. At that, the LHR of two antipode fuel rods increased; the LHR of the other two shielded fuel rods decreased (Fig. 1).

After the operation under power cycling and exposure under the stationary level, an additional power ramp was done for all fuel rods, two of four refabricated fuel rods being shielded. The parameters of LHR cyclings in the first experiment with refabricated VVER-1000 fuel rods were as follows [8]:

- initial LHR, kW/m	-	21;
- LHR increment per a cycle, kW/m	-	8.5;
- LHR increase rate, kW/m/min	-	0.6;
- exposure after LHR change in a cycle, h	-	3.

In the second experiment, four refabricated fuel rods were tested. They were done from fragments of full-size fuel rods from a spent VVER-1000 FA. One fuel rod was equipped with a thermocouple to measure temperature in the fuel column center. Three other fuel rods were equipped with the CE. The fuel rods were installed in a specially designed IR, of which operation was the same as described above. The refabricated fuel rods were located in zirconium tubes to have a through coolant flow (Fig. 2) [4].

The fuel rods characteristics were as follows:

- burnup after operation at NPP, MWd/kgU	-	50…53;
- fuel column length, m	-	0.4;
- cladding material	-	alloy E110.

The test was performed in the MIR.M1 loop facility at a coolant inlet temperature of ~ 280°C and pressure ~ 16 MPa. During irradiation, there were 300 cycles of the LHR change; each cycling series was followed by exposure. The LHR was changed by moving circumferentially hafnium shielding couples by 90° relative to the tubes with refabricated fuel rods (Fig. 2). The parameters of LHR cyclings in the second experiment with refabricated VVER-1000 fuel rods were as follows:

- initial LHR, kW/m - 17…20;
- LHR increment per a cycle, kW/m - 7…10;
- LHR increase rate, kW/m/min - 0.7…1.0;
- exposure after LHR change in a cycle, h - 4…12.

2. RESULTS AND DISCUSSION

Analysis of the cladding integrity control system readings and samples of MIR.M1 loop facility coolant showed that all the fuel rods preserved their integrity under irradiation. During the experiment, the testing parameters were recorded as well as the readings of the in-pile measurement gages installed on some refabricated fuel rods.

After irradiation, PIEs were done. Below, there are the main results of fuel rods tests and examinations that show the peculiarities of the changes in the high-burnup VVER fuel rods performance under power cycling.

2.1 Change of fuel rods length and diameter

During the experiment with overall measurement of fuel rod parameters (i. 1.1), some parameters of one ~ 51 MWd/kgU burnup refabricated VVER-440 fuel rod were measured. It allowed the results to be presented in the form of parametric dependences. Figures 3 and 4 present the relative elongation and cladding diameter change vs. average LHR (ALHR), respectively. Figure 5 presents the relative elongation and change of the cladding diameter of the same fuel rod under the power cycling [6].

Figure 6 presents axial strain (level and amplitude) of the ~ 50 MWd/kgU burnup VVER-1000 fuel rod cladding irradiated under the power cycling with different number of power cycles and fuel-to-cladding interaction [7]. It also shows the LHR level corresponding to the tight cladding-to-fuel bound. Figure 7 presents fuel temperature vs. relative elongation of ~ 53 MWd/kgU burnup refabricated VVER-1000 fuel rod at different irradiation stages under the power cycling [4].

Based on the above data, the following can be mentioned:

- There was a tight fuel-to-cladding bound at a certain LHR. Under further power increase, the cladding axial strain became higher. Then, as the total exposure time increases at a high level of cyclically changed power, the axial strain decreases and stabilizes;
- Maximal fuel rod elongation was observed during the first power increase. The cladding axial strain amplitude decreased as the number of cycles rose;
- Maximal fuel rod length decrease was observed after the power rise that was typical for the first cycles;
- Residual axial strain (by the in-pile measurement results obtained before and after irradiation) observed after the first cycles made up ~ 0.03…0.05%;
- Residual diametric strain of the ~ 50 MWd/kgU burnup refabricated VVER-440 fuel rod cladding made up ~ 0.1% after the first cycle and remained the same after the second one. The amplitude of the diameter change decreases significantly in the second cycle and further diameter change is the spring area occurs;
- Relative elongation and diametric strain of irradiated fuel rod claddings did not exceed ~ 0.1% (by the results of measurements performed in the hot cell before and after irradiation). These data correlated well with the results of the axial and diametric strain measured during irradiation, for instance in the experiment with the overall measurement of fuel rod parameters (~ 0.08% and ~ 0.06…0.1% for the relative elongation and relative diameter change, respectively) [7];
- At the beginning of cycling, the threshold LHR, at which a tight fuel-to-cladding contact is observed, made up ~ 7…8 kW/m for a ~ 51 MWd/kgU burnup refabricated VVER-440 fuel rod and ~12…15 kW/m for a ~ 53 MWd/kgU burnup refabricated VVER-1000 fuel rod. Further, this value increased gradually till a certain level during the power cycling.

2.2 Fuel rods temperature and LHR

In each of the above experiments, refabricated fuel rods under irradiation were equipped with thermocouples to measure temperature in the fuel column center. The experiments resulted in a large data array on the change of fuel temperature in the 50…60 MWd/kgU burnup VVER fuel rods under the power cycling.

To evaluate a qualitative dependence between fuel temperature and test duration (or burnup) under the power cycling, the relations of fuel temperature to the LHR were considered. To plot the curves, we used LHR values taken at the reference points where the LHR and coolant temperature were stable.

Figures 8 and 9 present fuel temperature vs. ALHR for ~ 51 MWd/kgU and ~ 60 MWd/kgU burnup refabricated VVER-440 fuel rods, respectively [9, 3]. The same relation for a ~ 49 MWd/kgU burnup refabricated VVER-1000 fuel rod is given in Fig. 10. Figure 11 presents the LHR at the thermocouple location in the ~ 50 MWd/kgU burnup refabricated VVER-1000 fuel rod vs. fuel temperature at different irradiation stages for test parameters at a coolant temperature higher than 255°C [4]. Figure 12 presents the change in the ~ 50 MWd/kgU burnup refabricated VVER-1000 fuel rod temperature normalized to the LHR equal to 22 kW/m at the thermocouple location vs. the average fuel rod burnup increment [4].

Analysis of the above data showed that the fuel temperature normalized to a certain LHR decreased after the first cycles and then increased as the burnup and the number of cycles became higher (Fig. 12). Probably, the temperature decrease was conditioned by the tightening of the fuel-to-cladding interaction due to the fuel pellets fragmentation and relocation; further temperature increase was caused by less fuel thermal conductivity at higher burnup and FGR.

2.3 Fission gas release

A higher FGR was observed in some of the VVER fuel rods irradiated in the MIR.M1 loop facility. The peculiarity of these cycling experiments was that the maximal LHR values exceed the designed operating levels. Here, under cycling, the minimal LHR values were either equal to the fuel rod LHR ones at the last stage of the designed operation or close to the maximal ones [5].

The FGR of the ~ 51 MWd/kgU burnup refabricated VVER-440 fuel rod registered by the PF in the experiment with the overall measurement of fuel rod parameters is shown in Figure 13 and characterized by the following [7]:

- FGR occurred both at the LHR increase and its decrease to the initial level after a certain exposure at the upper power level; the major part of fission gas releases during the first cycle;
- When operating at the upper LHR level after the first and second power increase, the FGR was still going on. Moreover, the FGR rate decreased significantly during a ~ 6-hour exposure; no FGR was observed at a low power level;
- Difference in the FGR rates (at the beginning of the cycle and during exposure) confirmed two release mechanisms to exist («explosive» and «diffusive»).

Figure 14 presents the change in the fuel temperature and gas pressure under the ~ 49 MWd/kgU burnup refabricated VVER-1000 cladding during the first forty cycles. It follows from the above data that multiple power cyclings did not cause any significant increase in the gas pressure (i.e. FGR). The major part of the gas pressure increase was observed under the transient conditions before cycling [10].

Figure 15 presents the PIE results on the FGR from 51…63 MWd/kgU burnup (accounting its increase under irradiation) refabricated VVER-440 and VVER-1000 fuel rods tested under the power cycling vs. the ALHR (max value) [5].

Results of experiments performed within the above burnup ranges and under the irradiation conditions show no significant difference in the FGR of VVER-440 and VVER-1000 fuel rods. In addition, the number of LHR cycles (up to 300) does not influence significantly the intensification of FGR at the ALHR that does not exceed ~ 30 kW/m. It should be noted that in the experiment with the overall measurement of fuel rod parameters, the FGR in the ~ 51 MWd/kgU burnup refabricated VVER-440 fuel rod evaluated by PIE (~ 13.5%) correlated well with the corresponding data obtained during test (Fig. 13).

CONCLUSION

In conclusion, it should be said that:

- All the VVER fuel rods tested in the MIR.M1 loop facility at the increased LHR, as compared to the NPP designed one, preserved their cladding integrity;
- Experimental data were obtained on the axial and radial cladding strain and FGR from 50…60 MWd/kgU burnup VVER-440 and VVER-1000 fuel rods as well as on the kinetics of these parameters and fuel temperature change under power cycling;
- Non-destructive PIE results correlated well with the corresponding data obtained during testing with the use of in-pile measurement gages.

The tests of the 50…60 MWd/kgU burnup VVER fuel rods performed under a 100-60-100% power cycling range and further PIE confirmed their high performance and reliability. Information about the irradiation conditions and tests and PIE results is used to assess the high-burnup VVER fuel rods performance under the same operating conditions and to verify calculation codes.

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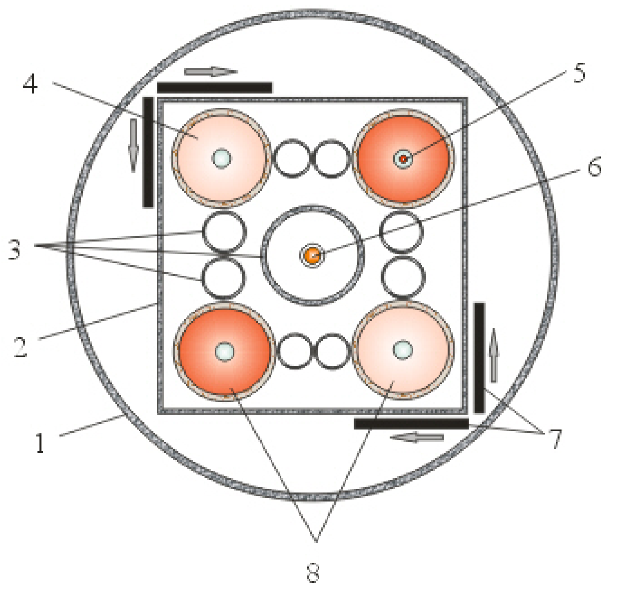
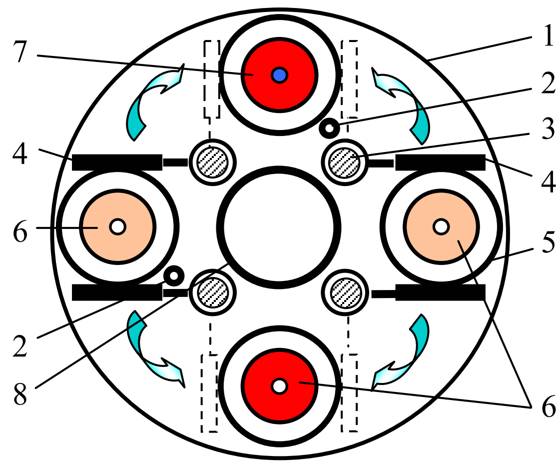


1 - IR duct; 2 - guiding jacket; 3 - displacers; 4 - refabricated fuel rod with PF; 5 - refabricated fuel rod with thermocouple; 6 - neutron detector; 7 - hafnium movable shielding; 8 - refabricated fuel rods with CE

Figure 1. IR cross-cut to test refabricated VVER fuel rods under power cycling (option I)



1 - bottom flange; 2 - neutron detector; 3 - shielding rotation axis; 4 - hafnium movable shielding; 5 - through flow tube; 6 - refabricated fuel rods with CE; 7 - refabricated fuel rod with thermocouple; 8 – displacer

Figure 2. IR cross-cut to test refabricated VVER fuel rods under power cycling (option II)

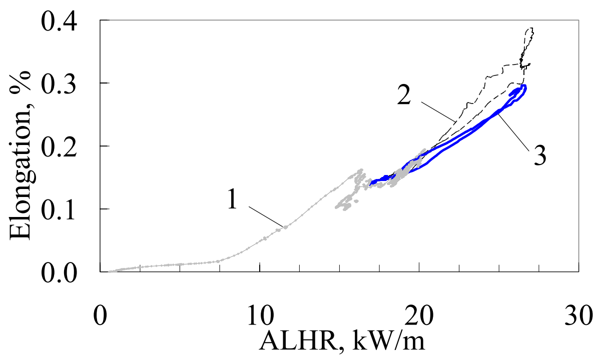


Figure 3. Relative elongation of ~ 51 MWd/kgU burnup refabricated VVER-440 fuel rod vs. ALHR during start-up (1), during the 1st (2) and 2nd (3) cycles

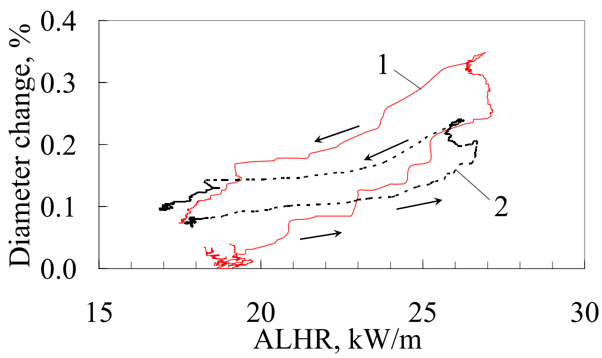


Figure 4. Relative change of ~ 51 MWd/kgU burnup refabricated VVER-440 cladding diameter vs. ALHR during the 1st (1) and 2nd (2) cycles

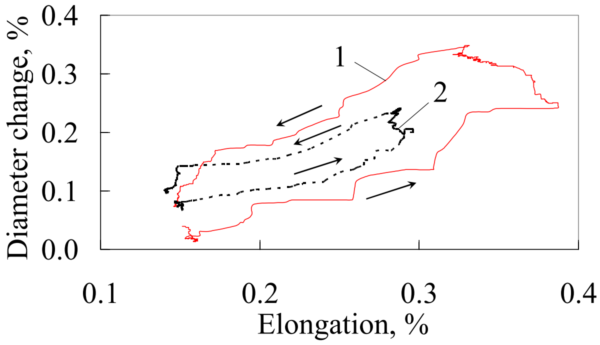


Figure 5. Relative elongation vs. relative diameter change of ~ 51 MWd/kgU burnup refabricated VVER-440 fuel rod during the 1st (1) and 2nd (2) cycles (arrows indicate the direction of a parameter change in time)

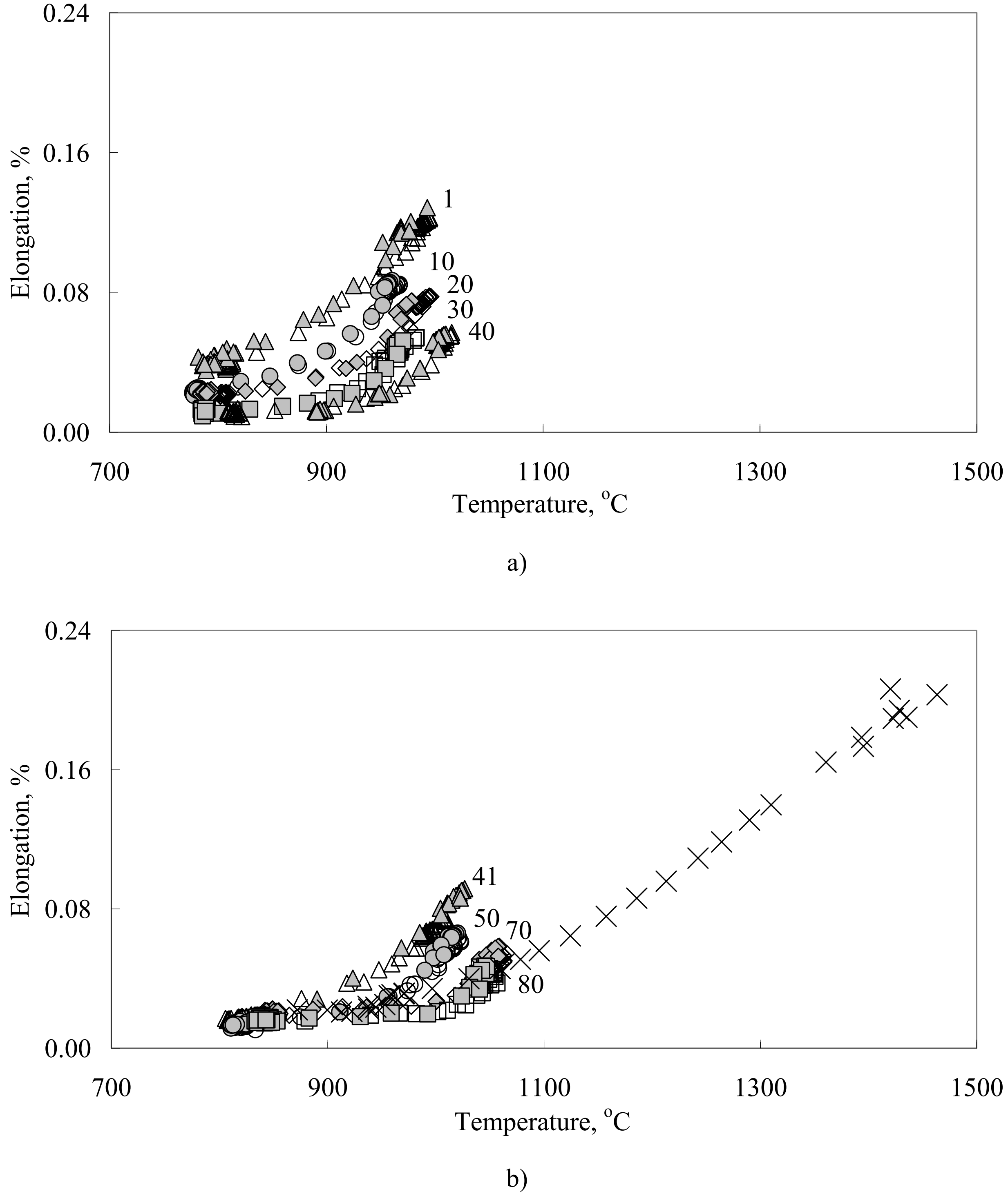
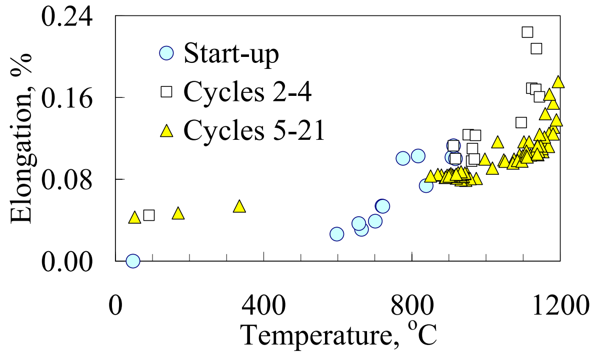
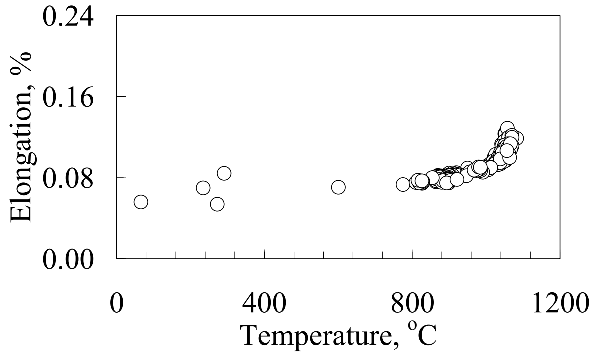


Figure 6. Relative elongation of ~ 50 MWd/kgU burnup refabricated VVER-1000 fuel rod vs. fuel temperature under power cycling: first 40 cycles (a); the other 40 cycles and power ramp (×) after intermediate exposure (b); power increase (Δ, ○, ◊, □) and decrease (▲,●,♦, ■) (figures are number of cycles)



a)



b)

Figure 7. Relative elongation of ~ 53 MWd/kgU burnup refabricated VVER-1000 fuel rod vs. fuel temperature under power cycling: start-up and cycles 2-21 (a); cycles 121-182 (b)

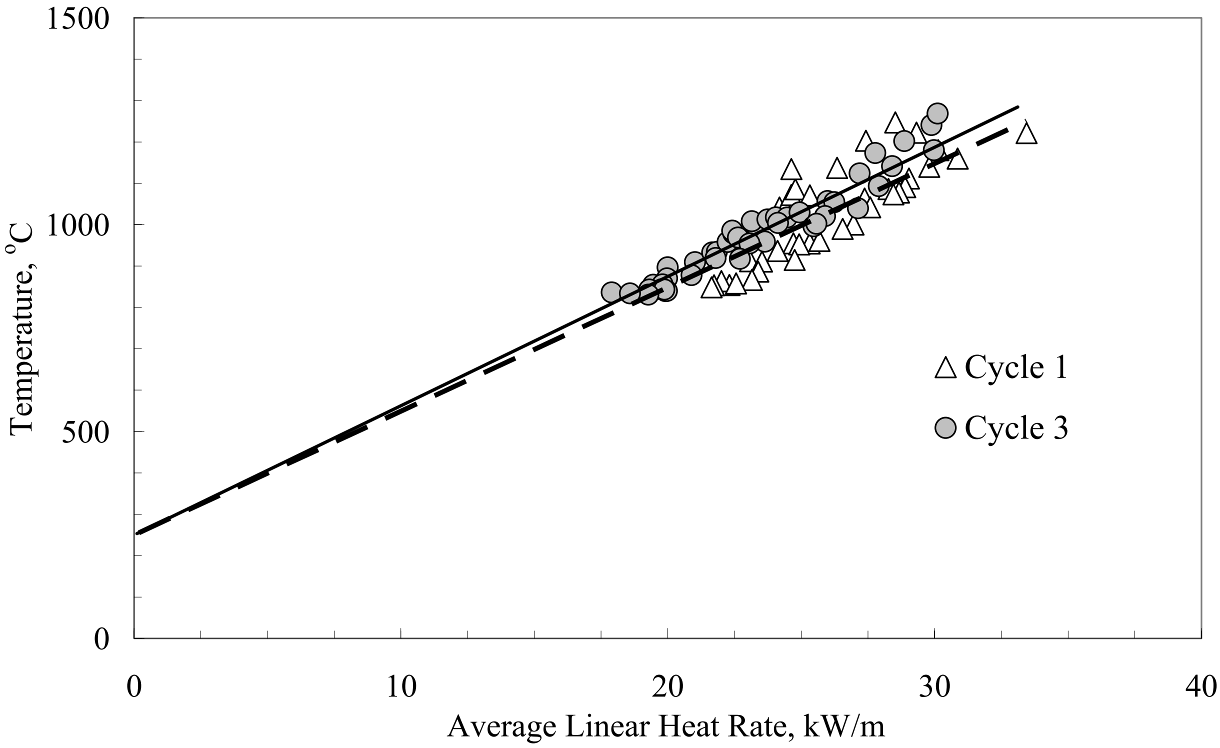


Figure 8. Fuel temperature vs. ALHR for a ~ 51 MWd/kgU burnup refabricated VVER-440 fuel rod under power cycling

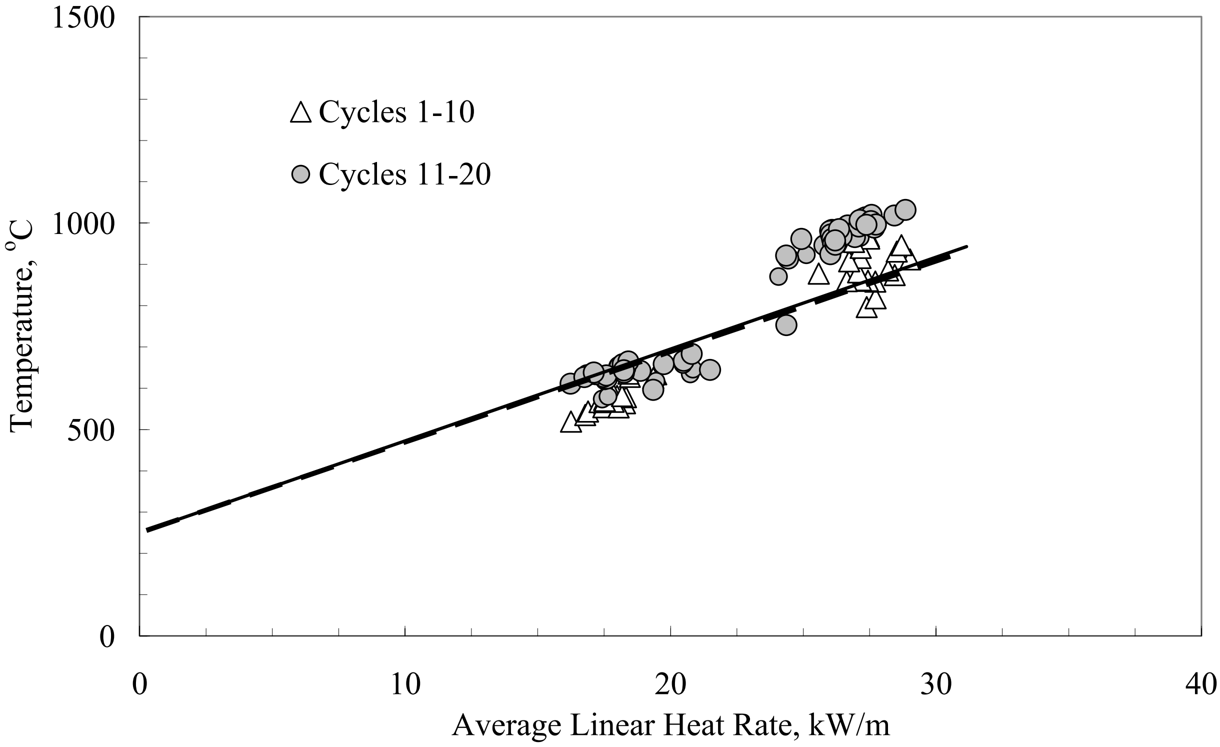


Figure 9. Fuel temperature vs. ALHR for a ~ 60 MWd/kgU burnup refabricated VVER-440 fuel rod under power cycling

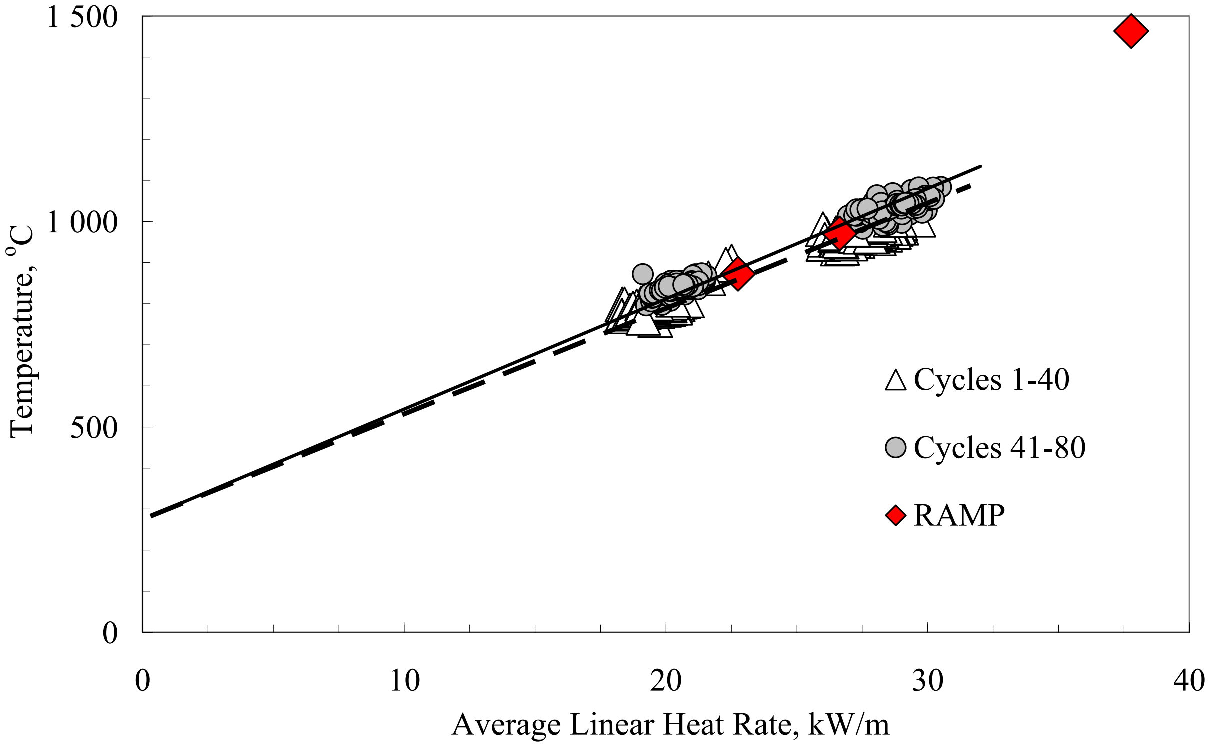


Figure 10. Fuel temperature vs. ALHR for a ~ 49 MWd/kgU burnup refabricated VVER-1000 fuel rod under power cycling

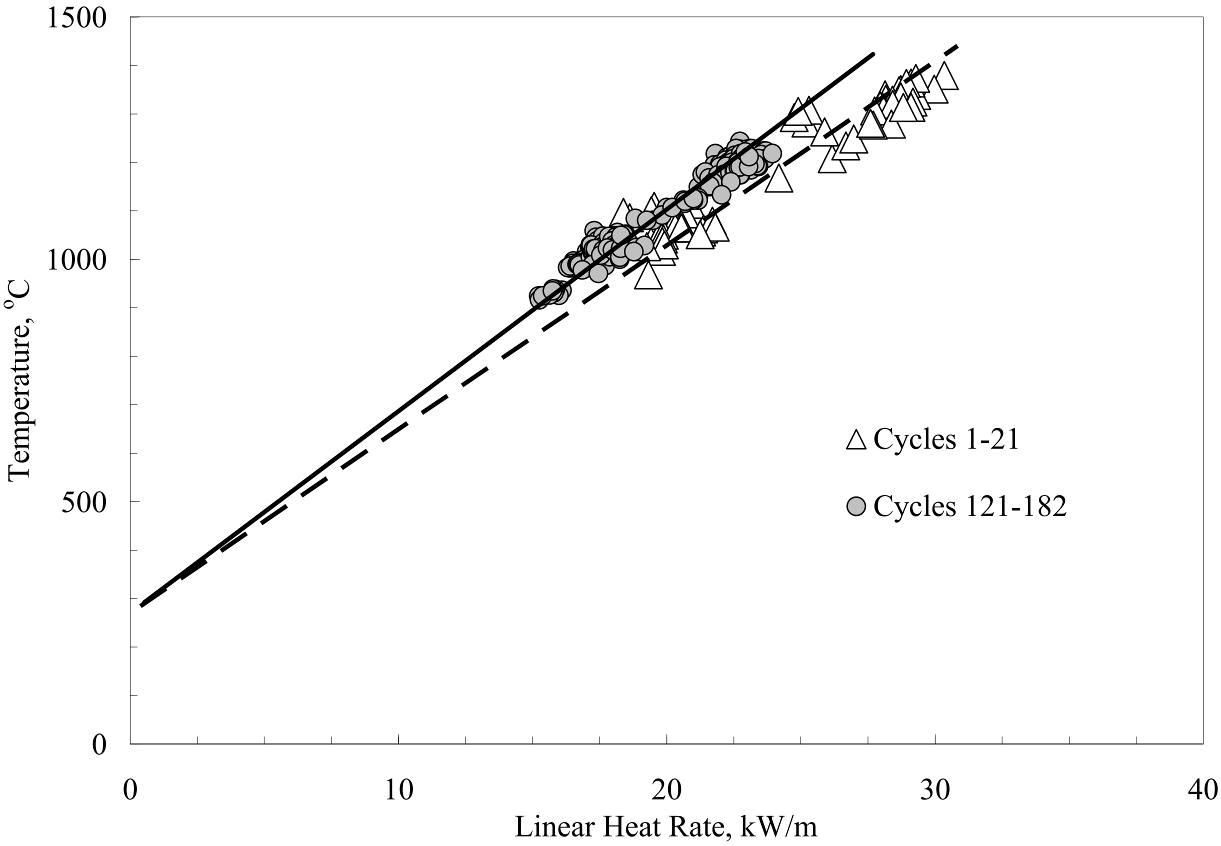


Figure 11. Fuel temperature vs. LHR at the place of thermocouple location
for a ~ 50 MWd/kgU burnup refabricated VVER-1000 fuel rod under power cycling
for test parameters at a coolant temperature higher than 255°C

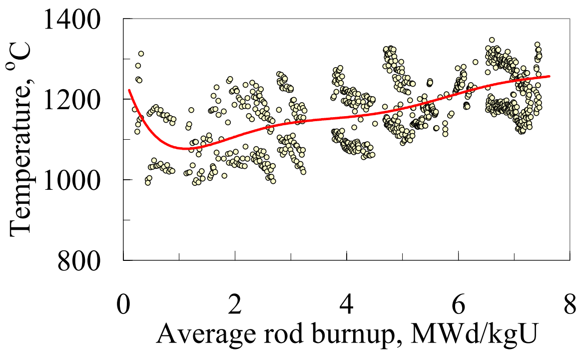


Figure 12. Change in the ~ 50 MWd/kgU burnup refabricated VVER-1000 fuel rod temperature
normalized to the LHR equal to 22 kW/m at the thermocouple location
vs. the average fuel rod burnup increment under power cycling

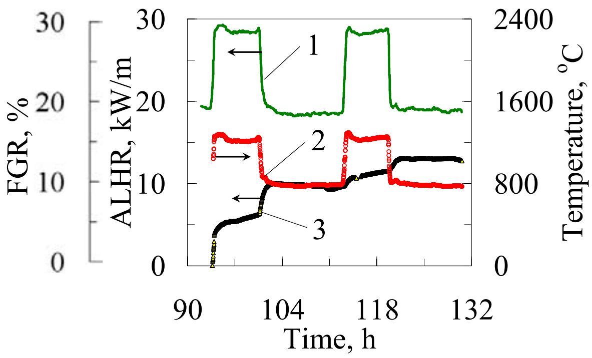


Figure 13. Change of ALHR (1), fuel temperature (2) and FGR (3)
for ~ 51 MWd/kgU burnup refabricated VVER-440 fuel rod under power cycling

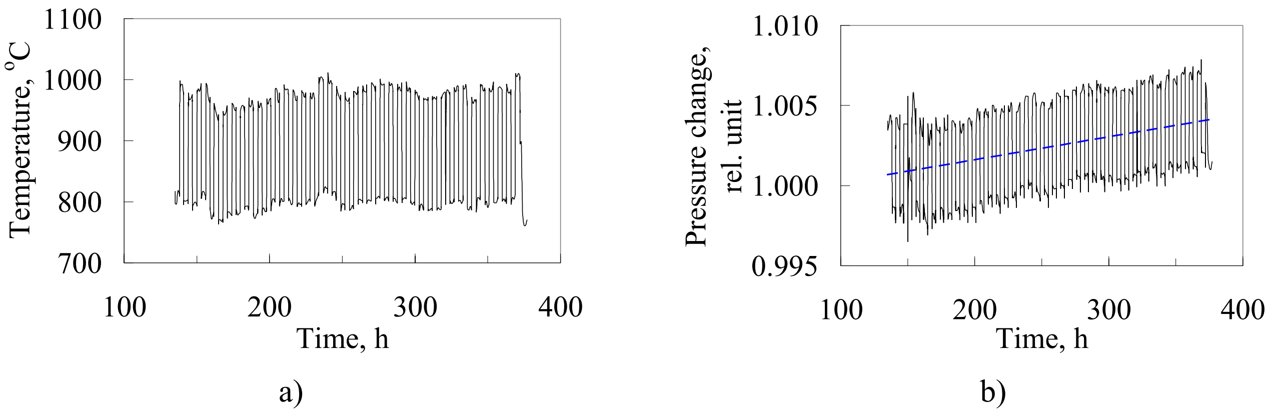


Figure 14. Change of fuel temperature (a) and under-cladding gas pressure (b)
in the~ 49 MWd/kgU burnup refabricated VVER-1000 fuel rod under power cycling (cycles 1-40)

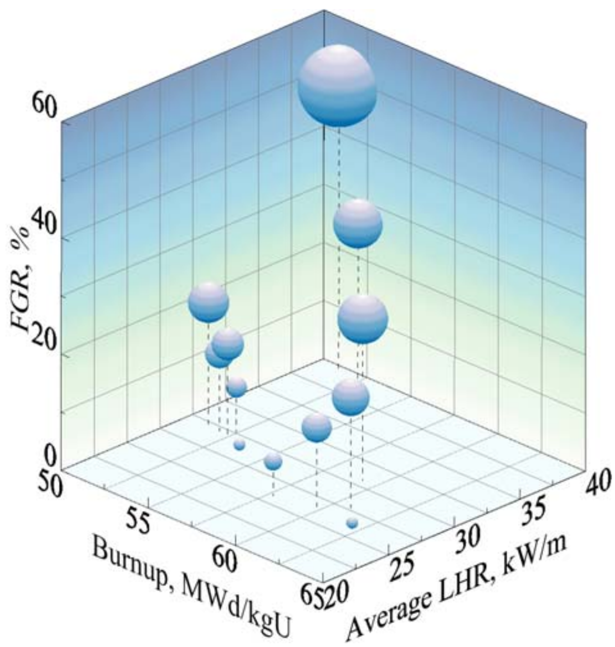


Figure 15. FGR in ~ 51…63 MWd/kgU burnup VVER fuel rods
vs. ALHR (max value) under power cycling