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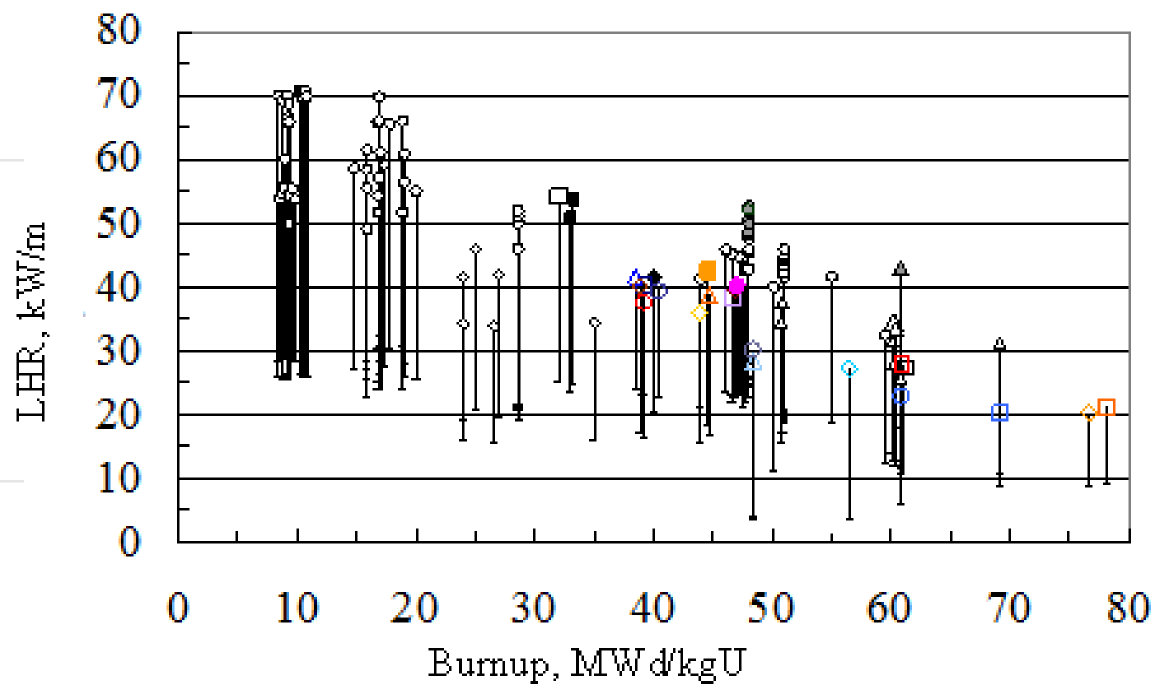
ROSATOM STATE CORPORATION ENTERPRISE

POWER RAMPING AND CYCLING TESTING OF VVER FUEL RODS IN THE MIR REACTOR

A.G. Eshcherkin*, V.A. Ovchinnikov, E.E. Shakhmut, E.E. Kuznetsova, A.L. Izhutov, V.V. Kalygin

INTRODUCTION

A series of experiments has been conducted at the MIR reactor with simulating power ramp, step-up and cycling conditions to experimentally confirm the maximum inner pressure and stress limits for the water-cooled reactor fuel rod claddings both under abnormal operating conditions and power cycling. As a result of these experiments, linear heat rate (LHR) and cladding ultimate residual strain have been obtained at which fuel leakage occurs or does not occur, as well as gas release from the fuel composition and source data to calculate cladding stress.



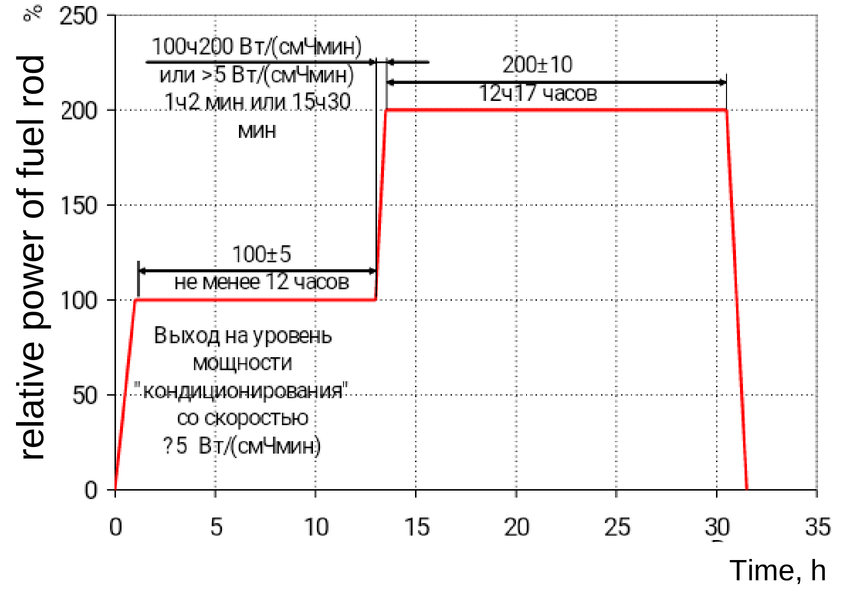
The safety-critical criteria for the nuclear power plants (NPPs) operating VVER are identified by the following initial events:

- uncontrolled withdrawal of control rods;
- unintended decrease of boron concentration in coolant;
- improper connection of the main circulation loop;
- human error when damping xenon variation.

Tested were refabricated or full-size VVER fuel rods and gadolinium fuel rods with different burnup from standard or modernized fuel assemblies (FAs) operated at NPPs.

INTRODUCTION

In the first power ramping stage, the fuel rods were tested for at least 12 hours under thermal loads and parameters specific to the end of irradiation at a NPP. Then the power was increased at a rate of 5...200 W/(cm×min) depending on the simulated initial event, techniques applied in similar tests and requirements of the national licensing authorities. The linear heat rate was increased up to the level at which fuel leakage was expected to occur or fuel rods performance was confirmed. After that the fuel rods were tested for about 12... 17 hours at constant power.



These experiments show that fuel rods leakage occurs according to the stress corrosion cracking mechanism (SCC) that depends on the following parameters:

- **nuclear fuel burnup;**
- **LHR ratio after and before power increase (power increase amplitude);**
- **LHR increase rate;**
- **time interval under stress.**

Power ramp → 5…30 minutes

Power ramp → 1…2 minutes

POWER INCREASE TIME

The amplitude, LHR increase rate, cycling mode, time of operation at reduced and increased power depend on the simulated process, power increase method and reactor design.

Fuel rod power change techniques

Different techniques are used at research reactors to change fuel rods power:

•axial displacement of absorbing screens heightwise the core and tested fuel rods; for this purpose, a scram rod is introduced into the core;

•axial displacement of the fuel rods relatively the screen; in this case, the power increase field moves along the fuel rod;

•azimuthal displacement of the fuel rods or absorbing screens in the irradiation rig (IR); in this case, there is no considerable impact on reactor operation;

•horizontal movement of the fuel rods along with the channel relatively the core with no considerable impact on reactor operation;

•change in the pressure (amount) of absorbing gas (He-3) in the tubes serving as absorbing screens.

Each technique has its pros and cons.

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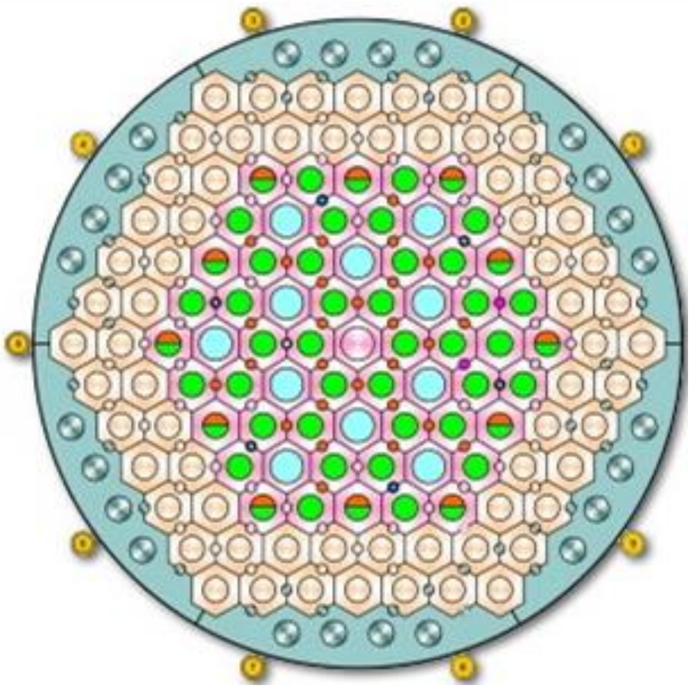
Fuel rod power change techniques applied at the MIR reactor

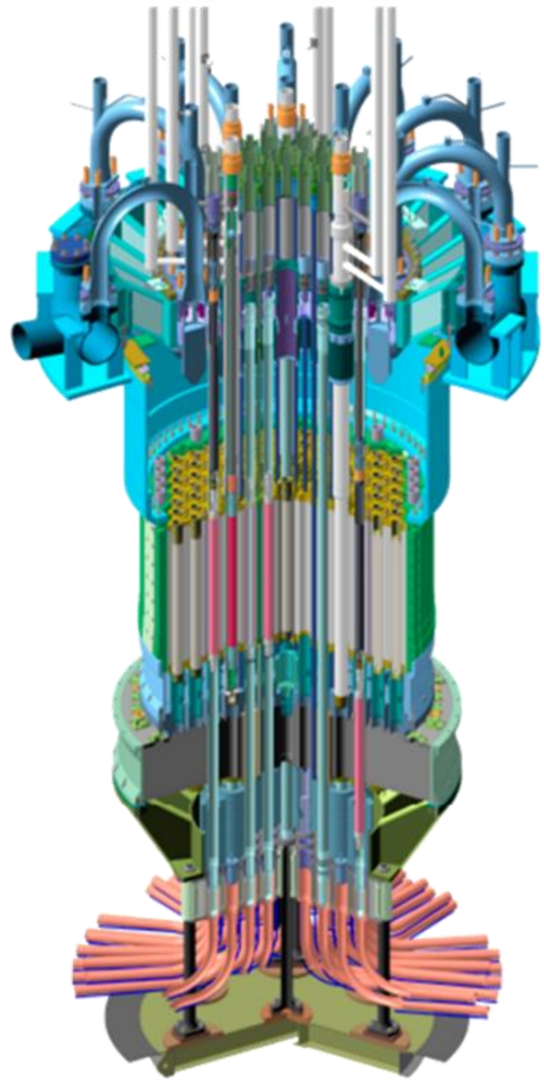


– operating FA channel

– experimental channel

– combined operating FA with absorber

– control rod channel



Loop-type test reactor MIR was purposely designed to perform long-term lifetime tests of fuel assemblies, fuel rods and structural materials of various reactors. MIR is a pool-type reactor with beryllium moderator and reflector. Figure 1 shows reactor core (1 m high) arrangement. Since 1990s, the MIR reactor has been used to develop, implement and improve fuel rod power change test techniques. For such experiments, specific techniques have been developed and successfully applied as well as experimental rigs and in-pile gages.

Fuel rod power change techniques applied at the MIR reactor

During this period of time, about 120 VVER fuel rods have been tested under the power ramping and step-up modes; about 20 VVER fuel rods have been tested under the power cycling conditions. In 2011 the professionals from VNIINM and RIAR developed a new program for a series of ramp tests with Russian-made fuel rods and gadolinium fuel rods of VVER and PWR including thinned cladding fuel rods and increased diameter fuel pellets with no hole.

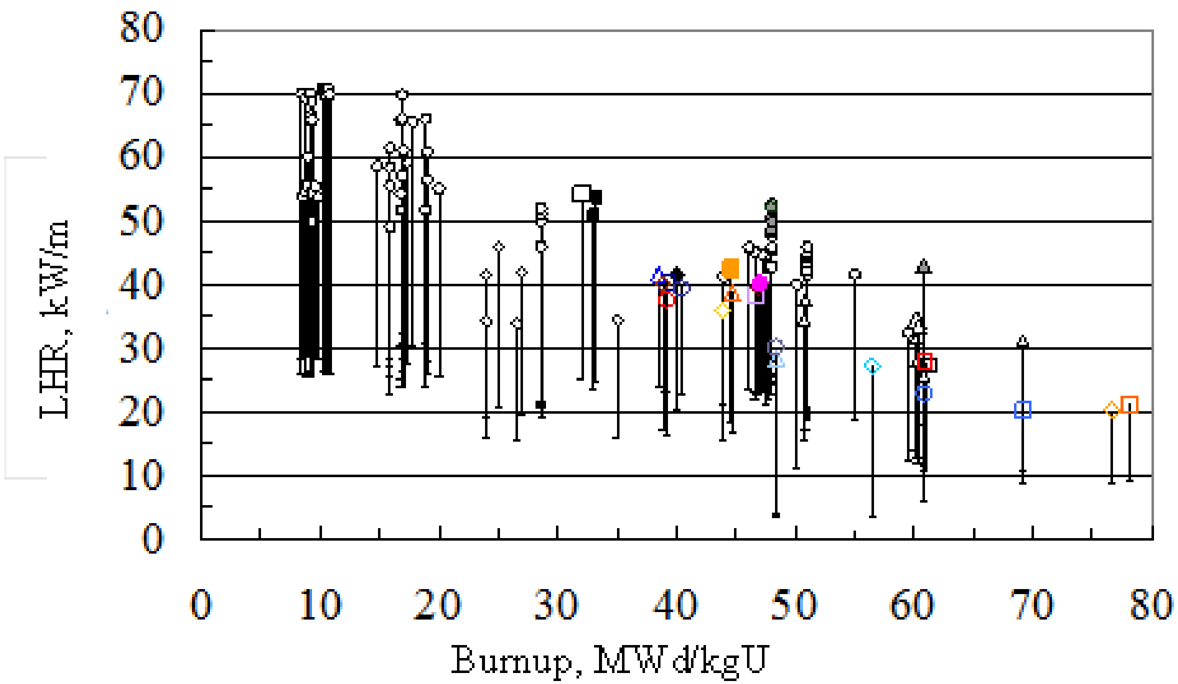


Figure 2 – LHR increment for fuel rods under the power ramping and step-up modes

Fuel rod power change techniques applied at the MIR reactor

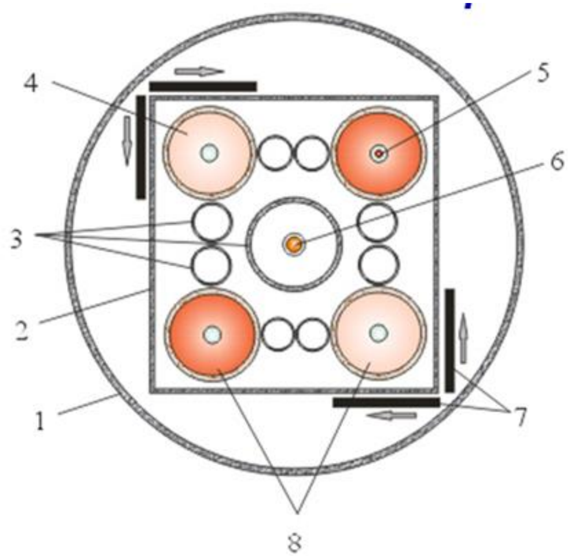
Since 2012 five experiments (NG1…NG5) have been performed in which three full-size Gd fuel rods and eleven full-size fuel rods (FSFR) have been tested. The next experiments are being prepared.

The MIR reactor physical and design parameters enable power ramping tests without using extra absorber in the irradiation rig. In such tests the reactor was brought to power providing for the required initial conditions in the loop channel. The control rods closest to the loop channel with the irradiation rig were in the low position. After all parameters had become stable at this power level, there was a power ramp with the necessary amplitude. At the first stage the closest control rods were removed in parallel with compensation of inserted positive reactivity by immersing the control rods in other core areas. In this very moment the IR power was kept constant, and the reactor power was decreasing. Then a power ramp was done by increasing the total reactor power within the set time interval. After that, the IR power was kept constant by removing periodically the control rods.

Following this algorithm, the power ramp was used within 5…30 minutes, and the ratio of power after ramp to power before ramp (amplitude) made up 1.5…3 relative units (see Figure 2).

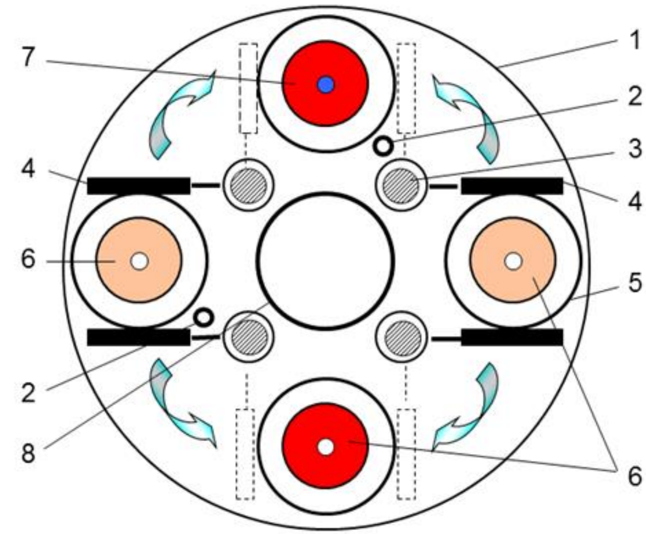
Fuel rod power change techniques applied at the MIR reactor

Experimental rigs with moving hafnium absorbing screens (plates) were specifically designed for fuel power cycling tests at the MIR reactor. Their layouts are presented in the figure 3.



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

Irradiation rig (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

Irradiation rig cross-cut to test refabricated VVER fuel rods under power cycling (option II)

Figure 3 – Experimental rigs to test fuel rods under power cycling

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Fuel rod power change techniques applied at the MIR reactor

Several such tests have been conducted when the power change amplitude made up ~1.5 relative units (see Figure 4) and the power change time was 10…20 minutes.

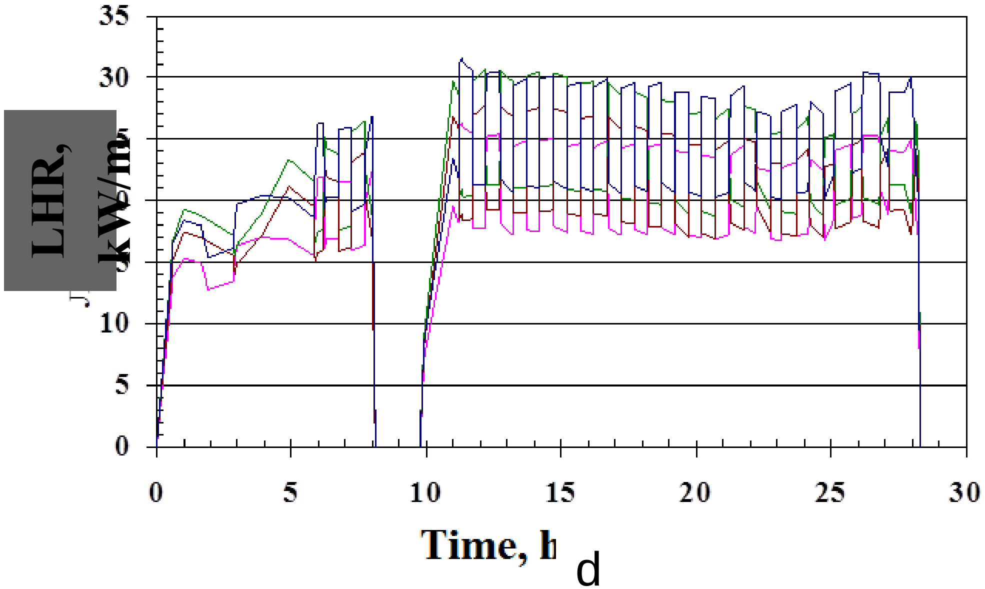


Figure 4 – LHR of different fuel rods during power cycling tests

An irradiation rig was designed [2] to test both shortened (refabricated, experimental) and full-size VVER-1000 fuel rods (~3.9 m long) under rapid power change conditions. The fuel rod test part is 1…1.5 m high taking into account the MIR core height (1m) and extrapolated neutron escape areas above and under the core.

Fuel rod power change techniques applied at the MIR reactor

Figure 5 shows the IR schematic representation. The IR enables changing the linear heat rate about twice during several and more seconds at constant reactor power. The power is changed due to screen rotation about the rig axis or fuel rods basket. The screen is rotated with the use of the driven shaft located in the space above the reactor. A similar rig provides for tests under power cycling conditions.

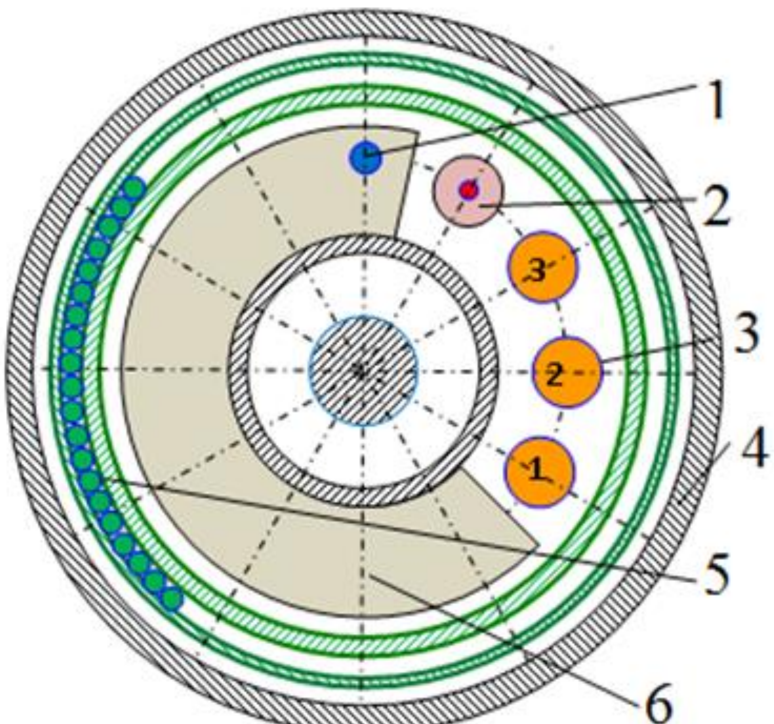


Figure 5 – IR to test fuel rods under power ramping (top view):

1 – self-powered detector (SPD);
2 – thermometric fuel rod;
3 – full-size fuel rods;
4 – loop channel;
5 – absorbing screen;
6 – central tube with a lateral displacer

Fuel rod power change techniques applied at the MIR reactor

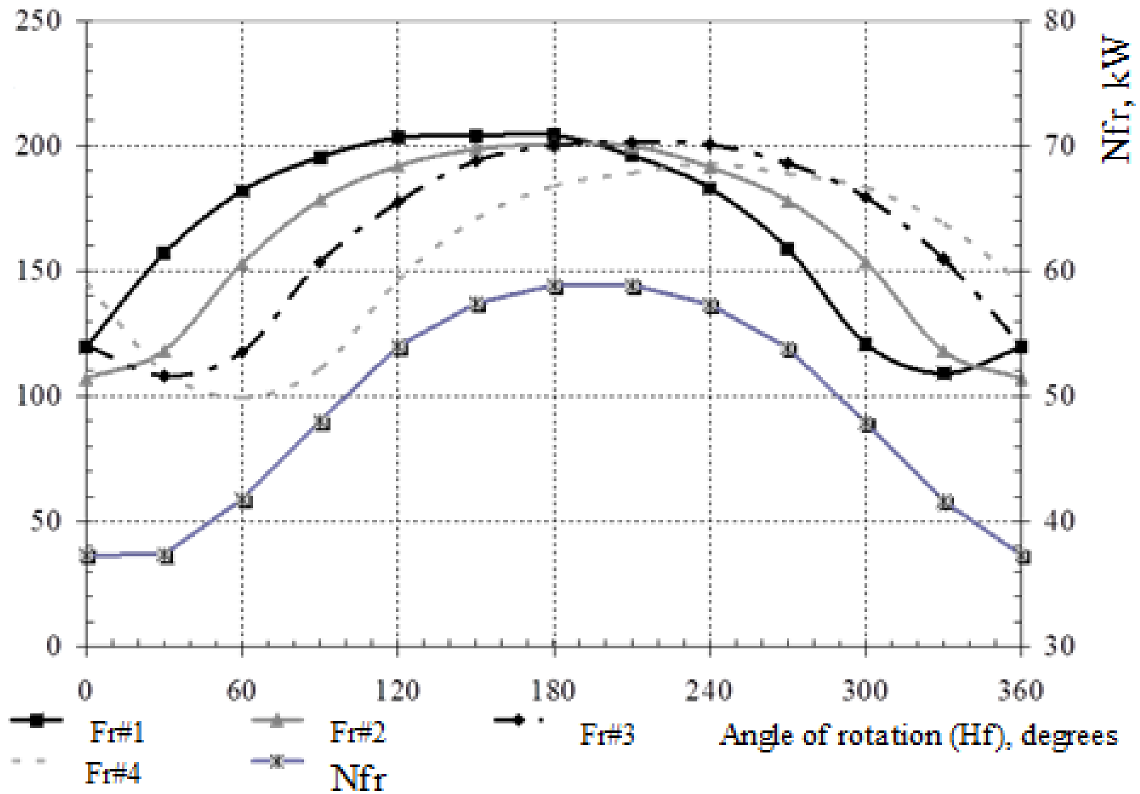


Figure 6 – Max LHR and total power of fuel rods vs. absorbing screen angle of rotation (counterclockwise) at specific reactor power

Fuel rod power change techniques applied at the MIR reactor

A similar rig was tried out. The screens were rotated at constant power of FAs surrounding the experimental rig. The neutron detector and fuel temperature gage readings were recorded. The neutron detector readings were compared with the calculation data for the neutron flux density. Acceptable reproducibility was observed, the deviation not exceeding 3%. After check the reactor was shut down.

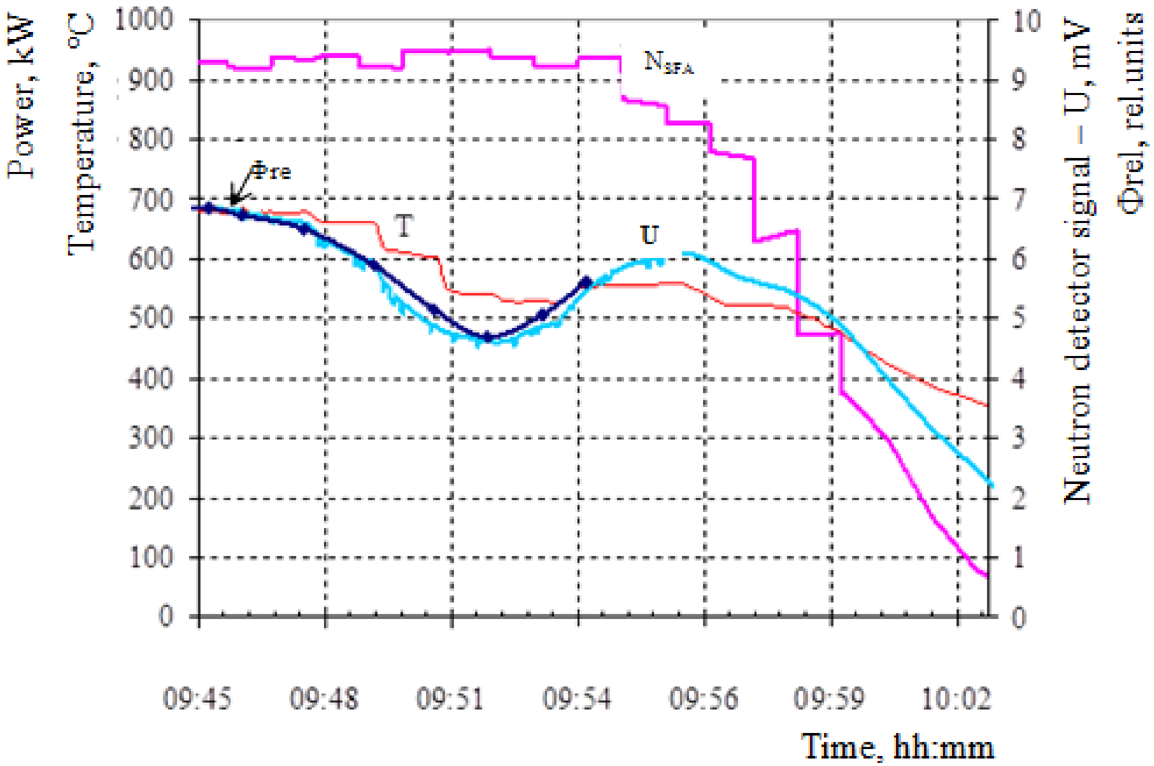
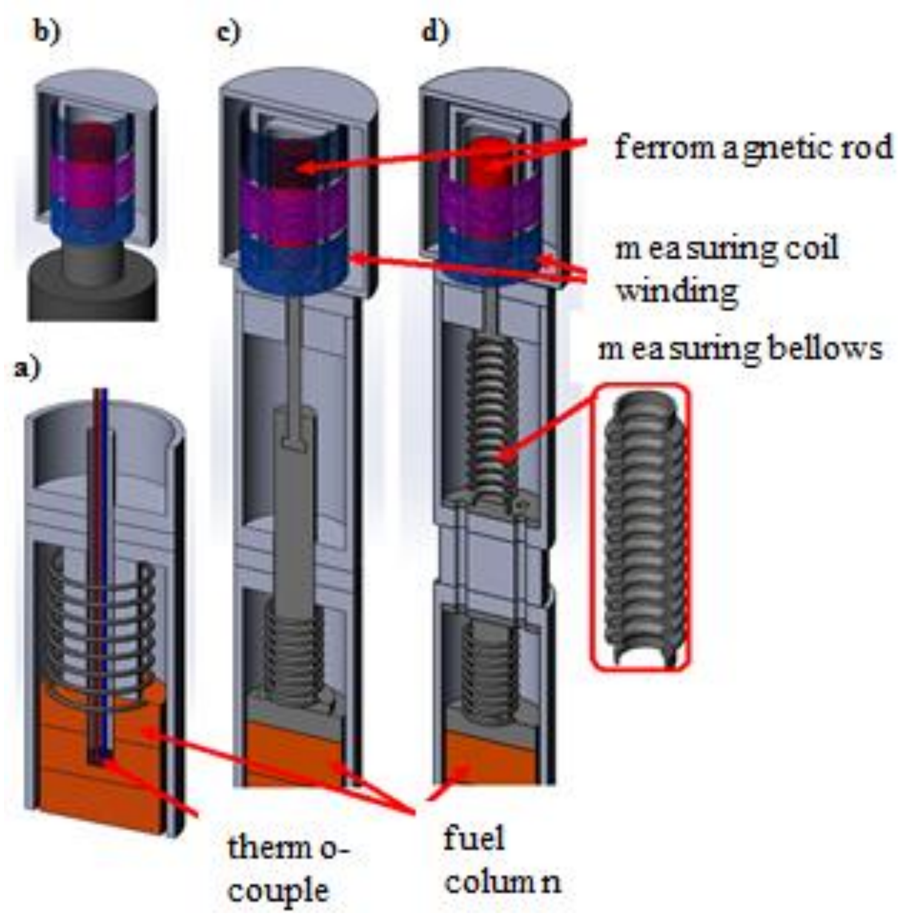


Figure 7 – IR trial operation

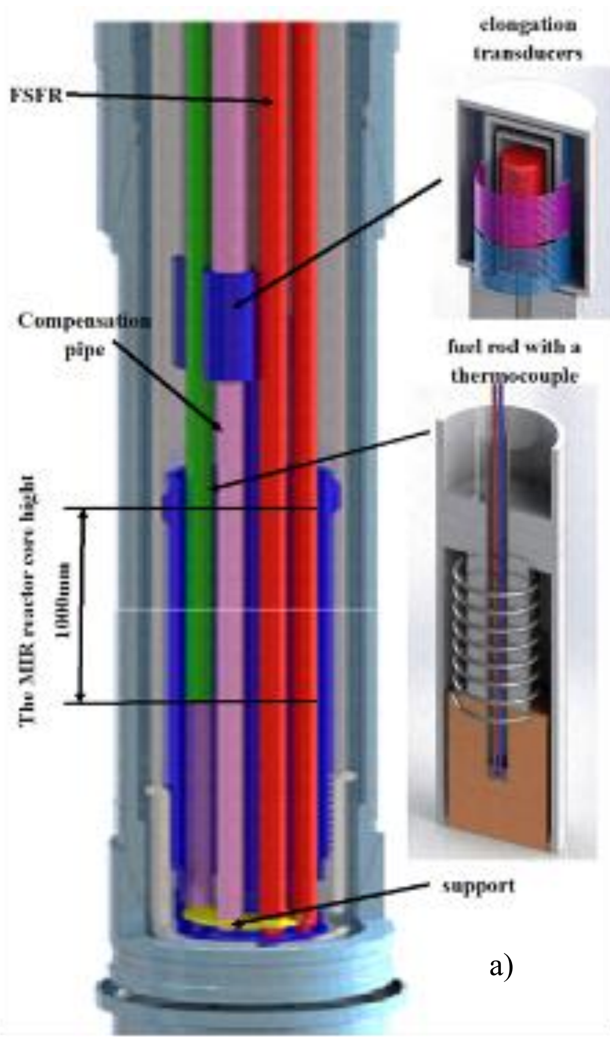
Measured parameters of the fuel rods and irradiation rig during tests



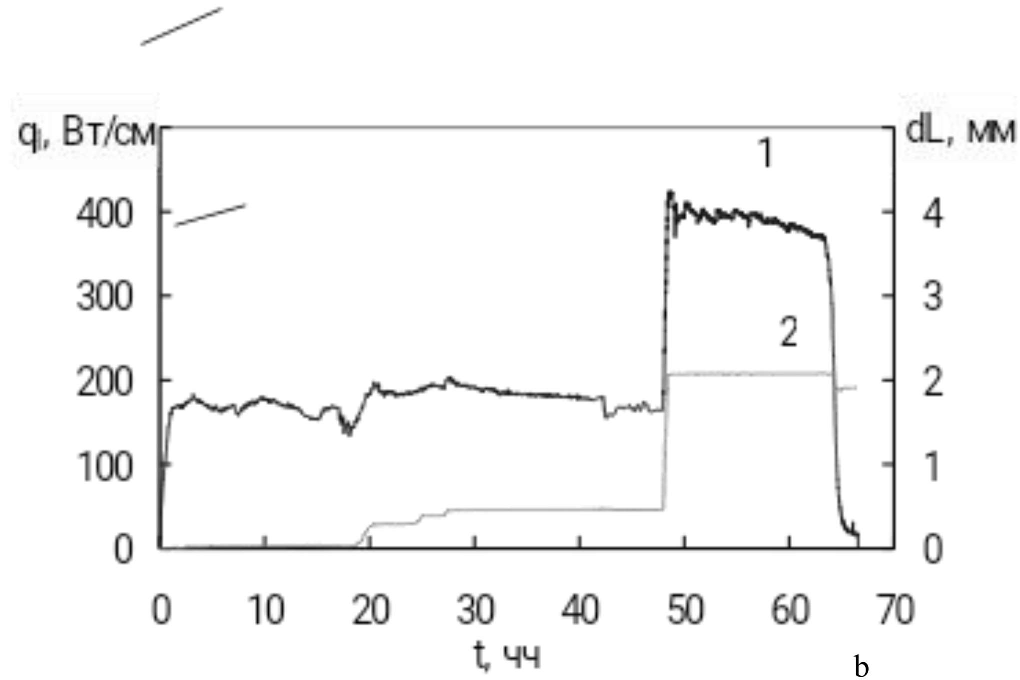
During in-pile tests cladding thermomechanical loading and stress relaxation can be monitored using, for example, fuel rod or fuel column elongation transducers; fission gas release under the cladding can be checked using pressure gages. The temperature in the fuel meat center is measured by chromel–alumel or tungsten–rhenium thermocouples depending on the measured temperature range. Figure 8 presents schematic design of some in-pile gages developed at JSC “SSC RIAR”.

Figure 8 – In-pile gages to measure fuel rod temperature (a), fuel cladding elongation (b), fuel column elongation (c), gas pressure under the cladding (d)

Measured parameters of the fuel rods and irradiation rig during tests



a)



b
)

Figure 9 – Rig with elongation transducers intended for the full-size fuel rods test part (a) and results of measuring LHR (1) and fuel rod elongation (2) in one of the experiments (b)

Measured parameters of the fuel rods and irradiation rig during tests

During tests at the MIR reactor fuel cladding integrity is checked using standard systems of monitoring the rate of gamma radiation dose from loop facility pipelines (see Figure 10). The peak in the diagram shows that there is loss of fuel cladding integrity.

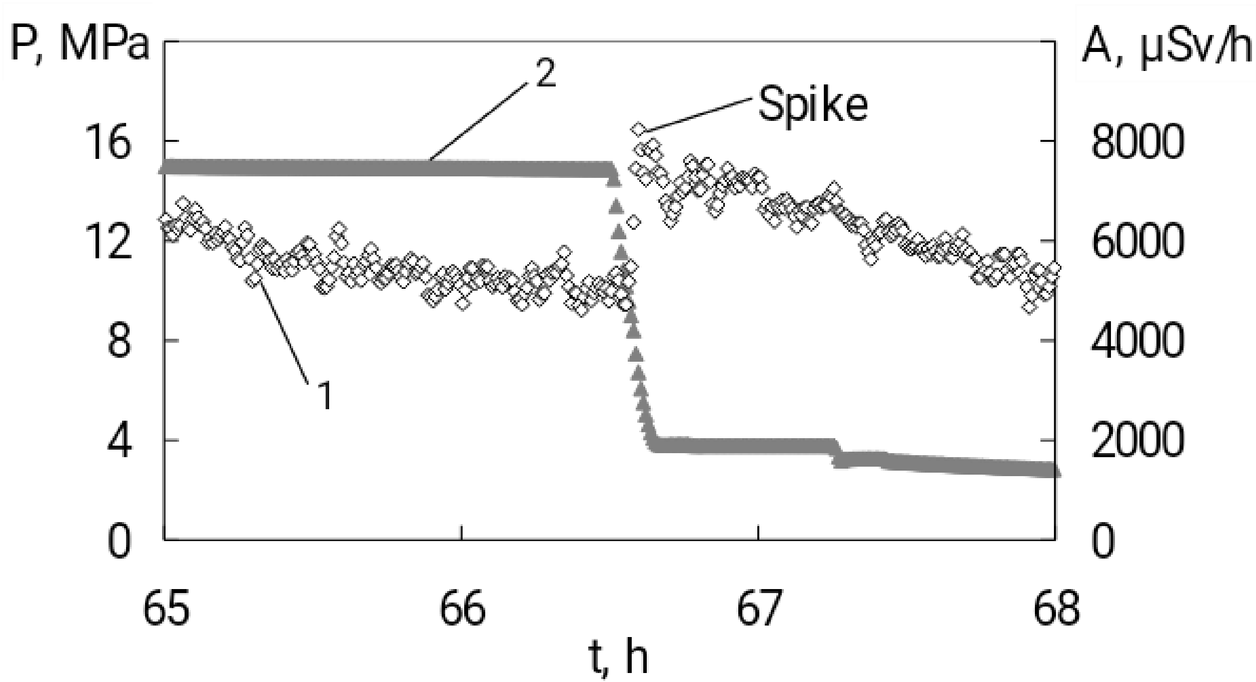


Figure 10 – Change in the radiation dose rate (1) from pipelines when reducing pressure (2) after reactor shutdown in one of the experiments

Some results of post-irradiation examinations in the hot cells

After testing and decay heat decrease the fuel rods are sent for examinations to the RIAR's hot cells. In these examinations the pre-test calculation and test measurement results are confirmed. Table 2 contains changed fuel rod length measured by transducers in the experiments and obtained through direct measurement after experiments (residual elongation).

Table 2 – Fuel rod elongation

Full-size fuel rod #	Measured elongation at the maximum thermal neutron flux density/ after reactor shutdown, mm	Residual elongation direct measurement data, mm
4	2.07 / 1.91(see Figure 9)	1.91 ± 0.14
6	1.23 / 1.06	1.06 ± 0.14
8	3.21 / 2.55	2.47 ± 0.11
309	3.18 / 1.26	1.17 ± 0.11

Some results of post-irradiation examinations in the hot cells

When examining the fuel rod condition after power ramping, several fuel rods were detected having through cracks in the cladding resulted from stress corrosion cracking. The remaining fuel rods kept their integrity.

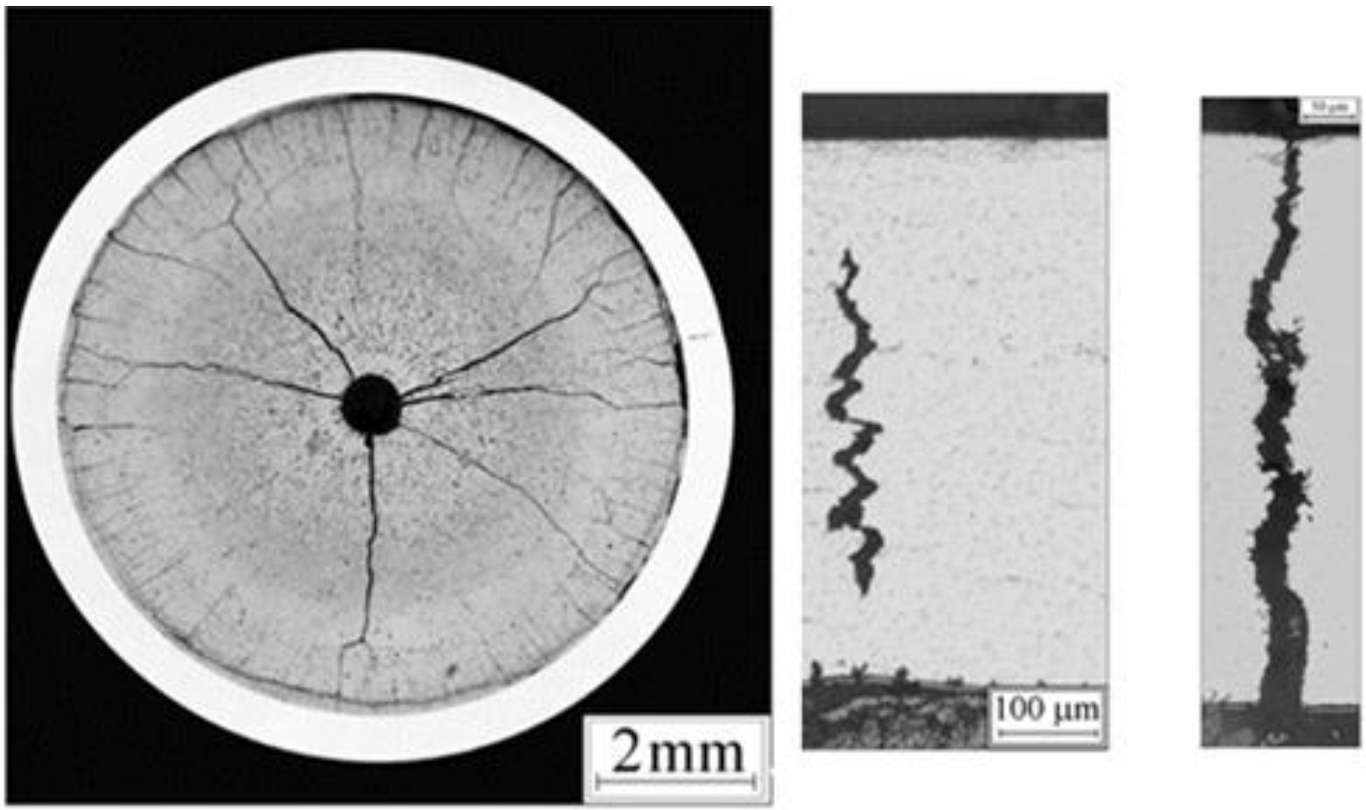


Figure 11 – Structure of a leaky fuel rod

Some results of post-irradiation examinations in the hot cells

During the examinations gamma scanning (see Figure 12) was carried out, fuel rod cladding length and diameter were measured (see Figure 13), and gas composition in the plenum was examined.

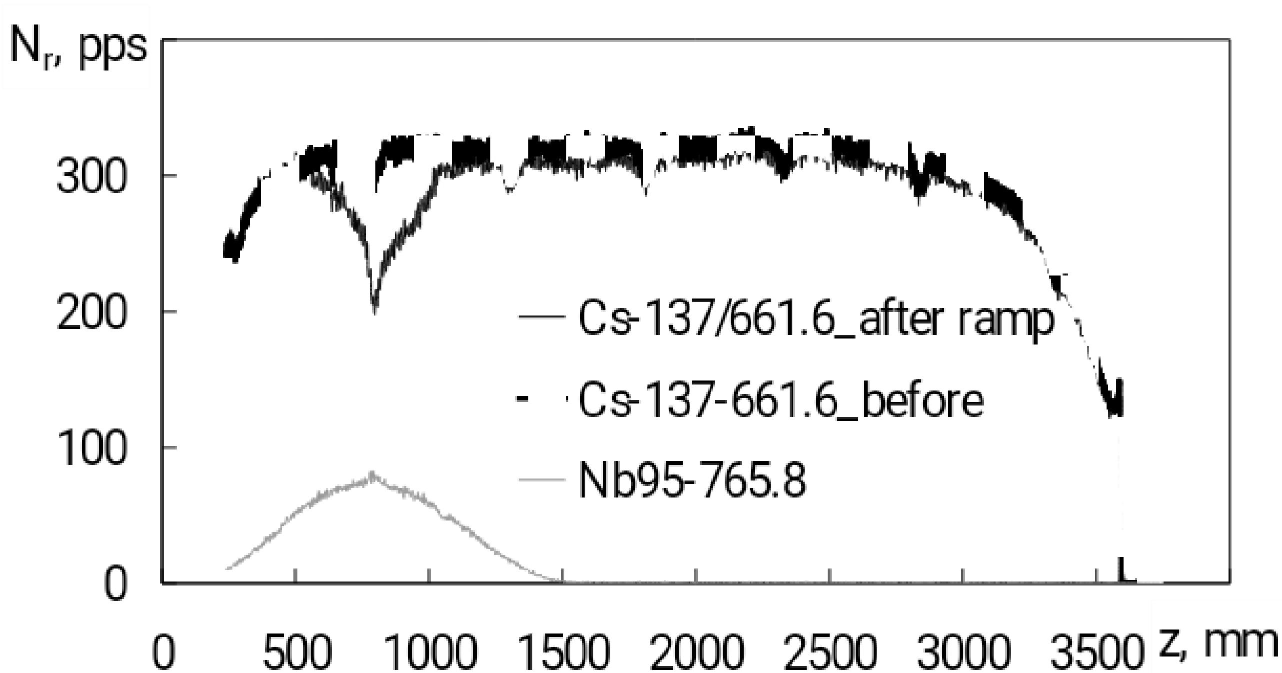


Figure 12 – Gamma intensity heightwise distribution of 137Cs before tests (1), 137Cs (2), 134Cs (3) after tests (I1) and 95Nb (4), 95Zr (724 keV) (5) (I2) for a leaky full-size fuel rod

Some results of post-irradiation examinations in the hot cells

Change in the fuel rod diameter in different areas heightwise being specific to the relevant LHR increment in ramp and burnup, strain was observed in the areas 500…700 mm long.

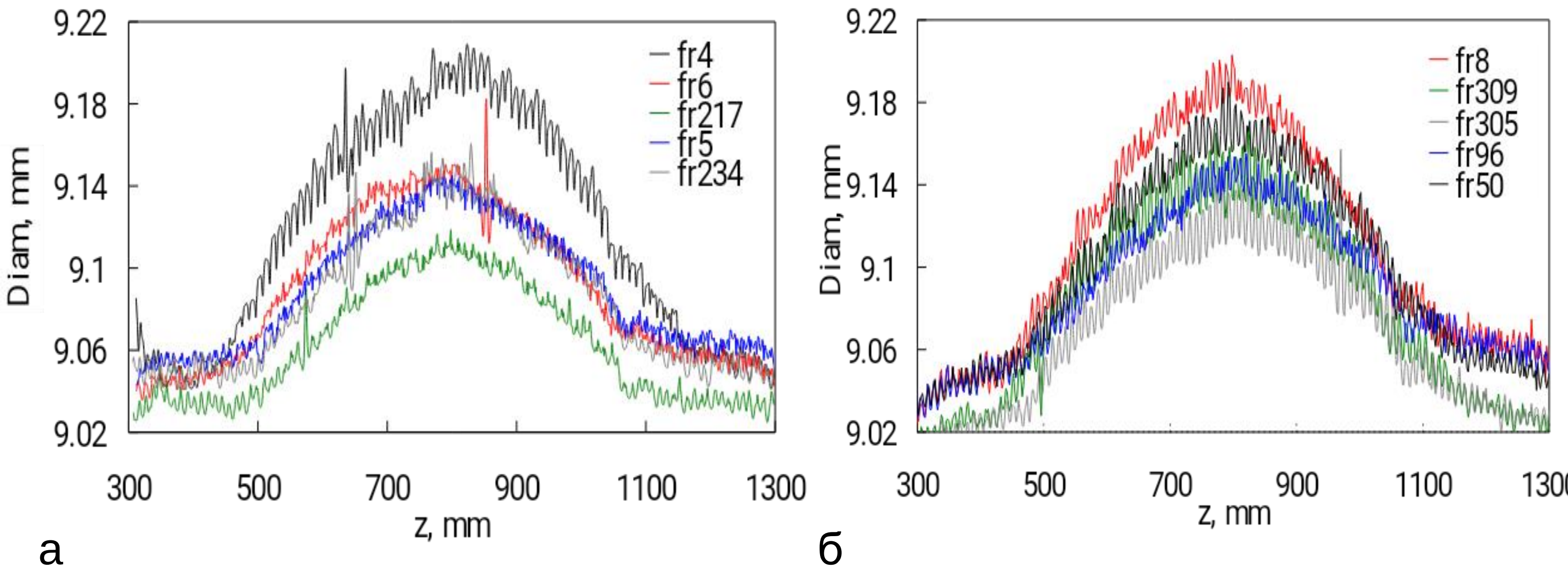


Figure 13 – *Some* diameter measurement results for fuel rods under power ramping (the results of NG4 (a) and NG5 (b) experiments)

Some results of post-irradiation examinations in the hot cells

Figure 14 shows claddings residual strain for the VVER fuel rods containing fuel pellets with no central hole at the relevant LHR for different burnup fuel rods.

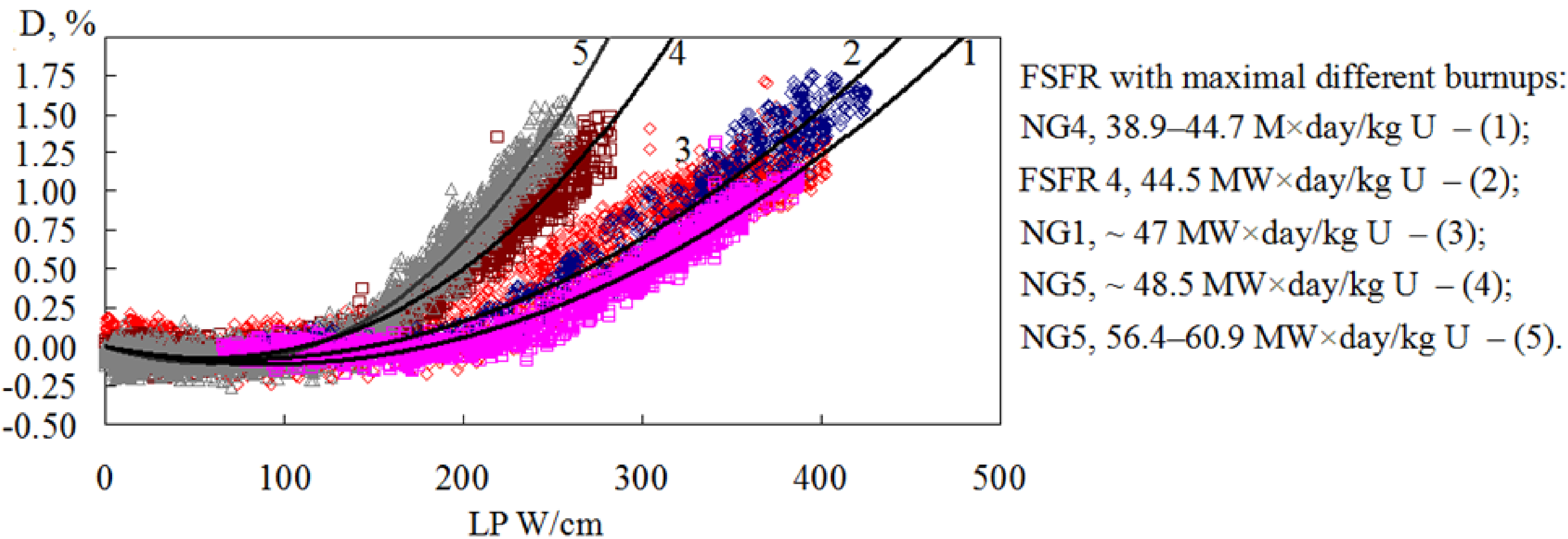


Figure 14 – Ratio of cladding residual strain to LHR for different burnup fuel rods

CONCLUSION

About 120 VVER fuel rods have been tested under the power ramping and step-up modes; about 20 VVER fuel rods have been tested under the power cycling conditions.

Techniques and procedures have been developed for power ramping, step-up and cycling tests.

In-pile gages have been designed to measure fuel rods parameters. The in-pile measurement results have been confirmed by hot cell examinations.

Further work is being carried out to improve the experimental base of the MIR reactor and hot cells to perform power change tests of fuel rods.

The tests enabled obtaining the data related to VVER fuel rod behavior under power change resulted from abnormal operation. Good reliability of the tested fuel rods was demonstrated.

The gained experience provides for further tests under power change modes with other fuel rod types and different coolants (water, gas); ampoule tests are also possible.

Thank you for your attention!