EXPERIMENTAL CAPABILITIES OF THE MIR.M1 REACTOR TO TEST LWR ADVANCED FUEL

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ABSTRACT

From the time of its foundation and by these days JSC "SSC RIAR" has been one of the Russia's largest research centers. Being an integrated experimental base, it provides for comprehensive investigations of components and units of the existing and advanced nuclear facilities, first of all, fuel and structural materials of reactor cores. The RIAR's experimental base comprises five test reactors, including reactor MIR.M1, and materials testing laboratories.

A variety of experimental equipment and parameters of reactor MIR.M1 enable testing of LWR fuel rods and FA fragments under conditions simulating steady-state, transient modes and design-basis accidents.

The paper presents technical characteristics and experimental capabilities of reactor MIR.M1. Described are the key research trends and test programs, of which the most important and promising is studying the nuclear fuel behavior in different modes and justifying its advanced concepts. Presented are the designs of irradiation rigs (IR) equipped with different in-pile gages to examine fuel rods characteristics and control testing conditions.

1. Introduction

Development of new nuclear fuel and enhancement of advanced one, including its design engineering, technical feasibility demonstration, adoption and use at commercial nuclear power plants (NPP), call for necessary and experimentally verified data. Nowadays the companies involved in the fuel development and production perform irradiation testing in research reactors along with operational performance tests by inserting experimental fuel rods of advanced design in standard fuel assemblies (FA) as well as fabricate test FAs based on advanced fuel rods for their use at NPP.

It might be well to note that NPPs can operate enhanced fuel under steady-state conditions in normal operational modes. Irradiation tests of prototype nuclear fuels in high-power nuclear test reactors equipped with special-purpose loop facilities (LF) are distinguished with minimization of potential risks due to fuel failure, testing at the highest power level maintainable, as well as testing under transient modes and design-basis accidents, interim inspections including availability of hot cells for post irradiation examinations.

Test reactor MIR.M1 equipped with different loop facilities, along with the hot cells located within touching distance at the JSC "SSC RIAR" site, has unique performance potential to conduct experiments in support of R&D and operational performance of innovative fuels and structural materials.

2. Reactor MIR.M1

MIR.M1 is under operation since 1967. It is a channel-type reactor with a beryllium moderator and reflector and it has loop facilities with different coolants. The reactor is mainly used to test different nuclear fuels under conditions simulating steady-state and transient modes, and design-basis accidents (Tables 1 - 3) [1, 2]. In 1975, the reactor was refurbished: the core was replaced and some process systems were improved. The reactor core was refurbished in such a way to increase its experimental capabilities. At the beginning of 2000-s, the reactor was upgraded, beryllium blocks were replaced as well as core key components; the reactor control system was modernized.

Parameter	**Value**
Nominal thermal power, MW	100
Reactor operation per year, days	230÷240
Fuel	UO_2, 90% enriched in ^{235}U
Core height, mm	1000
Number of loop channels	11
Expected operational lifetime	till 2035

Tab 1: Key parameters of reactor MIR.M1

Cells for irradiation	Up to 49, height – 1100 mm	**Neutron flux density, $cm^{-2}\cdot s^{-1}$**		**Damage dose accumulation rate, dpa/year**
		E > 0.1 MeV	E < 0.68 eV	
Core	11 cells for loop channels, ∅ ≤ 148.5 mm	$2.0\cdot10^{14}$	$5.0\cdot10^{14}$	1.5
	38 cells, ∅ ≤ 34 mm	$3.0\cdot10^{14}$	$5.0\cdot10^{14}$	5.0

Tab 2: Experimental capabilities of reactor MIR.M1

The MIR.M1 reactor has got the following major test facilities and devices [1 - 3]:
- LFs that simulate the VVER and PWR operational regimes including water chemistry;
- rigs and devices to test fuel and core components, heat being removed with the primary water or water from the reactor pool coolant system;
- hot cells and related equipment;
- inspection facility for fuel rods and experimental FAs (EFA) in the reactor storage pool.

Parameter	**Loop facility**					
	PV-1	**PV-2**	**PVK-1**	**PVK-2**	**PVP-2**	**PG**
Coolant	Water	Water	Water, boiling water	Water, boiling water	Water, boiling water, steam	He, N_2
Number of loop channels	2	2	2	2	1	1
Capacity of one channel, kW	1500	1500	1500	1500	2000	160
Coolant temperature, °C	350	350	350	355	550	600
Max pressure, MPa	16.8	17.8	16.8	17.8	20	20
Max coolant flow rate through a loop channel, t/h	16	16	14	14	10	-

Tab 3: Parameters of MIR.M1 loop facilities

The MIR.M1 reactor demonstrates the following unique capabilities:
- testing of fuels and other core components under conditions that fully simulate the operational ones of different power reactors;
- simultaneous testing in different reactor loop facilities due to flexible distribution of the neutron flux over the reactor core;
- inspection facility in the reactor storage pool and two hot cells for interim examinations of irradiated items.

The key activities are as follows [4 - 6]:
- testing of LWR fuel rods with improved fuel and cladding materials under normal operating conditions;
- examination of LWR fuel rods under transient modes (RAMP and cycling);
- testing of improved VVER fuel rods under simulated LOCA and RIA;
- examination of fission gas release (FGR) out of VVER fuel rods with artificial defects;
- testing of fuel from research reactors.

Figure 1 shows the layouts of irradiation rigs used for testing [4, 5].
The promising capabilities of the MIR.M1 reactor are:
- testing of accident tolerant fuel VVER, PWR and BWR with claddings made of advanced materials (ceramics, steels, protective coatings, etc.);
- examination of new fuels VVER and PWR (MOX, REMIX, thorium fuel, UO_2 added with absorbing and moderating materials, etc.);
- testing with severe damage of fuel VVER, PWR and BWR;
- development of new loop facilities for Generation IV reactors.

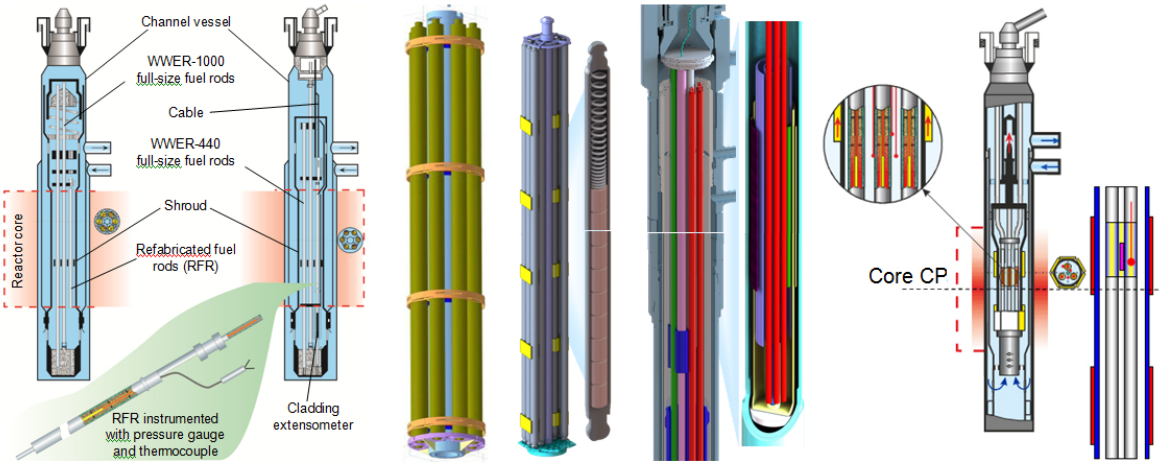


Fig 1. Dismountable irradiation rigs to test fuel, FA fragments and fuel rods

To examine the characteristics of fuel rods and conditions of their testing, different in-pile sensors have been developed to provide the on-line control and measurements during the experiment. The key parameters of the sensors are given in Table 4 [7].

Parameter to measure	Design	Measurement range	Error	Dimensions, mm	
				diameter	length
Coolant and cladding temperature	Chromel-alumel cable-type thermocouple	up to 1100 °C	0.75%	0.5÷3.0	-
Fuel temperature	Chromel-alumel cable-type thermo-probe	up to 1100 °C	0.75%	1.0÷1.5	-
	Therm-probe VR 5/20, Mo+BeO-duct	up to 2300 °C (up to 1750 °C*)	~ 1.5%	1.2÷2.0	-
Gas pressure change in the fuel rod	Bellows + LVDT	0÷20 MPa	calibration	16	80
Cladding elongation	LVDT	0÷10 mm*	calibration**	16	80
Fuel column elongation	LVDT	0÷10 mm*	calibration**	16	80
Neutron flux density (rel.unit)	Rh, Hf direct charge sensor	10^{15}÷10^{19} n/(m^2·s)	~ 1÷3 %	2÷4	50÷100

* - depends on the length, design and material of a fuel rod/fuel column
** - sensitivity – (1÷2) μm

Tab 4: Types and characteristics of in-pile sensors installed on IRs and fuel rods

2.1 Testing under steady-state modes

Purpose of testing:
- to justify fuel rods performance and check new designs, to reveal peculiar changes in the fuel rods conditions depending of their design and fabrication technology;
- to get experimental data on the operational characteristics of fuel and claddings under conditions close to standard ones, including power, temperature and water chemistry;
- to track changes in the fuel rods conditions at a rising burnup and pre-set power level and to prepare high-burnup fuel rods for RAMP, LOCA and RIA experiments.

To test of LWR fuel rods under steady-state modes, LFs are used, for instance in loop facility PV-2, with the related water chemistry. One LF can be used to test 2÷4 EFAs with fuel rods of different modifications, the length of their active part being ~1 m or ~0.5 m, respectively.

At present, the following arrangement of PWR fuel rods is used in the EFAs inserted into the loop channel (Figure 2):
- EFA with 10 fuel rods and 2 guide tubes in a rectangular jacket that separates the coolant flow;
- EFA with 12 fuel rods and 4 guide tubes/pins in a round jacket ∅60×0.8 mm. Here, a coolant separator is a tube ∅66×1.5 mm.

Such arrangements allow for a periodical removal of fuel rods from the EFA for interim examinations performed at the inspection facility of the reactor storage pool; also, single fuel rods can be removed and replaced with either dummies or new ones.

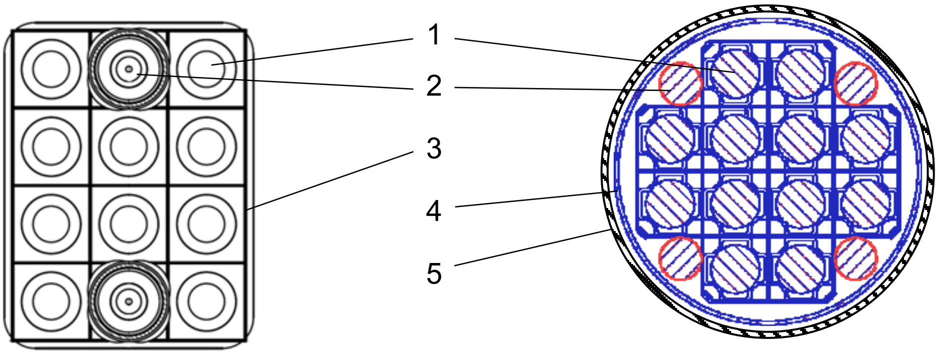


Fig 2. Cross-sections of EFAs to test PWR fuel rods:
1 – fuel rods; 2 – guide tubes; 3 – jacket separating coolant flow;
4 - jacket; 5 – coolant flow separator in the loop channel

Figures 3 and 4 show the change in linear heat rate (LHR) and temperature in the center of the VVER-1000 fuel rod columns during tests in the MIR.M1 reactor under conditions simulating normal operation [8].

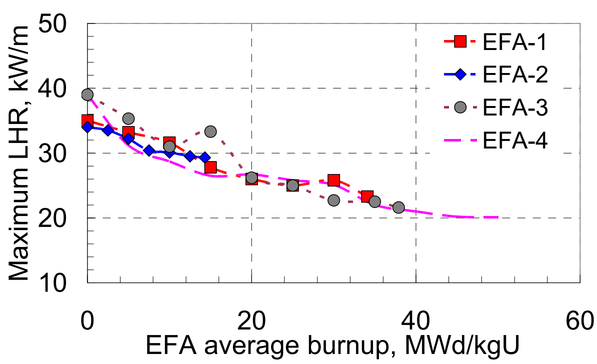


Fig 3. Change in the maximal LHR of VVER-1000 fuel rods during their testing in the MIR.M1 reactor

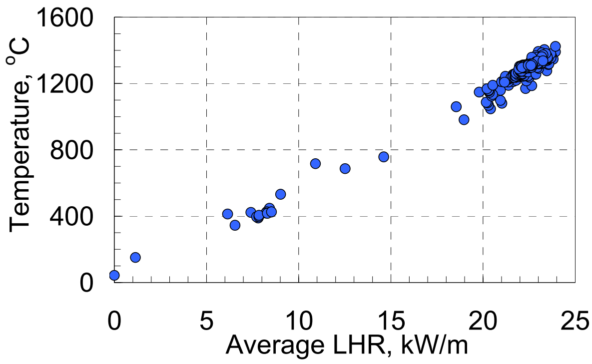


Fig 4. Change in the temperature in the VVER-1000 fuel rod column center vs. average LHR

2.2 Power ramping and cycling

Characteristics of the MIR.M1 loop facilities, for instance PV-2, allow RAMP and power cycling to be done for full-size and refabricated LWR fuel rods, of which burnup achieves 50÷70 MWd/kgU.

In the RAMP experiments, the LHR of fuel rods under test is raised by re-distributing the heat rate in the reactor core. For this purpose, either the position of control rods is changed increasing the reactor power, if necessary, or the absorber is moved around the fuel rods in the IR [5, 9]. In case the position of control rods is changed and reactor power in increased, the 2÷2.5 times LHR raise can be achieved in ~ 5÷15 minutes. If the absorber is moved around the fuel rods in the IR (Figure 5), then the LHR raise rate makes up 10÷20 kW/(m·min).

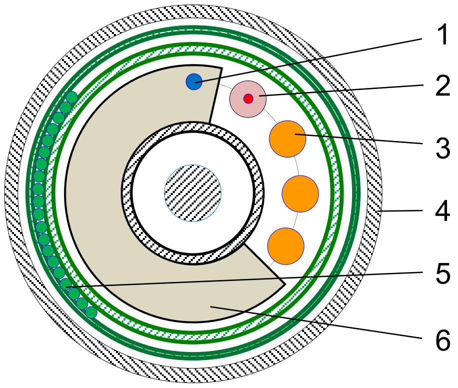


Fig 5. IR to test fuel rods under power ramping:
1 – direct charge sensor; 2 – fuel rod with a thermocouple; 3 – full-size fuel rod;
4 – loop channel body; 5 – absorber; 6 – central tube with a lateral displacer

If this IR is used for power cycling testing, then the displacer (pos. 6, Fig. 5) can be replaced with fuel rods. If the mass of absorber is increased and an additional screen is installed close to the central tube, then the LHR can be raised by 4÷5 times by rotating the absorber/fuel rods.

The MIR.M1 reactor was successfully used to test VVER-1000 fuel rods under power cycling conditions. Figures 6 and 7 show the change in the fuel column temperature during the testing and the dependence between the VVER-1000 fuel rod elongation and fuel temperature, respectively [4, 5].

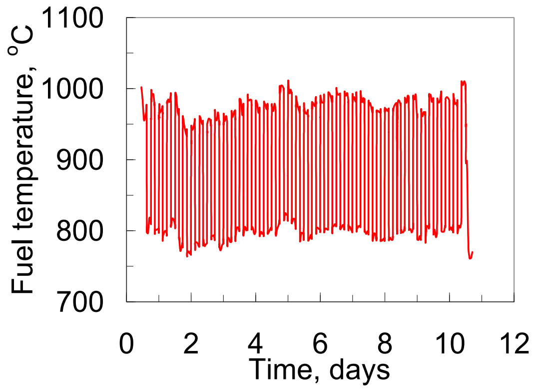


Fig 6. Change in the VVER-1000 fuel rod temperature during the experiment under power cycling mode

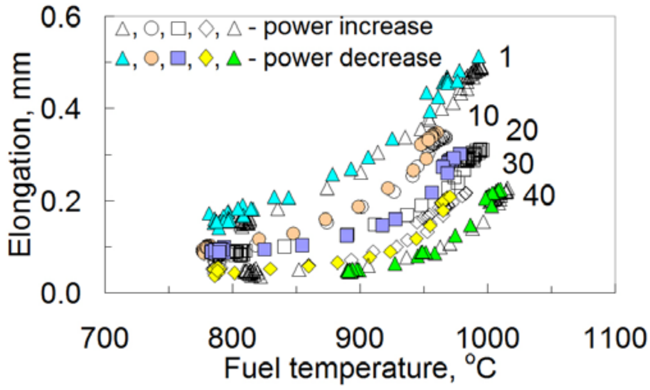
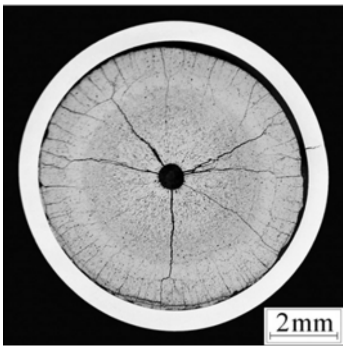
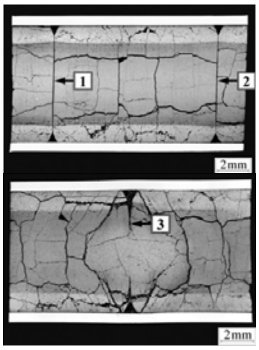


Fig 7. Elongation of the fuel rod vs. fuel temperature during the power cycling (figures mark the number of cycles)

Figure 8 presents the structure of fuel of a VVER-1000 ~45 MWd/kgU full-size fuel rods after the RAMP experiment [9].





a) b)

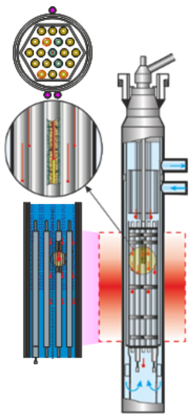
Fig 8. Macro-structure (a) and micro-structure (b) of fuel of a VVER-1000 ~45 MWd/kgU full-size fuel rods after the RAMP: b) 1, 2 - normal joints of fuel pellets, 3 - a joint with corrugation and gap

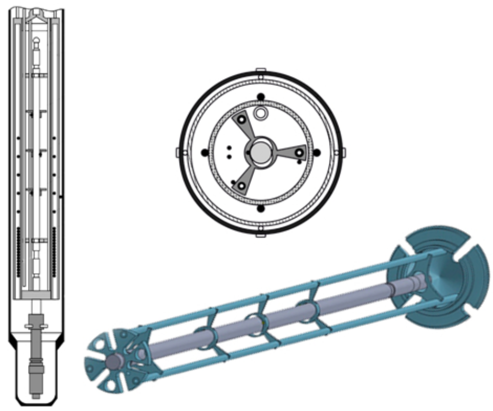
2.3 Design-basis LOCA

Experiments simulate conditions typical for the second and third stage of the maximal VVER-1000 design-basis accident with the break of the main circulation pipeline. Developed and applied are the techniques and IRs to test both VVER FA fragments and single fuel rods (Figure 9). The first IR is a fragment of 19-fuel rod VVER-1000 FA where some fuel rods are refabricated, including those with high burnup and equipped with sensors to measure the gas pressure and fuel and cladding temperature. The second IR can house one instrumented refabricated fuel rod [4, 5, 10].

The purpose of tests is to get experimental data on:

- deformation of the fuel rod bundle to use these data in the calculation codes for fuel rods thermo-mechanical state;
- fragmentation of high-burnup fuel, its axial displacement and release into the coolant in case of cladding fracture.





a) b)

Fig 9. IR to test an FA fragment (a) and a single fuel rod (b) under LOCA conditions

Experiments with FA fragments are performed in the loop channel with a sealed cooling circuit connected to the loop facility PVP-2, of which design provides for normal operation at a higher coolant activity (up to ~$3.7 \cdot 10^{10}$ Bq/kg). The LF primary equipment is installed in sealed boxes to avoid any release of radioactivity. The experiments are performed in four stages:

- irradiation of fuel rods at a nominal LHR level;
- evaporation of water at the upper part of the channel at a power close to the residual heat rate level;
- heating of fuel rods in vapor at the pre-set rate;
- re-flooding of EFA.

The fuel rod bundle is heated up to the required cladding temperature at a rate of (1÷4)°C/s. The experiment is stopped by the reactor shutdown.
Figure 10 shows an example of such scenario. The diagrams demonstrate a temperature area with different cladding heating rates. Parameters set for each experiment are as follows: cladding heating rate, maximal cladding temperature, parameters of EFA re-flooding at the end of testing. At the stage of water evaporation from the channel upper part, the cladding temperature is evaluated by the pressure in the cooling circuit, at which the process equipment operates reliably.

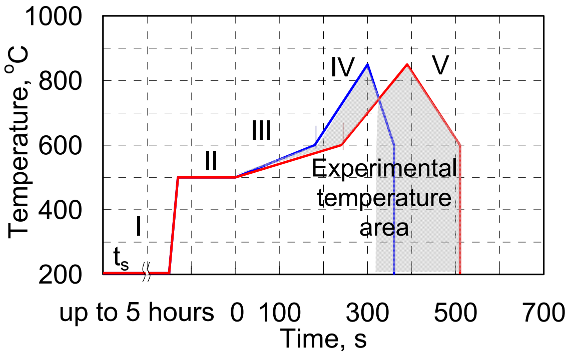


Fig 10. Temperature scenario of experiment: I – evaporation mode (up to ~ 5 hs);
II – exposure at a temperature of cladding drying (150÷250s);
III–IV-V- second and third stage of the maximal design-basis accident
(III - 180÷240s, IV - 120÷150s, V - 60÷120s)

In case of temperature scenario presented in Figure 10, the length of the fuel rod active part that is subject to overheating and where a significant cladding deformation is observed makes up (450÷500) mm. The maximal cladding temperature achieved during the experiments made up 950°C. The cladding temperature non-uniformity in the area of maximal deformation did not exceed 20°C.
In the experiments with a single fuel rod, its power is changed by the reactor power variation. Figure 11 presents one of the temperature scenario options.

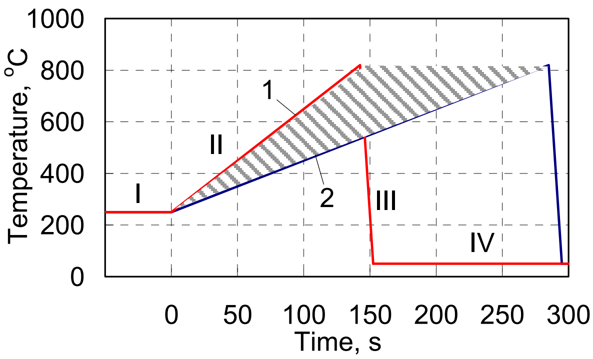
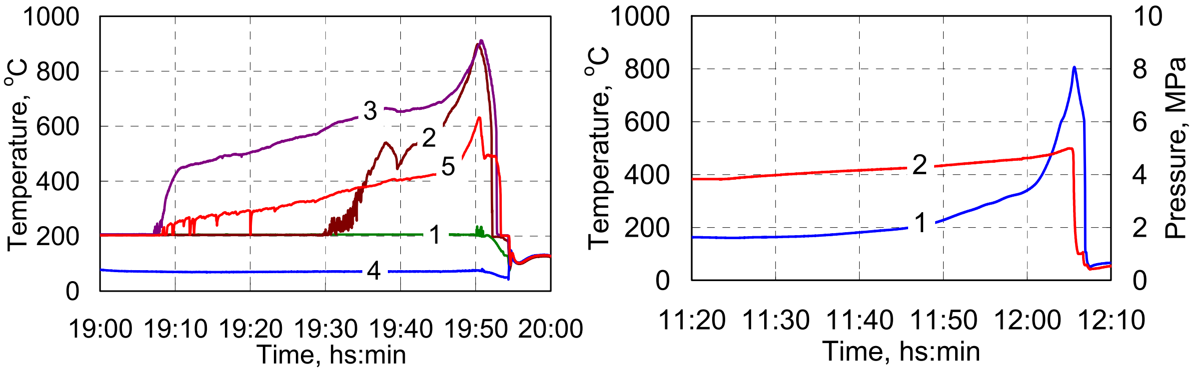


Fig 11. Temperature scenario of experiment with the cladding temperature elevation rate of 4°C/s (1) and 2°C/s (2): I-IV – transient areas

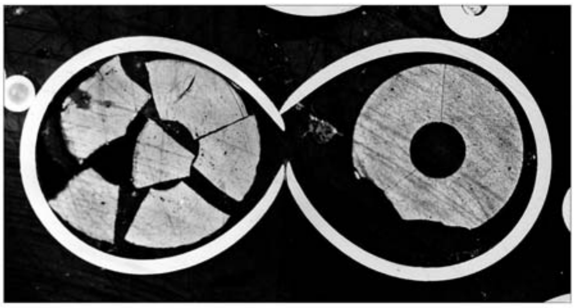
Since the IR in its initial state has a coolant phase boundary line, this scenario does not lead to water evaporation. The time to heat the cladding up to 250°C is not limited. To simulate the fuel rod re-flooding and create a thermo-shock of (400÷450)°C (transient area III, Figure 11), cold water is supplied to the IR inlet. Stage IV is a long cooling. Experiments at the MIR.M1 reactor resulted in cladding temperatures of (700÷900)°C achieved at a heating rate of (2÷5) °C/s.
During testing, the following parameters are measured on-line: fuel and cladding temperature, gas pressure under the cladding, coolant temperature at the inlet and outlet of the EFA and loop channel, heat rate in the loop channel (by means of a direct charge

sensor). Figure 12 shows a recorded change in the test parameters during LOCA experiments. Figures 13 and 14 show an FA fragment and single fuel rod after the experiments [4, 5, 10].



a) b)

Fig 12. Change in test parameters during the LOCA experiments
at the MIR.M1 reactor: (a) FA fragment, (b) single fuel rod
a) change in the cladding temperature at a distance of 562 mm (1), 757 mm (2)
and 887 mm (3) from the support grid. Change in the coolant temperature
at the inlet (4) and outlet (5) of the EFA; b) change in the cladding temperature (1)
above the spacer grid and gas pressure (2) under the cladding



a) b)

Fig 13. Deformation of cladding of a refabricated fuel rod (a) and unirradiated fuel rod (b)
after testing an FA fragment (LOCA experiment)

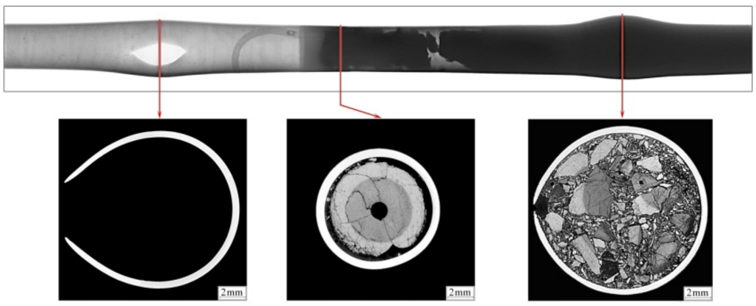


Fig 14. Deformation of a single fuel rod cladding after LOCA experiment
(figures indicate a distance from the fuel rod bottom)

2.4 Testing under limiting regimes with fuel melting

Tests are aimed at evaluating the LHR corresponding to the high burnup fuel melting point. Objects of tests are experimental LWR fuel rods with tube-type pellets and no central hole; fuel burnup achieves 70÷80 MWd/kgU. The fuel rods are equipped with sensors to measure temperature and gas pressure under the cladding. Several fuel rods can be tested simultaneously, including full-size fuel rods ~ 3.9 m long from spent VVER-1000 FA.

The MIR.M1 reactor parameters allow increasing the high burnup fuel rods LHR up to 80÷90 kW/m. The fuel rod power is controlled by the heat balance method and also by comparing readings of direct charge sensors and thermocouples.
Figure 15 presents a typical scenario of testing under limiting regimes:
- the initial fuel rod LHR is increased up to a level corresponding to the end of its operation at an NPP and the fuel rod is irradiated at this LHR for 12÷24 hours;
- the LHR is increased stepwise (0.5÷2) kW/m with a certain exposure time after each step till stress in the cladding decreases as well as FGR into the plenum;
- then the fuel rods are irradiated at a high LHR level for several hours till stress in the cladding decreases as well as FGR rate into the plenum;
- at the final stage, the LHR is increased up to the fuel melting point and the reactor is shutdown.
Figure 16 presents the calculation results of the fuel temperature distribution lengthwise the LWR fuel rods with tube-type pellets and no central hole vs. the LHR under limiting regimes with fuel melting test.

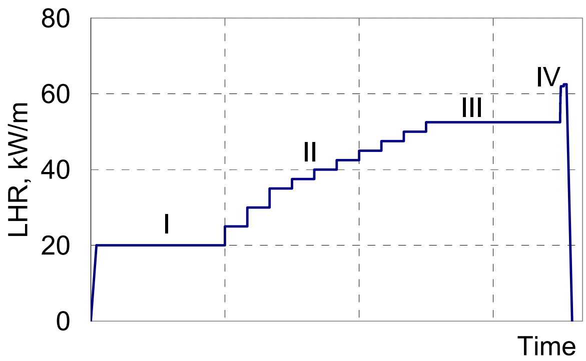


Fig 15. Scenario of testing under limiting regimes with fuel melting:
I - LHR corresponding to the end of fuel rod operation at an NPP (12÷24 hs);
II – LHR stepwise increase; III – LHR level below fuel melting point;
IV – LHR level corresponding the fuel melting point

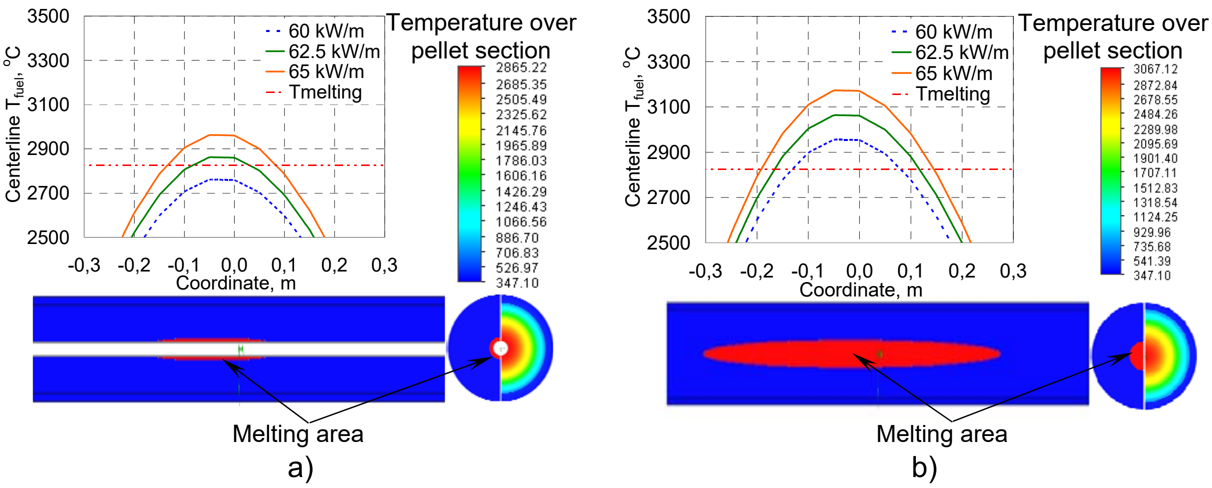


Fig 16. Fuel temperature distribution lengthwise the LWR fuel rods vs. the LHR:
a) fuel pellet with a central hole, b) fuel pellet with no central hole

3. Conclusion

JSC “SSC RIAR” has a unique fleet of different test reactors, well-equipped hot cells for post-irradiation examinations of irradiated fuel and structural materials and all necessary engineering infrastructures to prepare for and perform a full cycle of experimental research. Both irradiation tests and post-irradiation examinations are based on representative techniques and modern equipment and are performed by highly-skilled personnel.

The existing MIR.M1 reactor test programs and techniques allow getting experimental data on the performance and behavior of fuel rods under different conditions simulating steady-state and transient modes, and design-basis accidents as well as on changes in characteristics and properties of fuel under irradiation. These data are used to develop, justify and license the innovative LWR fuel and to check and improve calculation codes used to assess fuel rods conditions.
In 2016, JSC “SSC RIAR” was assigned the IAEA ICERR status that marked the world-wide recognition of its unique competencies and widest experimental capabilities as well as proved readiness of its infrastructure and personnel for further widening of both international and bilateral cooperation with foreign partners.

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