Joint Project
"Research into VVER fuel rods behavior under LOCA conditions in the MIR.M1 reactor"
as part of the OECD NEA Multinational Experimental Program
(JSC "SSC RIAR" Proposal)

1. JSC "SSC RIAR" experimental capabilities

JSC "SSC RIAR operates the MIR.M1 reactor which maximum thermal power is 100 MW and maximum thermal neutron flux density is $5 \cdot 10^{14}$ $cm^{-2}s^{-1}$. MIR.M1 is a special-purpose unique research reactor to perform loop tests for fuel elements and fuel assemblies of various power and research reactors in stationary and transient conditions and also to simulate accidental conditions.

MIR.M1 physical parameters and a large number of control rods (up to 41 pcs.) to change reactivity make it possible to perform tests simultaneously at different thermal neutron flux densities, which may differ by 50 times.

The MIR.M1 experimental facility includes a research reactor with experimental loop facilities, two hot cells, cooling pools and a critical assembly (physical prototype). More information on the MIR.M1 technical parameters and experimental capabilities is provided in the information booklet on the RIAR's website:
http://niiar.ru/sites/default/files/buklet_mir_ang_p.pdf

The JSC "SSC RIAR" experimental infrastructure involves the Reactor Materials Testing Complex equipped with hot cells, engineer and research infrastructure to perform a full scope of post irradiation non-destructive and destructive examinations for irradiated fuel rods and fuel assemblies (including full-size FAs of VVER, RBMK and BN-type power reactors).

RIAR annually performs post irradiation examinations for VVER spent fuel assemblies delivered to the RIAR's site from various nuclear power stations. To date, more than 100 fuel assemblies of power reactors of various types have been examined. Among them are fuel assemblies of both standard and improved design, either spent or with high burnup. A part of these assemblies is kept in the cooling pool and they can be used for different reactor experiments, including LOCA.

The Reactor Materials Testing Complex operates an area to refabricate fuel rods where the full-size fuel rods irradiated in power and other type reactors are used to make experimental samples to be tested in research reactors and hot cell stands. Depending on the test goals and conditions, refabricated fuel rods are equipped with sensors of various types.

2. Experience in performing LOCA in MIR.M1

The MIR.M1 reactor operated at JSC "SSC RIAR" is the main facility to perform research into the behavior of power reactor fuel rods under loss-of-coolant accident conditions (LOCA).

The unique features that can be implemented in the MIR.M1 reactor to study fuel rods behavior under LOCA conditions are as follows:

- the test object can be either a fuel rod bundle or a single experimental fuel rod made by refabrication from a fragment of a VVER fuel rod with a given burnup and a fuel meat length of 1000 mm,
- during the experiment, the second (reflood) and the third (quench) stages of the transient can be implemented;

- tests are carried out in the steam-gas medium (to avoid additional oxidation of the fuel rod cladding in the presence of air);

- refabricated experimental fuel rod is equipped with a pressure gage to measure fuel rod inner pressure and to detect leakage during the experiment;

- main experiment parameters that can be implemented when simulating LOCA in the MIR.M1 loop facility:
    - Clad heating during the second stage up to 700÷1200 °C with the heating rate from 1.5 to 5 °C/s;
    - Pressure drop on the cladding up to 7 MPa;
    - Pressure in the capsule with the experimental fuel rod in the range 0.1÷0.15 MPa during the testing;
    - Rate of water level rise in the experimental rig during the third stage (quench) in the range of 0.2÷0.3 m/s.

– during the experiment, the following parameters can be measured on-line:
    - coolant temperature (at the inlet and outlet of the experimental rig active part);
    - temperature of the experimental fuel rod cladding (at three points heightwise);
    - relative heat rate (it is measured with an in-reactor direct charge detector and with standard ion chambers of the reactor);
    - gas pressure in the lower free space of the experimental fuel rod.

During the last few years, a series of experiments to simulate LOCA with single VVER-1000 fuel rods have been carried out in the MIR.M1 reactor. The target test parameters are shown in Table 1.

Table 1

Fuel rod characteristics and LOCA experiments target parameters implemented in MIR.M1

Parameters	**Experiment No. 1 MIR-LOCA/72**	**Experiment No. 2 MIR-LOCA/45**	**Experiment No. 3 MIR-LOCA/69**
Dimensions of the fuel rod cladding	Outer diameter- 9.1 mm, Cladding thickness- 0.685 mm	Outer diameter- 9.1 mm, Cladding thickness- 0.585 mm	
Cladding material	Alloy E110	alloy E110 opt. sponge W-Ch	alloy E110 based on sponge zirconium
Fuel pellet size	Ø 7.73 mm, CH* Ø 1.4 mm	Ø 7.93 mm, Without CH*	
Fuel burnup, MWday/kgU	77.7	45.3	69.3
Target parameters for the second stage			
Cladding target temperature, ºC	1000…1200	800…850	700…750
Cladding heating rate, ºC/s	3…5	1…4	
Target parameters for the third stage			
Cladding temperature before quench	800	700	600
Rate of water level rise, m/s	0.1…0.3		
Water temperature, ºC	20…25		

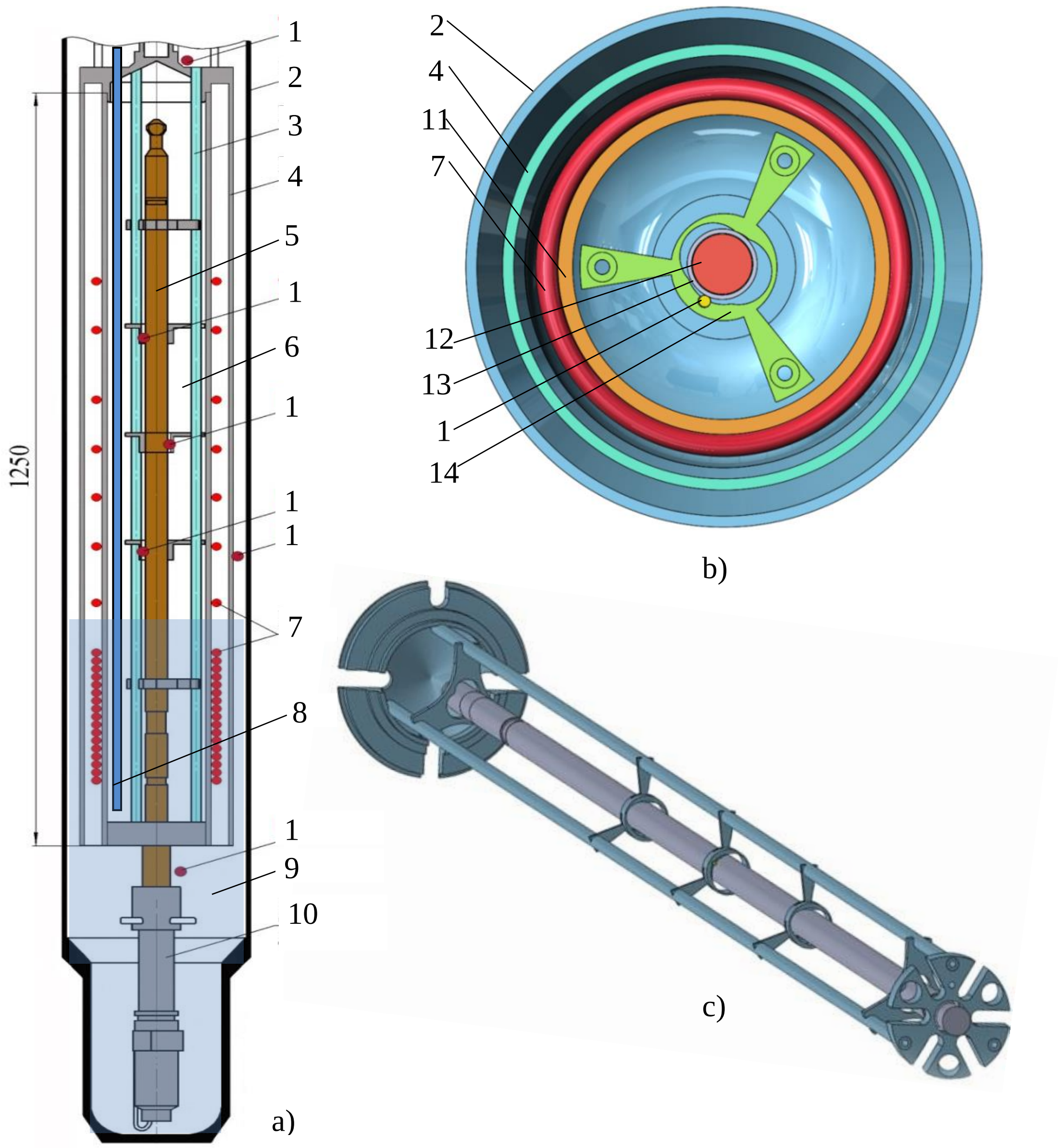
* CH – central hole

The design of the experimental capsule-type experimental rig developed by JSC “SSC RIAR” (shown in Figure 1) includes the following main components:

-three spacer elements (with a spacing of 200mm) which ensure the temperature gage is pressed against the fuel rod cladding during the remote mounting in the hot cell;

-two sections of the electric heater to simulate the thermal effect of surrounding fuel rods in the VVER-1000 FA and to ensure the initial circulation of water steam;

-two pulse tubes to supply water and to remove gas from the upper part of the experimental rig to the reactor pool.



1 – thermocouple;
2 – capsule body;
3 – bearing basket;
4 – thermo-insulating shell;
5 – experimental fuel rod;
6 – steam;
7 – electrical heater;
8 – tube to fill water in;
9 – water;
10 – pressure gage;
11 – basket jacket;
12 – fuel meat;
13 – cladding;
14 – spacer element.

Figure 1. Experimental rig to test a single fuel rod under LOCA conditions:
a) experimental rig schematics; b) experimental rig cross-section; c) assembled fuel rod with a basket

In the course of testing, the bottom part of the experimental fuel rod and the pressure gage are immersed in water. The water level is at an elevation of 150÷170mm from the fuel meat lower edge; steam-argon mixture is above.

To create a quench on the cladding (3rd LOCA stage), the water level is elevated by pumping water from the hydraulic stand into the capsule through a pulse tube.

The tests are done in the steam-argon mixture; the capsule is filled with argon at purposely designed stand. During testing, the pressure of steam-argon mixture is maintained at a level of 1atm.

Figure 2 presents the experimental fuel rod schematics:

Figure 2. Experimental fuel rod schematics:
1 – ferromagnetic fuel meat; 2 – pressure gage;
3 – free lower volume; 4 – VVER fuel rod fragment with a fuel meat 1m long; 5 – free upper volume

Before sealing, the refabricated fuel rod is filled with helium till the target pressure, which is further controlled with a pressure gage.

Below, there is a procedure of experiment to test fuel rod behavior under LOCA in the reactor MIR.M1:

1. Reactor is brought to power.
2. Power is supplied to the electrical heater to heat fuel rod cladding up to 250÷270°C.
3. Fuel rod is heated up to the target temperature at the set heating rate by a constant raise of reactor power.
4. Once the target temperature is achieved, the reactor is shut down by safety rods.
5. Cold water is supplied to the capsule thus creating a cladding quench.
6. End of experiment: heat is switched off; long-term cooling of fuel rod.

Once the experiment is over, the visual inspection of fuel rods as well as destructive and non-destructive examinations are performed in the hot cell. The PIEs are aimed at measuring the deformation and its location heightwise the fuel rod cladding, amount and composition of gas under the cladding, hydrogen content and zirconium distribution in the cladding material, cladding oxidation degree and other parameters characterizing the thermomechanical state of fuel rod and mechanical properties of its cladding.

The results obtained during the reactor tests and PIEs show the state of a fuel rod after testing.

The key results generated after three experiments are given in Table 2:

Table 2

Key LOCA experiment results generated by RIAR

Parameter	**Experiment No. 1 MIR-LOCA/72**	**Experiment No. 2 MIR-LOCA/45**	**Experiment No. 3 MIR-LOCA/69**
Fuel rod fragment burnup, MWday/kgU	77.7	45.3	69.3
Leakage	yes	yes	no
Cladding ballooning and deformation	yes	yes	yes
Leakage parameters: - max clad T, ºC	830	770	-

- clad pressure drop, MPa - max heating rate, °C/s	6.41 4.0	4.81 3.18	
Maximal testing parameters: - clad T, °C - clad heating rate, °C/s	1190 9.8	807 4.2	748 1.2
Time for pressure attenuation in the fuel rod after leakage, s	8	42	-
Fuel fragmentation	yes	yes	yes
Relocation, dispersion	yes	no	no
Release into coolant	yes	no	no

More details about LOCA experiments can be found in:

– P.V. Fedotov, A.V. Kumachev, O.A. Nechaeva, V.V. Novikov, A.V. Salatov, M.V. Sypchenko (JSC «VNIINM»), A.V. Alexeev, A.V. Goryachev, I.V. Kisseleva, V.N. Shulimov (JSC «SSC RIAR»), M.A. Bykov, V.M. Mahin, S.I. Zaitsev, M.O. Zakutaev (JSC «OKB Hydropress»), K.V. Lioutov, S.S. Pylev, V.V. Tebin, E.Yu. Tshepetilnikov (Research Center «Kurchatov Institute»), A.S. Gusev (JSC «OKBM Afrikantov»), Yu.V. Pimenov (JSC «TVEL»). Experimental and settlement studies of VVER fuel rods behavior under LOCA conditions (MIR-LOCA/60 experiment) // Enlarged Halden Programme Group Meeting. Norway.10th-15th March, 2013/ Proceedings of the Fuel and Materials Sessions. HPR-378.Vol.1.F1.10.

– Fedotov, P.V. F; Kumachev, A.V.; Nechaeva, O.A.; Novikov, V.V.; Salatov, A.V.; Sypchenko, M.V.; (JSC «VNIINM»), Alexeev, A.V.; Goryachev, A.V.; Kisseleva, I.V.; Shulimov, V.N. (JSC «SSC RIAR»). Experimental and Computational Studies of VVER High Burnup Fuel Behaviour Under LOCA Conditions (MIR-LOCA/60 Test) // High Burnup Fuel: Implications and Operational Experience; Buenos Aires (Argentina); 26-29 Nov 2013 / Proceedings of a Technical Meeting

http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/47/100/47100051.pdf?r=1

– P.V. Fedotov, A.V. Kumachev, V.I. Kuznetsov, V.V. Novikov, A.V. Salatov, M.V. Sypchenko (JSC «VNIINM»), A.V. Alexeev, A.V. Goryachev, O.I. Dreganov, A.L. Izhutov, I.V. Kisseleva, V.N. Shulimov (JSC «SSC RIAR»), Yu.V. Pimenov (JSC «TVEL»). LOCA test with high burnup VVER fuel in MIR reactor. TopFuel conference Proceedings Part II, Zurich, Switzerland, 13-17 September 2015. ISBN 978-92-95064-23-2, www.topfuel2015.org. P 391-400.

https://www.euronuclear.org/events/topfuel/topfuel2015/transactions/topfuel2015-transactions-oral-2.pdf

To widen the database on the fuel rod behavior under LOCA, a joint project is proposed under the OECD NEA Multinational Experimental Program.

3. Joint Project goals and objectives

The main goals and objectives of the Joint Project “Research into VVER fuel rods behavior under LOCA conditions in the MIR.M.1 reactor” to be implemented at the RIAR’s site under the OECD NEA Multinational Experimental Program:

1) Widening of experimental database on behavior of new design VVER-1000 fuel rods (including rods with a high burnup) under LOCA conditions:

- determine the leakage parameters (peak cladding temperature, heating rate, pressure drop on the cladding);
- investigate the fuel cladding state (oxidation, deformation);
- investigate the fuel pellets state (fuel fragmentation, relocation, dispersion, and radial movement of the fuel fragments).

2) Codes verification (for instance, the codes used by the state-level regulators when performing a safety analysis for NPPs with VVER reactors).

4. Joint Project work scope

The fuel rods irradiated earlier in standard TVS-ALPHA assemblies at Russia’s NPPs with VVER reactors can be used to investigate VVER fuel rods behavior under LOCA conditions.

Currently, there are fuel rods potentially available for investigations from several FAs irradiated up to a different average burnup.

Table 3 shows available testing parameters:

Table 3

Available testing parameters under the Joint Project

	#1	#2	#3	#4	#5	#6
Burnup, Mwd/kgU	41.4÷41.5	50.9÷57.6	54.9÷62.1	41.4÷41.5	50.9÷57.6	54.9÷62.1
PCT, °C	800÷850	800÷850	800÷850	1000÷1100	1000÷1100	1000÷1100
Heating rate, °C/s	1,5…3	1,5…3	1,5…3	2…5	2…5	2…5

Once the reactor testing is completed, the experimental fuel rods will be subject to post-irradiation examinations (PIEs), for instance, as follows:

– Fuel rod visual inspection and photographing, burst opening and length in the ballooning region;
– X-ray radiography of the fuel rod, possible loss of fuel in case of cladding loss of integrity;
– Gas quantity and composition under the cladding when puncturing the gas plenum (if there is no leakage);
– Cladding profilometry, circumferential strain distribution;
– Fuel loss (weighing of poured-out fuel debris);
– Particle size distribution for the fuel pellet fragments using a sieve analysis (depending on the fuel meat state after testing);
– Determination of the cladding residual plasticity based on mechanical testing results;
– Optical metallography of the cladding (cladding size, thickness of oxide film and α-Zr(O) layers after testing);
– SEM and EPMA;
– Hydrogen concentration in the cladding using thermal extraction.

Sample cutoff section coordinates for investigations are selected based on the non-destructive examination results.

Below is an enlarged list of work under the Joint Project:

Stage 1 (preparatory stage)

1.1. Develop a temperature scenario and experiment procedure, perform justifying calculations in support of testing parameters, determine the scope of design documents for the irradiation rig and develop/finalize them;

1.2. Examine the initial fuel rod to be refabricated;

1.3. Fabricate an experimental fuel rod and qualify it;

1.4. Fabricate an irradiation rig and parameter monitoring sensors;

1.5. Assemble the irradiation rig with a refabricated fuel rod, test the measuring system;

Stage 2 (experiment)

2.1. Prepare the MIR.M1 loop facility for the experiment

2.2. Experiment

Stage 3 (post-irradiation examinations)

3.1. Post-test calculation of neutronic and thermal-hydraulic testing parameters (it is also possible to perform post-test calculation using the codes available under the OECD NEA Joint Project).

3.2. PIEs

According to RIAR's estimations, the total period to perform the full scope of work related to one experiment is about 20 months. It is suggested to perform two experiments during 3 years under the Joint Project (2020-2022).

5. Prospects to develop the work on the LOCA experiment

Upon completion of the first joint project on investigating single VVER fuel rods behavior under LOCA conditions in the MIR.M1 reactor, the following joint projects can be implemented based on the obtained results:

– Investigation of PWR/BWR fuel rods behavior under LOCA conditions (model experimental fuel rods can be used that have been fabricated earlier at RIAR with the use of components transferred by overseas customers and irradiated under different research programs);

– Investigation of a bundle of VVER/PWR/BWR fuel rods behavior under LOCA conditions (an experimental FA with 19 VVER-1000 fuel rods has been investigated before in the MIR.M1 reactor).