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Testing of IRT-3M (U-Mo) LEU Lead Test Assemblies in the MIR Reactor

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ABSTRACT

In June 2015, two IRT-3M (U-9%-Mo) lead test assemblies started their irradiation in the MIR reactor under the RERTR Program. This fuel is used at many research pool-type reactors designed in Russia. The tests are aimed at the experimental verification of the fuel assemblies performance up to U-235 60% burnup. Atomized U-9%Mo particles (63-160)µk in size made by spraying are used as fuel. The uranium density in the fuel meat makes up 5g/cm^3. The paper presents data on the test parameters and conditions of the fuel assemblies as well as parameters and results of the IRT-3M and IRT-U assemblies tests completed in 2008. The work is carried out under the financial support of the Argonne National Laboratory (USA).

1. Introduction

The RERTR's key goals are the design, irradiation and qualification of full-size fuel assemblies with low-enriched uranium fuel intended for research reactors. Many types of Russian-designed research reactors use fuel assemblies of IRT type with tube-like fuel elements installed concentrically one into another. The first decade of 2000s was devoted to research and development activities to design LEU U-9%Mo fuel and then to fabricate two full-size 6-element fuel assemblies of IRT type as well as two fuel assemblies IRT-U with rod-type fuel elements. These full-size IRT FAs were tested in the MIR reactor from 2007 till 2008 [1]. These tests could be split into 2 periods. During the first period, two FAs (6-element and IRT-U) were irradiated up to the target average burnup of 40%. Two other FAs were supposed to be irradiated up to the average burnup of 60%. However, the irradiation was stopped since cladding leakage was detected by the control system based on delayed neutrons. The average burnup of the IRT-3M No.2 FA achieved 50.3%. Post-irradiation examinations showed that the leakage was caused by faults in the fabrication technology.

In 2015, as the fabrication process was improved, there were fabricated two new full-size 8-element IRT-3M FAs. Their tests started in June 2015 and the assemblies will be irradiated to achieve the average burnup of no less than 60%.

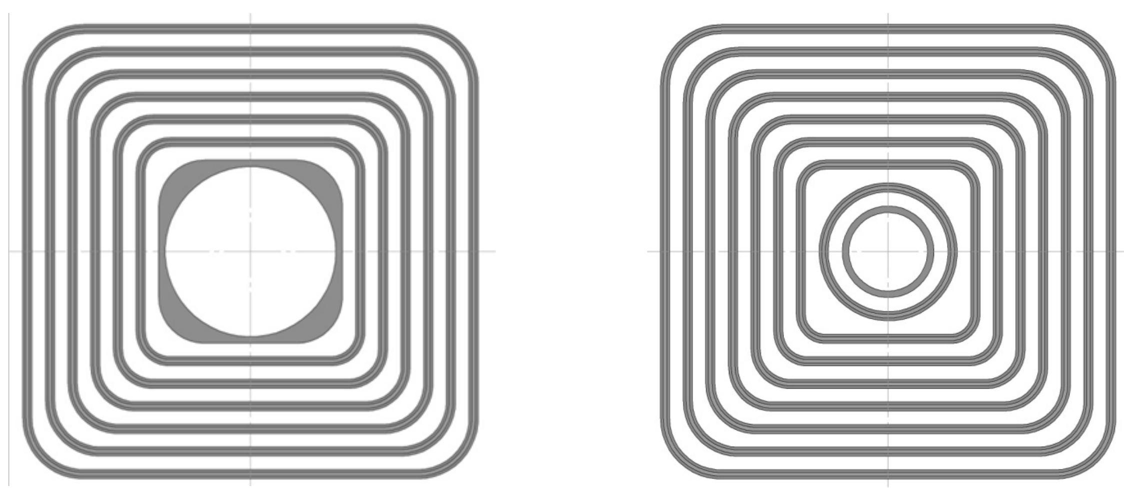
2. Design and parameters of ITR FAs

An IRT-3M FA consists of tubular fuel elements of square profile located concentrically and upper and lower plugs. The fuel elements are spaced by top and bottom spacer grids. Inside fuel elements can move in the axial direction within the axial thermal gap. The outside fuel element is carrying and coupled with the upper and lower plugs by rivets. The upper plug has a groove to grip the FA by a reloading device.

An FA fuel element is a three-layer tube; the inner layer is a U-containing meat; two outer layers are cladding and plugs made of aluminum alloy SAV-1 to protect the meat from the environmental effect and prevent fission gas release into the coolant.

U-Mo powder dispersed into the Al matrix is used as fuel. The mass fraction of molybdenum in the alloy makes up 9±0.5%. The mass fraction of 235U in the mixture of U isotopes in the meat makes up 19.7±0.25 %. The density in uranium is 5.0 - 6.0 g/cm^3 in total.

The 6-element FA IRT 3-M differs from the 8-element one not only in the number of fuel elements but also in the design. There are displacers made of SAV-1 Fig.1a and Fig.1b in the center holes of FAs.



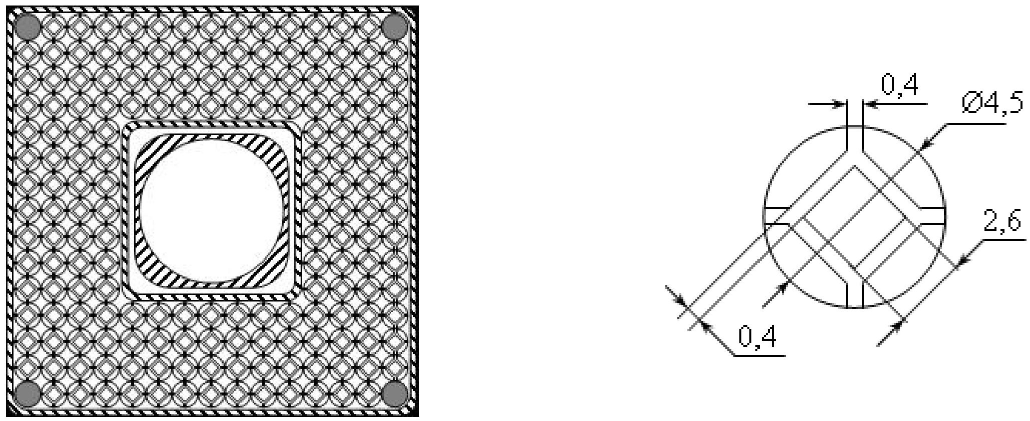
a) b)

Figure1. FA IRT-3M

a) 6-element;

b) 8-element.

The other type of FA irradiated in the MIR reactor is IRT-U. It is a dismountable design [2] consisting of a fuel element bundle of square section (Fig.2a) and displacers coupled with top and bottom spacer grids. The fuel element bundle is located between two shrouds (Fig.2b). A fuel element is a rod of square section with ribs; it has a cladding twisted round its axis right-hand with a pitch of 320mm, two plugs and meat. The carrying component of the design is an outside shroud 1mm thick. The shroud unites the upper and lower plugs and spacer grids with fuel elements into a single piece by means of indents. The shroud, upper and lower plugs are made of aluminum alloy SAV-1, claddings are made of aluminum alloys SAV-1 and Amg2.



a) b)

Figure 2. IRT-U FA design
a) FA cross-section;
b) Fuel element cross-section.

Table 1 presents the key FA parameters.

Table 1. Key parameters of IRT-3M and IRT-U FAs.

Parameter	Value		
	IRT-3M (6-element)	IRT-3M (8-element)	IRT-U
Cladding thickness, mm	0.3 min	0.3 min	0.31-0.46
Fuel meat length, mm	564-600	564-600	620-635
Fuel meat material	U-9%Mo+Al	U-9%Mo+Al	U-9%Mo+Al
Cladding material	SAV-1	SAV-1	SAV-1, Amg2
Enrichment in ^{235}U, %	19.7	19.7	19.7
Mass of ^{235}U in FA, g	~350	~390	~360
No. of fuel elements	6	8	172

3. Test conditions

The tests were conducted in research reactor MIR that enables, due to its design peculiarities, irradiating several FAs at a time. Experimental channels were purposely fabricated and installed into the core cells, from which standard Be-blocks had been removed. The experimental channels were connected to the primary circuit. The coolant went top-bottom. Figure 3 presents the hydraulic layout of the FAs tests.

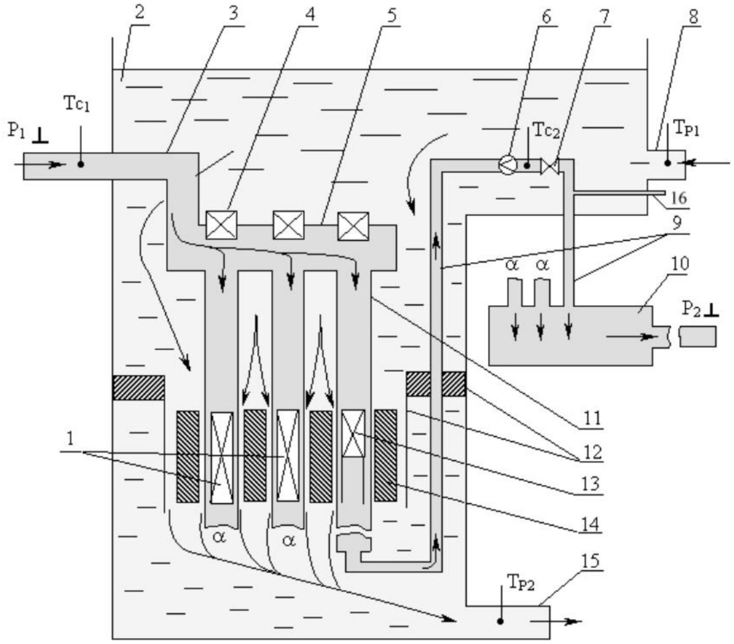


Figure 3. Hydraulic layout of the FAs tests
(Tc_1, Tc_2 – thermometers, P_1, P_2 – pressure gauges)
1 – standard FA; 2 – reactor pool; 3 – primary pipeline; 4 – channel plug; 5 – header; 6 – flow meter; 7 – valve; 8 – coolant inlet into the reactor pool; 9 – core outlet pipe; 10 – “hot” header; 11 – reactor channel; 12 – reactor baffle; 13 – experimental channel; 14 – Be-block; 15 – coolant outlet from the reactor pool.

Table 2 presents the test conditions for two IRT-3M FAs (6-element) and two IRT-U FAs.

Table 2. Test conditions for full-size IRT-3M and IRT-U FAs

Parameter	Value			
	IRT -3M (6-element)		IRT-U	
Thermal capacity, kW • average • maximal	452 800	369 800	503 722	286 661
Inlet coolant pressure, MPa	1.08	1.08	1.08	1.08
Inlet coolant T, °C	4-60	40-65	4-60	40-65
Coolant velocity, m/s	6.6	6.6	5.9	5.2
Outer surface T, ^{0}C • average • maximal	67-87 86-106	58-78 86-106	80-100 95-115	65-85 95-115
Burnup, % • average • maximal	40.3 48.7	50.3 63.2	40.1 55.4	46,6 61,1

As it can be seen from the data, the maximal average burnup of IRT-3M No.2 made up 50.3% instead of targeted 60%. That is why there were started tests of two IRT-3M FAs (8-element design) either up to a burnup of 60% or until the loss of integrity with the purpose to perform the final qualification of this type of FAs. In June 2015, the FAs were loaded into the core. The irradiation continues up to now. Table 3 presents the key parameters of the above-said tests.

Table 3. Test parameters for full-size IRT-3M FAs (8-element)

Parameter	Value			
Irradiation cycle	1		2	3
Test duration, days	30	90	120	120
Average burnup at the end of irradiation cycle, %	6	24	44	60
Power range, kW	1070-1310	960-1170	822-1005	660-805

Thermo-hydraulic calculations were done to justify the test safety. Table 4 presents the calculation results.

Table 4. Parameters of thermo-hydraulic tests of IRT-3M FAs (8-element)

Parameter	Value		
	Irradiation cycle		
	1	2	3
FA power, kW	1310	1005	805
Average burnup of U-235, %	0	24	44
Heat flux non-uniformity factor over the FA, rel. unit.	1,66	1,44	1,21
Max heat flux on the fuel element surface, kW/m^2	1382	929	630
Coolant inlet temperature, °C	70	70	70
Coolant flow rate, m^3/h	80	65	50
Average coolant velocity, m/s	7,48	6,08	4,6
Maximal temperature of the cladding outer surface, °C	111	105	102
Maximal fuel meat temperature, °C	116	108	104

Note: the values are given for the beginning of every irradiation cycle.

4. Results of IRT-3M and IRT-U tests

Post irradiation examinations of IRT-3M FA No.2 (6-element design) were done using sample with the maximum fuel burnup. To examine IRT-U FA No.2, samples with the maximum burnup were also selected.

On the whole, the fuel condition was found satisfactory; a cladding-to-meat contact was tight. The oxide film layer thickness on the surface of the IRT-3M FA outside fuel element cladding achieved 18μm on the edges and 19μm on the corner roundoffs.

Figures 4-5 present photos made by SEM. There is a tight contact between fuel particles and matrix.

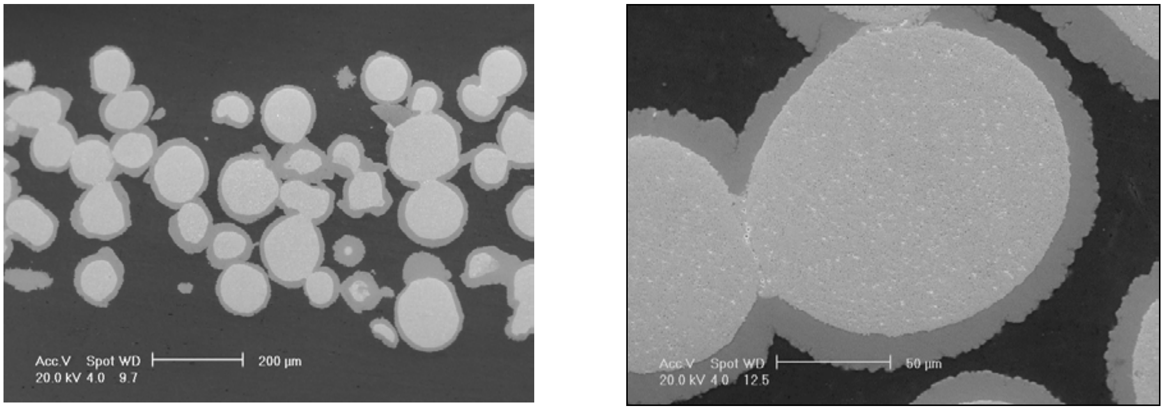


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Figure 4. SEM images of macro- and micro-structure of IRT-3M No.2 FA fuel meats.

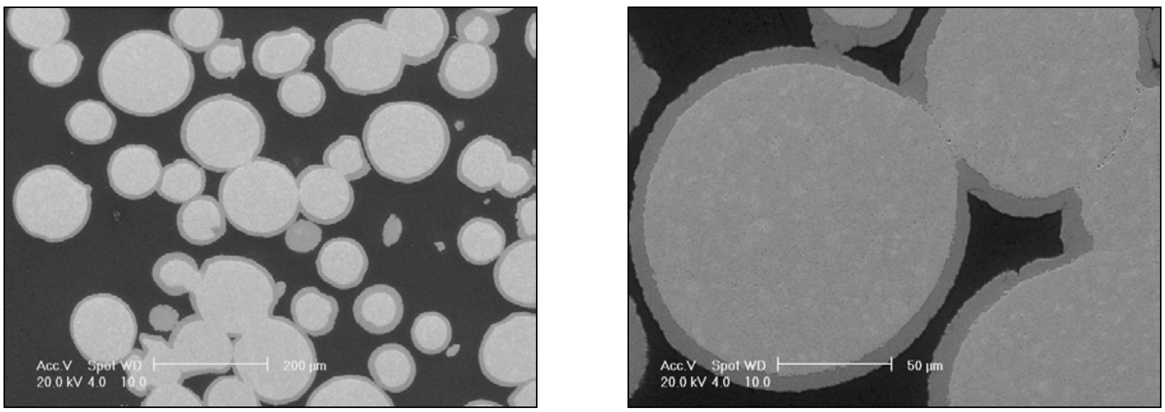

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Figure 5. SEM images of macro- and micro-structure of IRT-U No.2 FA fuel meats.

The U-Mo-to-matrix interaction layer is not uniform around the fuel particles periphery (Fig.6). Interaction layer average size is ~12μm.

The interaction layer structure is uniform; no pores were revealed in it (Fig.7). Pores of large diameter (up to 1μm) were revealed at the place of fuel particles junctions. The pores locate mainly on the grain boundaries of the U-Mo particles (Fig.8).

As noted above, irradiation of the second IRT-3M FA was stopped because cladding leakage was detected by the control system. The average burnup achieved over the FA made up 50.3% instead of targeted 60%.

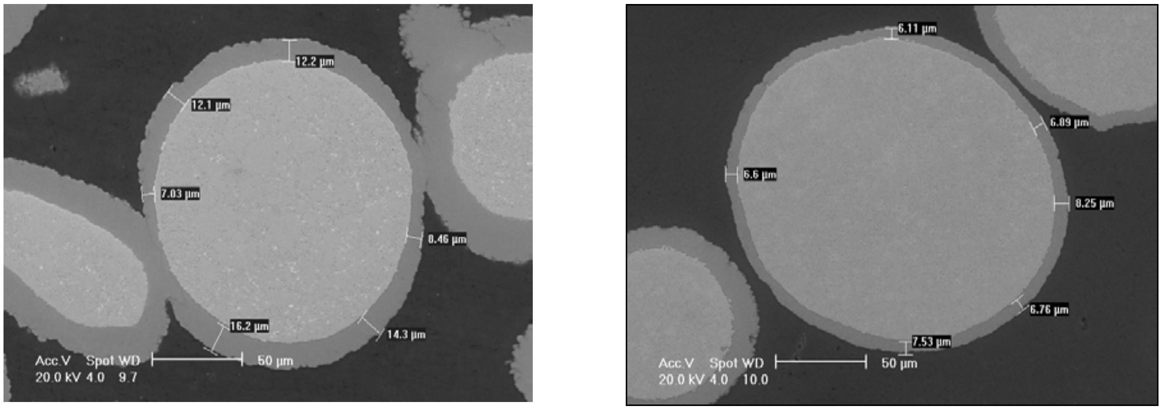

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Figure 6. SEM image of fuel particles and evaluation of their interaction with the matrix in the IRT-3M outside fuel element and IRT-U fuel element No.14.

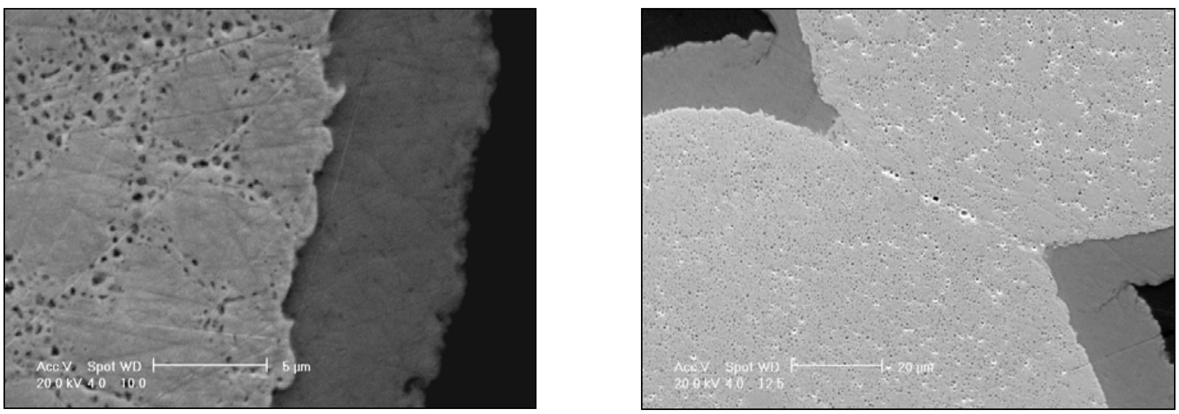

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Figure 7. Interaction layer structure (a) and appearance of porosity at the place of junction of two fuel particles (b) in the IRT-3M FA.

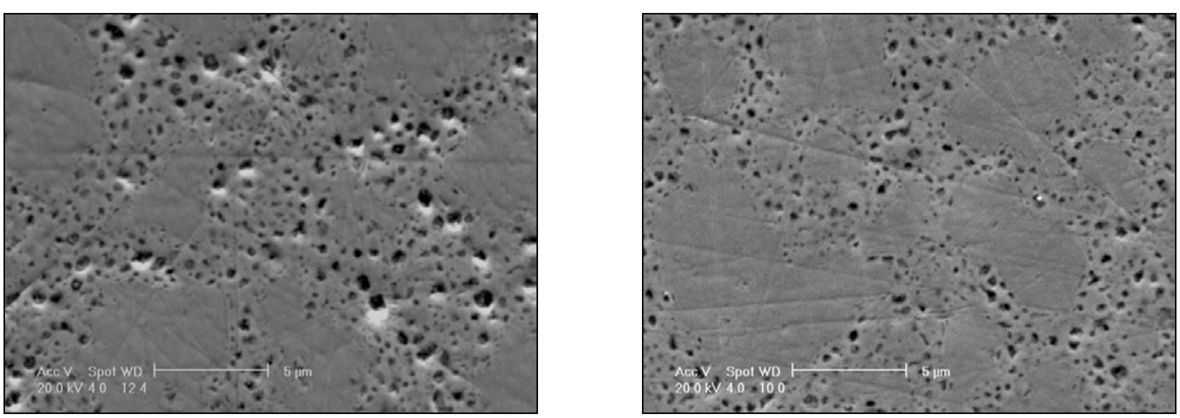

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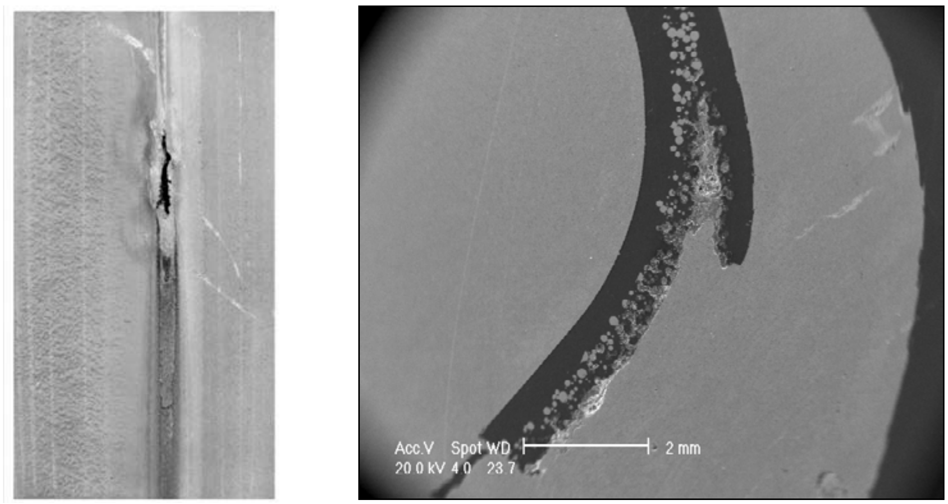
Figure 8. SEM image of the U-Mo structure in the outside fuel element of IRT-3M FA (a) and IRT-U FA fuel element No.14 (b).

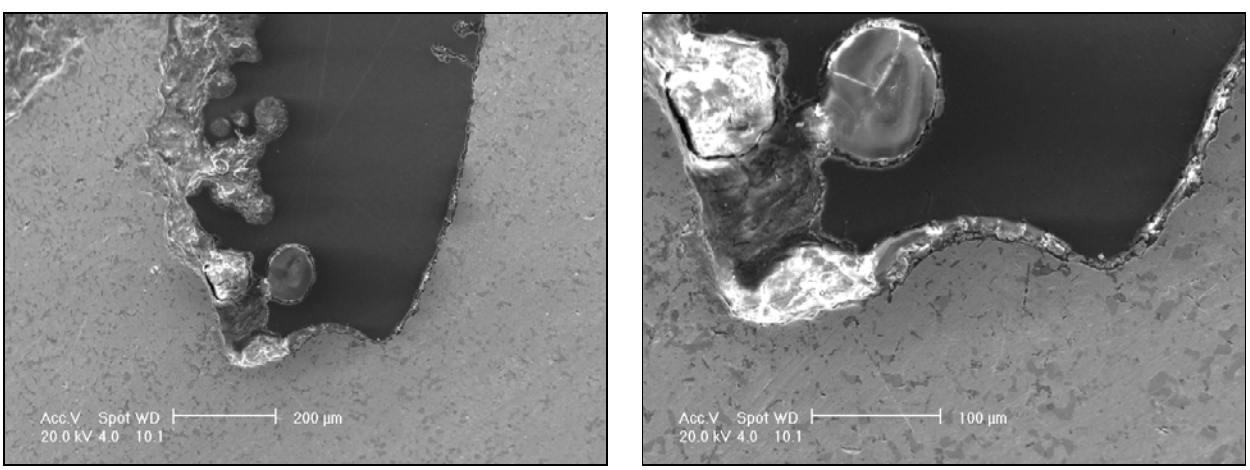
The visual inspection revealed one leaky fuel element. A through defect ~ 15mm long was found outside the cladding of fuel element No.5. The defect located on the fuel element rib at a distance of ~245mm from the fuel element bottom. Figure 9a shows the fuel element with a defect. Figure 9b presents a fuel element cross-cut at the defected area. A strong oxidation of fuel particles and matrix is observed at the place of contact with coolant.



a) b)

Figure 9. Fuel element with a defect (a) and cross-cut at the place of defect (b).

SEM examinations of the defected area close to the outer surface of cladding revealed a spherical figure resembling a fuel particle (10a). The circle radius of this figure made up 100-150μm; a residual interaction layer between a fuel particle and either Al matrix or cladding was found (Fig.10b). Uranium was detected in this layer by the electron probe X-ray micro-analysis. This evidences about an as-fabricated defect since fuel particles were found away to the outer surface of fuel element.



a) b)

Figure 10. Micro-structure of the fuel meat at the place of defect. The area marked on the left-hand photo is zoomed on the right-hand one.

5. Current status of IRT-3M FAs (8-element) testing

The following activities were done to prepare tests of 8-element IRT-3M FAs:

- measurements of overall dimensions and gaps between fuel elements;
- evaluation of enrichment in ^{235}U;
- hydro-weighing;
- measurement of pressure drop in the irradiation channel to evaluate the FAs hydraulic resistance.

The measurements and evaluations showed a full compliance of the IRT-3M FAs with the specifications. The hydraulic resistance FAs will be evaluated at the beginning and end of each irradiation cycle.

The 8-element IRT-3M FAs are being tested at present. As of the mid of September, the irradiation duration made up 35 effective days. It should be mentioned that the FA power was at a level of 1300kW for 10 days continuously; no leakage was revealed. The calculated burnup for both FAs ranges within 11-12%. The fist target burnup of 6% having been achieved, the FAs were brought to power of 960-1170kW. Figure 11 shows changes in power during tests.

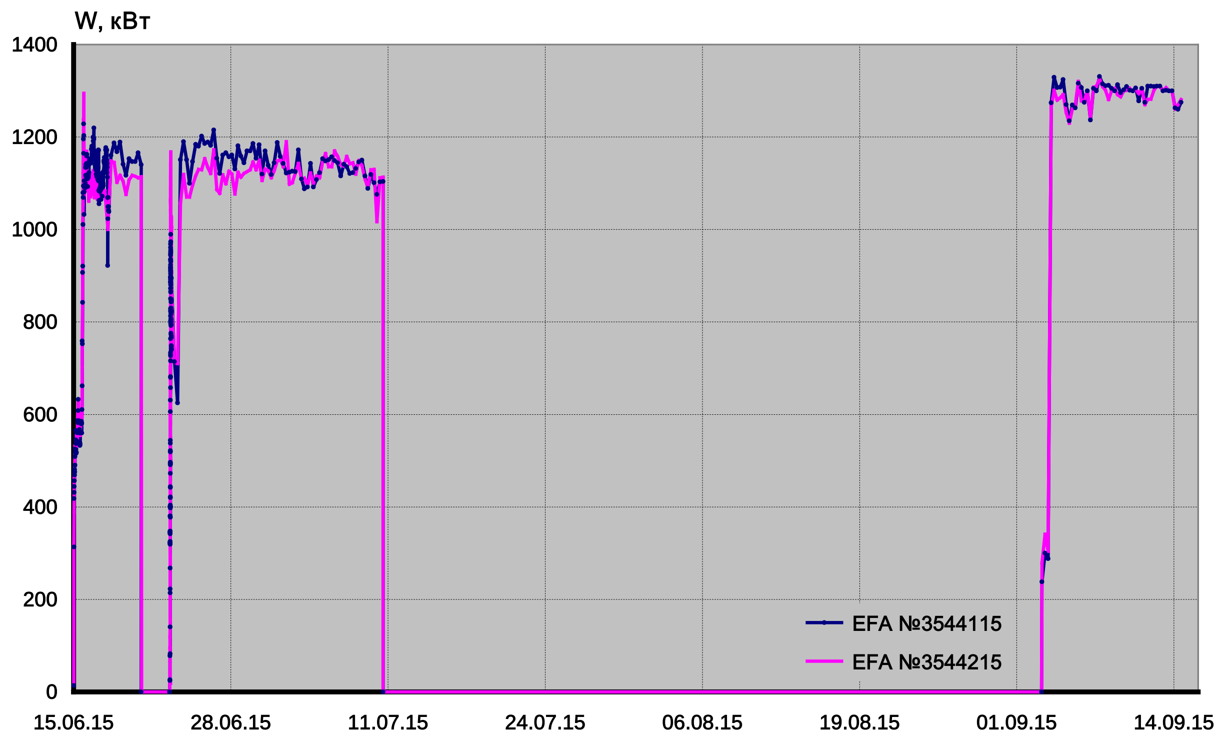


Fig.11 – IRT-3M FA power schedule

Note: There were maintenance works at the reactor from the mid of July till the beginning of September.

6. Conclusions

Two LEU U-Mo9% full-size lead fuel assemblies were fabricated at NCCP under the contract with ANL. The fabrication technology was improved during FAs fabrication process.
In June 2015 the irradiation testing of these fuel assemblies was launched in the MIR reactor. The irradiation tests aim at achieving an average U-235 burnup of ~60% over the fuel assembly for ~250 FPDs.
As of September 15, 2015 the maximal calculated burnup was ~12%. The irradiation tests are expected to finish in June 2016.

7. References

[1] A.L. Izhutov, V.V. Alexandrov, A.Ye. Novosyolov, V.A. Starkov, A.V. Sheldyakov, V.Yu. Shishin, V.V. Iakovlev. The Status of LEU U-Mo Fuel Investigation in the Mir Reactor. 31st International Meeting on Reduced Enrichment for Research And Test Reactors. November 1-5, 2009, Beijing, China.

[2] A.L. Izhutov, V.A. Starkov V.A., V.V. Pimenov V.V. et al. “The status of testing LEU U-Mo full-size IRT type fuel elements and mini-elements in the MIR reactor”, The 2008 International Meeting on Reduced Enrichment for Research and Test Reactors, October 5-9, 2008, Washington D.C., USA.