Lifetime Testing of Two IRT-3M (High Density U-9%Mo) LEU Lead Test Assemblies in the MIR Research Reactor

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ABSTRACT

The paper describes the main conditions and results of fuel verification tests conducted in the MIR reactor of two IRT-3M type lead test assemblies (LTA) based on LEU U-9%Mo fuel of ~5.4 g/cm³ U in the fuel meet. The testing was conducted for 382 calendar days of which 228 days were the period of time when the MIR reactor was operated at power. The average burnup of U-235 in the LTA was ~ 61.3 and ~ 62.6 %, respectively.

No leakage of the fuel tube claddings was detected by the on-line control equipment during irradiation, the increase in the LTAs hydraulic resistance under irradiation was insignificant. Thus the IRT-3M LEU U-9%Mo can be used in the research reactors under the operational parameters verified in this experiment.

1. Introduction

The issue of research reactors conversion is a part of a wide range of R&D tasks, among which the key one is the development of the high-dense LEU uranium fuel fabrication technology. Considerable success has been recently achieved in this area [1, 2]. In particular, the promising type of fuel, regarding its density and radiation resistance, is shown to be uranium-molybdenum alloy (U-9%Mo). That is why, when developing a new IRT-3M high-dense LEU LTA, there was selected uranium-molybdenum fuel in the aluminum matrix fabricated by extrusion.

To justify the application of IRT-3M LEU LTA, lifetime tests [3] were performed in 2007-2008 in the MIR reactor for two full-size 6-tube lead test assemblies (LTAs). One of them was irradiated up to the average $^{235}$U burnup of 40%. Due to leakage, irradiation of the second LTA was stopped at an average $^{235}$U burnup of ~50.3% instead of scheduled 60%. According to the PIE, the cause of cladding leakage was an as-fabricated failure.
In 2015, as the manufacturer (PJSC "NCCP") improved the fabrication procedure, two 8-tube IRT-3M LTAs were fabricated and tested in the MIR reactor from June 2015 till July 2016. The goal of the lifetime tests was to experimentally confirm the performance of IRT-3M LTAs up to the average $^{235}$U burnup of no less than 60%.

At present, the IRT-type fuel assemblies are operated at many Russian-design research reactors: IR-8, IRT-MEPhI, IRT-T in Russia and LVR-15 in the Czech Republic and VVR-SM in Uzbekistan.

2. Design characteristics of IRT-3M LTA and experimental channel

IRT-3M LTA [4] consists of 8 fuel tubes of square cross-section, top and bottom end components (Fig.1). The tube-like fuel tubes are spaced with spacer grids located at the top and bottom end components. The inner fuel tubes can move axially within the axial thermal gap. The LTA bearing element is the outer fuel tube which is fixed to the top and bottom end components. The top end component has a groove for a reloading device to grip the LTA.

Each LTA fuel tube has three layers, where the inside layer is fuel meat and outside layers are claddings made of aluminum alloy (SAV-1). The claddings are in tight contact with the fuel meat. Inside the eighth (inner) fuel tube there is a cylindrical displacer consisting of a perforated tube with a sealed orifice inside.

The fuel meat is atomized spherical U-Mo alloy particles dispersed into the pure Al matrix. Average size of U-9%Mo particles is $\sim (60-160) \mu$m. The enrichment of uranium by $^{235}$ isotope is $\sim 19.7\%$. The density $U$ in the fuel meat is $\sim 5.4$ g/cm$^3$. The LTA total length is $\sim 882$ mm; the active part length is $\sim 600$ mm; the fuel tube thickness is 1.4 mm; the fuel meat thickness is $\sim 0.55$ mm; the cladding thickness is $\sim 0.42$ mm but no less than 0.3 mm, the gap between fuel tubes is $\sim 2$ mm.

Fig.1 – IRT-3M LTA.

A peculiar feature of the IRT-3M LTA design is a square cross-section. So as to provide the hydrodynamic conditions similar to the operational ones of such type of fuel assemblies in a pool-type reactor, a special experimental channel was designed and fabricated. The channel consists of several parts with different shapes of flow sections. At the active part level (Fig.2) where the LTAs were installed, there are displacers to shape a square section of the hydraulic
path. The coolant flows from top to bottom of experimental channel and of LTA correspondingly.

![Image](image1.png)

![Image](image2.png)

**Fig. 2**

a) 3D-model of the core part of experimental channel with IRT-3M LTA;  
b) Cross-section of the experimental channel with IRT-3M LTA.

Before tests, some preliminary examinations were done, namely:

- visual inspection to reveal defects;
- hydrostatic weighing of the LTA to evaluate the fuel swelling;
- measurement of gaps between fuel tubes and of fuel enrichment to see if they comply with the technical requirements.

The inspection did not reveal any defects on the IRT-3M LTA surface (Fig.3); it also confirmed the compliance of the measured gaps and fuel enrichment with the technical requirements.
3. Required test parameters

The irradiation was done according to the Test Program consisting of 4 cycles. The test parameters are given in Table 1.

Table 1. Test parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irradiation cycle</td>
<td>a</td>
</tr>
<tr>
<td>Test duration, days</td>
<td>30</td>
</tr>
<tr>
<td>Required burnup at the end of irradiation cycle, %</td>
<td>6</td>
</tr>
<tr>
<td>IRT-3M LTA power change range, kW</td>
<td>1070-1310</td>
</tr>
<tr>
<td>Inlet coolant pressure in the experimental channel, MPa</td>
<td></td>
</tr>
<tr>
<td>Inlet temperature in the experimental channel, °C</td>
<td></td>
</tr>
<tr>
<td>Coolant flowrate through the experimental channel, m³/h</td>
<td></td>
</tr>
</tbody>
</table>

During the tests, the data acquisition and measurement system (DAMS) controlled the following process parameters:

- LTA power (calculated with the account of thermal loss to the reactor pool);
- coolant temperature at the experimental channel inlet and outlet;
- coolant flow-rate through the experimental channel;
- coolant pressure at the experimental channel outlet;
- specific activity of delayed neutrons in coolant at outlet of experimental channel.
4. Main test results

The lifetime tests of two IRT-3M LTAs were performed from June 16, 2015 till July 3, 2016. The total testing time was 382 days, from which for 228 days the reactor was operated at full power. Figure 4 presents the diagram showing power change in two IRT-3M LTAs during the whole testing period. It can be seen from the diagrams that the power of both LTAs corresponded to the Test Program for all irradiation period. Moreover, during the first irradiation cycle that lasted for 10 days (September 5-15) the LTA power was maintained at a level of no less than 1310 kW that corresponds to the upper limit of the required power range for the first 30 days of testing (Table 1).

![Fig.4 – IRT-3M LTA power diagram](image)

Neutronic and thermo-hydraulic simulations of test conditions were performed using software MCU-4 [5] and ANSYS [6], respectively. Figures 5 and 6 show the axial and radial heat rate distribution vs. the average fuel burnup in the LTA.
Fig. 5 – Axial heat rate distribution in IRT-3M LTA at an average $^{235}$U burnup of:
   a) 0% and 6%; b) 24%; c) 44%; d) 60%.
   Note: “0 cm” – core mid-plane.

Fig. 6 – Radial heat rate distribution in IRT-3M LTA at an average fuel burnup of:
   a) 6%; b) 24%; c) 44%; d) 60%.
   Note: the order is from the outer fuel tube to the inner one.
As it can be seen from the diagrams, the outer fuel tube was the most stressed one. A local increase in the heat rate at the LTA edges was related to the increase in the thermal neutron flux due to water layers under and above the LTA that serve both as a moderator and reflector. According to the calculations (Fig. 5d, Fig. 6d), the heat rate became almost uniform over the LTA by the end of irradiation. The obtained heat rate distributions were used to calculate temperature fields in the LTA to justify the thermo-physical reliability of the tests. The inlet data (power, coolant flowrate through the experimental channel and its inlet temperature) were taken from the DAMS database. Tables 2 and 3 present the simulation results.

Table 2. Test parameters of LTA # 3544115

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average $^{235}$U burnup, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>LTA power, kW</td>
<td>1307</td>
</tr>
<tr>
<td>Coolant flowrate through LTA, m$^3$/h</td>
<td>~68</td>
</tr>
<tr>
<td>Coolant temperature at the</td>
<td></td>
</tr>
<tr>
<td>experimental channel inlet/outlet, °C</td>
<td>38/53</td>
</tr>
<tr>
<td>Max heat rate, $10^6$ kW/m$^3$</td>
<td>4,98</td>
</tr>
<tr>
<td>Max thermal flux density, MW/m$^2$</td>
<td>1,96</td>
</tr>
<tr>
<td>Max T, °C</td>
<td></td>
</tr>
<tr>
<td>Fuel meat</td>
<td>123</td>
</tr>
<tr>
<td>Outer surface of cladding</td>
<td>121</td>
</tr>
</tbody>
</table>

Table 3. Test parameters of LTA # 3544215

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average $^{235}$U burnup, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>LTA power, kW</td>
<td>1310</td>
</tr>
<tr>
<td>Coolant flowrate through LTA, m$^3$/h</td>
<td>~71</td>
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<tr>
<td>Coolant temperature at the</td>
<td></td>
</tr>
<tr>
<td>experimental channel inlet/outlet, °C</td>
<td>45/59</td>
</tr>
<tr>
<td>Max heat rate, $10^6$ kW/m$^3$</td>
<td>4,99</td>
</tr>
<tr>
<td>Max thermal flux density, MW/m$^2$</td>
<td>1,96</td>
</tr>
<tr>
<td>Max T, °C</td>
<td></td>
</tr>
<tr>
<td>Fuel meat</td>
<td>123</td>
</tr>
<tr>
<td>Outer surface of cladding</td>
<td>121</td>
</tr>
</tbody>
</table>

By the end of the test, the average $^{235}$U burnup in LTA #3544115 made up 62.2% and the maximum $^{235}$U burnup made up 82.1%, the one in LTA #3544215 made up 61.3% and 80.9%, respectively. No leakage and loss of integrity were found during irradiation by on-line measurement of delayed neutrons in coolant at outlet of experimental channel.

The maximum temperatures of the fuel meat and cladding surface were achieved at a burnup of 6%, but not at 0%, when the LTA power was the maximal during the whole testing period. It was related to the coolant temperature rise at the experimental channel inlet. The maximum fuel and cladding temperatures were calculated using the thermal conductivity values for unirradiated materials. It should be also mentioned that there was a significant cladding
temperature margin to boiling. The maximal cladding temperature did not exceed 131°C at the minimal saturation temperature of ~185°C. Figures 7-10 show the temperature distribution over the LTA cross-section and experimental channel. The kind of temperature field is the same for both LTAs.

Fig. 7 – Temperature distribution in the experimental channel and IRT-3M LTA at an average $^{235}$U burnup of: a) 0%; b) 6%; c) 24%; d) 44%; e) 60%.
To effectively control the LTA during the whole irradiation period, the hydraulic test parameters were recorded. The pressure drop was measured on a hydraulic path, including not only the IRT-3M LTA itself, but also the experimental channel and discharge pipeline. Using the methods of statistical analysis (least square method, F-test, χ²-criterion, etc.) to process the experimental data, a dependence was obtained between ⁵²³U burnup in the LTA and path hydraulic resistance:

\[ \xi_{2-2} = \alpha_{2-2} + \gamma \cdot B_{2-2}, \]
\[ \xi_{3-4} = \alpha_{3-4} + \gamma \cdot B_{3-4}, \]

Where: \( \xi_{2-2}, \xi_{3-4} \) – hydraulic resistance of experimental channels 2-2 with LTA #3544115 and 3-4 with LTA #3544115, MPa/(m³/h)²;
\[ B_{2-2}, B_{3-4} = ⁵²³U \text{ burnup in the LTA, rel. unit}; \]
\[ \alpha_{2-2} = (4.59 \pm 0.04) \cdot 10^{-5} \text{ MPa/(m}³/\text{h})²; \]
\[ \alpha_{3-4} = (4.04 \pm 0.04) \cdot 10^{-5} \text{ MPa/(m}³/\text{h})²; \]
\[ \gamma = (8.1 \pm 0.9) \cdot 10^{-6} \text{ MPa/(m}³/\text{h})². \]

Attention should be paid to the fact that the hydraulic resistance change dependence is linear vs. the average ⁵²³U burnup in the LTA, that, in its turn, may show a smooth dependence between the fuel swelling and burnup. The analysis results show that as ⁵²³U burnup in the LTA becomes higher, the pressure drop on the IRT-3M LTA takes place due to an increase in the fuel volumes and relative decrease in gaps between them. Pressure drop increase on the LTA for different coolant flow rates and average ⁵²³U burnup in the LTA is shown in Fig. 8.

To evaluate the LTA volume increase after irradiation as well as fuel swelling, the LTA volume was measured hydrostatically before and after irradiation. The analysis results show that the volume of IRT-3M LTA #3544115 increased by 22.5±3.5 cm³ and the one of IRT-3M LTA #3544215 increased by 19.5±3.5 cm³ at an average ⁵²³U burnup of 62.2% and 61.3%, respectively. The LTA fuel meat volume is ~ 376 cm³, the U-Mo particles volume is 122 cm³. Thus, the average swelling of the fuel meat makes up ~ 5.5% and the one of U-Mo particles is ~ 17.2%. The average specific U-Mo particles swelling is 1.87% of fissioned
nuclei. As the residual heat rate attenuated till the acceptable level, the irradiated LTAs will be examined using under-water TV cameras and the gaps between fuel tubes will be measured.

**Conclusion**

1. Lifetime tests of two-full-size IRT-3M LTAs #3544115 and #3544215 have been successfully completed. By the end of irradiation, the $^{235}$U burnup in the LTA # 3544115 made up 62.2% average in volume and 82.1% maximal at point. As for LTA #3544115, it made up 61.3% and 80.9%, respectively.

2. No leakage of the fuel tube claddings was detected by the on-line control equipment during irradiation. An increase in the LTA hydraulic resistance under irradiation was insignificant. The average specific U-Mo particle swelling made up $\sim 1.87$ $\%$ of fissioned nuclei.

3. The performance of IRT-3M LEU Lead Test Assemblies operated under the maximal power up to 1310 kW and the maximal thermal flux up to 1,96 MW/m², was experimentally confirmed that proves the possibility to use this type of fuel in the pool-type reactors like IR-8, IRT-MEPhI, IRT-T.

**Acknowledgement**

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**References**


