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Conversion of the MIR.M1 Reactor to LEU-fuel

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ABSTRACT

The paper covers the results of the calculated research of the MIR.M1 reactor conversion to LEU fuel. The work is performed within the framework of the RERTR program under the support of Argonne National Laboratory. Two LEU fuel types with 19.7% enrichment, UO_2 oxide and alloy U9%Mo, were studied during the research. The performed neutron-physical and thermal-hydraulic calculations allowed to obtain the comparative characteristics of the cores with different fuel types. It is shown that the conversion to LEU fuel is accompanied by a slight decrease (4-6%) of fast neutron fluence on the experimental fuel element claddings, significant decrease of the annual consumption of FAs (30-33%) and ^{235}U (8-12%). However, annual consumption of uranium increases by ~ 4 times. The calculation also showed that the conversion to LEU fuel does not result in the deterioration of thermophysical criteria (departure from nuclear boiling, margin to heat transfer crisis, etc.) of the reactor safe operation. It is concluded that the reactor conversion to LEU fuel is feasible in principle.

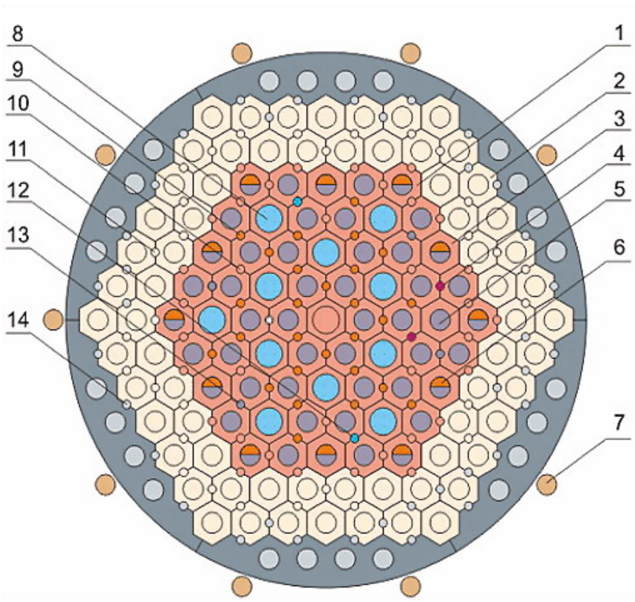
1. Introduction

The main task of the calculated research is to obtain comparative characteristics of HEU and LEU cores in order to determine the conversion feasibility. The paper presents the values that specify the characteristics covered earlier in [1].

2. Reactor MIR.M1

The reactor facility is located at the site of JSC "SSC RIAR", Dimitrovgrad. It has been in operation since 1967. By its physical characteristics, MIR.M1 is a thermal heterogeneous reactor that utilizes beryllium as a moderator and reflector and distilled water as a coolant. By its design features, it is a loop-type reactor immersed into a pool of water. The reactor facility is mainly designed at testing materials, items and experimental FAs, investigation of operation modes and tryout of a coolant technology for promising nuclear reactors of new generation.

The reactor core (fig. 1) consists of beryllium blocks. Zirconium channels for standard FAs and loop channels are positioned throughout the beryllium blocks. The core is 1000 mm in height. The equivalent core diameter is 1220 mm.



1 – Core Be-block
2 – Reflector Be-block
3 – Loop channel Be-block
4 – Control rod
5 – Standard FA
6 – Channel with an absorber
7 – Ionizing chamber
8 – Loop channel
9 – Shim rod
10 – Core Be-plug
11 – Reflector Be-plug
12 – Safety rod tube
13 – Safety rod tube with a plug
14 – Al-plug

Figure 1 – Core arrangement

A standard fuel assembly (fig.2) is composed of four coaxially positioned annular fuel rods fixed in upper and lower spacer grids. Each fuel rod represents a three-layer tube where the fuel is cladded with aluminum alloy (CAB-6). The cavity of the inner fuel rod is filled with annular aluminum displacer ∅ 34×2 mm. Outer diameter of the FA – 70 mm, overall length – 1484 mm. Fuel rods are 2 mm thick. There are three azimuthally oriented ribs on the external surface along the entire length of fuel rods. The 90% enriched UO_2 in the aluminum matrix is used as a fuel. The fuel meat thickness is 0.56 mm, cladding thickness is 0.72 mm. The content of ^{235}U per one standard fuel assembly is 345÷350 g.

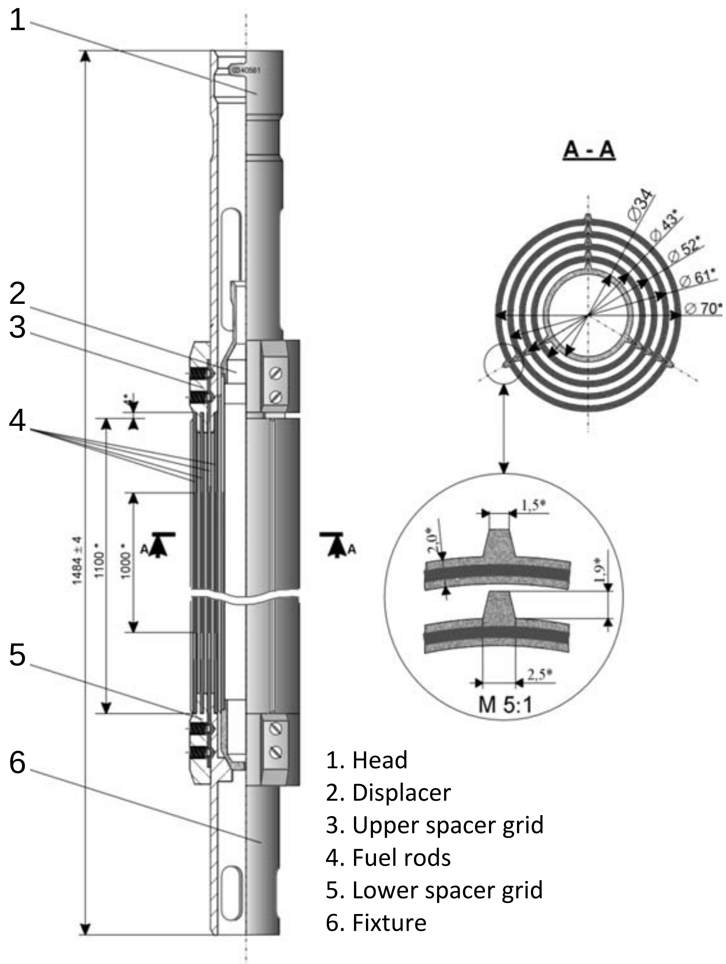


Figure 2 – Standard FA

3. Initial data

When doing calculations, some initial characteristics of the core were taken the same for all fuel types in order to avoid considering many options of possible reactor states. Among these characteristics are:

- reference core arrangement (fig. 3);
- depth of safety rods drop into the core;
- relative distribution of ^{235}U mass over the core at the beginning of the run;
- reactor capacity (40MW);
- reactor cycle (14 days).

The figure below presents the reference core arrangement. Such selection was done on the basis of the MIR.M1 operating experience. The loop channels are loaded with experimental FAs or with Be-plugs. One loop channel is filled with water. Other cells are loaded with standard FAs and channels with absorbers. Reference fast neutron flux values were registered on the claddings of fuel rods located in a cell marked in red. A fuel assembly consisting of 19 VVER fuel rods arranged in a triangular grid was considered as an experimental one in doing calculations. The experimental assembly represents a hexagonal wrapper made from alloy E-110. The fuel in fuel rods is 3.6% ^{235}U enriched UO_2.

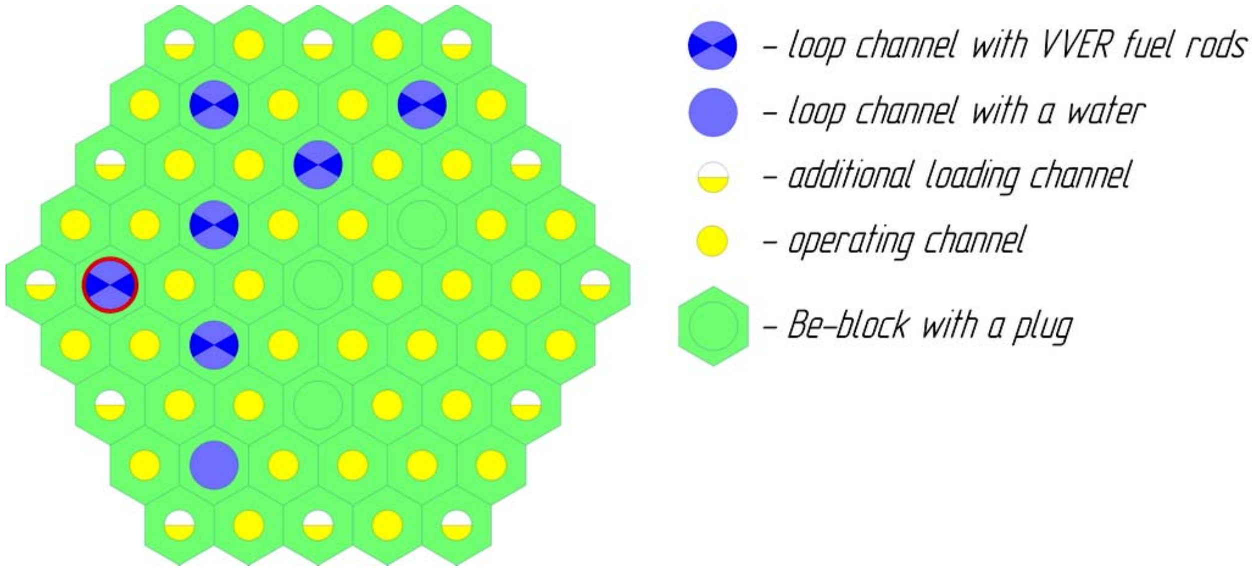


Figure 3 Reference core design

Two 19.7% enriched LEU fuels were considered for the reactor conversion: oxide fuel UO_2 and alloy U9%Mo. Preliminary estimates showed that to keep the reactivity margin, the ^{235}U loading in LEU should make up about 460 g. It is proposed to provide such content by the following:

- increase in fuel density (for both LEU fuels);
- increase in fuel meat thickness (for both LEU fuels);
- increase in a number of fuel rods (for UO_2 only).

The main comparative geometry and process characteristics of FAs with HEU and LEU fuels are presented in Table 1 and figure 4.

Table 1 Comparative characteristics of FAs with HEU and LEU fuels

Parameter	HEU	LEU-1	LEU-2
Fuel type	UO_2	UO_2	U9%Mo
Enrichment in ^{235}U, %	90	19.7	19.7
Thickness of - the fuel layer in the fuel rod, mm - the cladding, mm	 0.55 0.725	 0.94 0.53	 0.66 0.67
Mass of ^{235}U in the FA, g	350	460	460
Fuel meat density, g/cm^3 - in ^{235}U - in U	 0.91 1.01	 0.57 2.90	 1.02 5.16
Volumetric content of fuel in the fuel meat, rel.units	0.11	0.317	0.33
Number of fuel rods in the FA	4	6	4
Total surface of heat removal, m^2	1.37	1.72	1.37

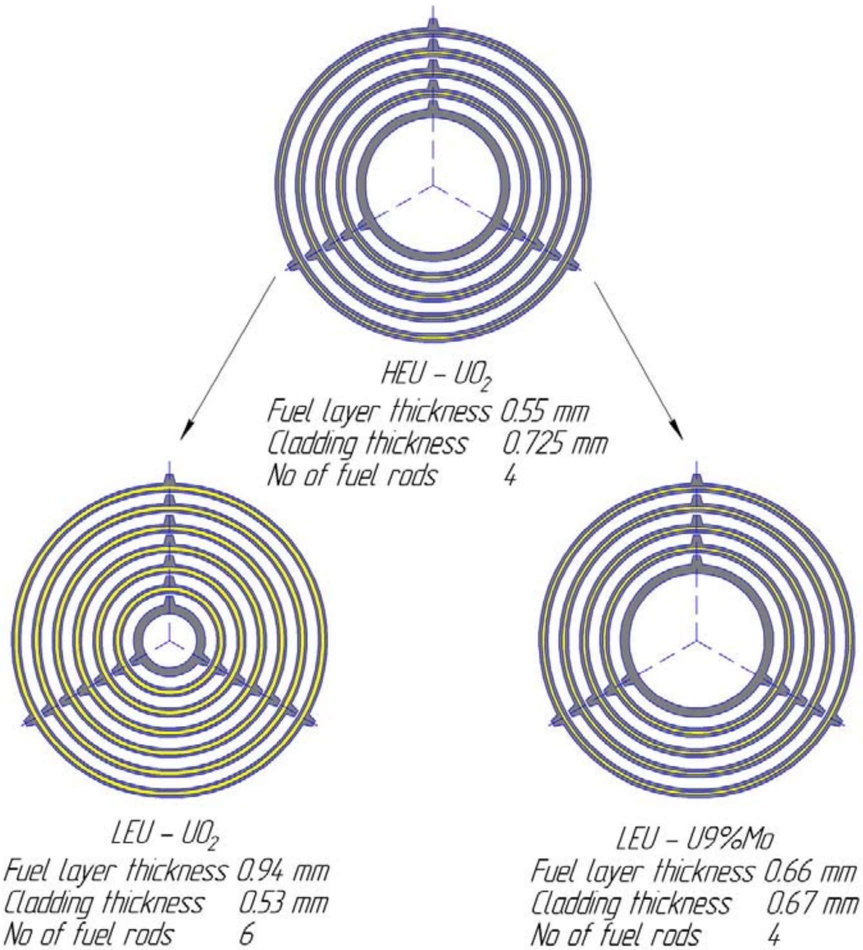


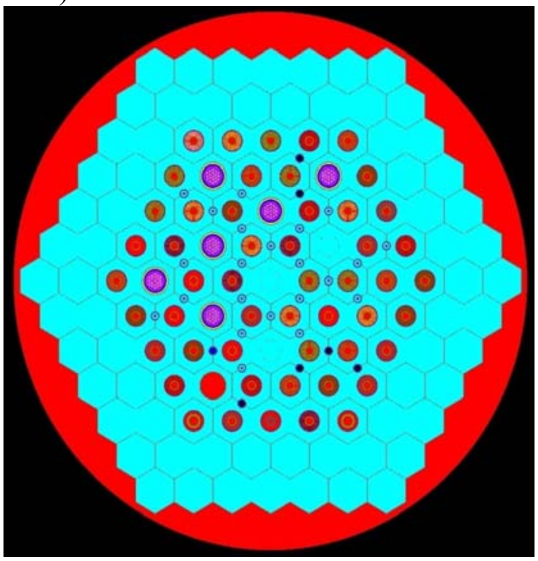
Figure 4 Cross-section of FAs with HEU and LEU fuels

In case of the LEU oxide fuel, it is impossible to provide the loading of 460 g ^{235}U only by the increase in density and thickness of the fuel meat. It is conditioned by the limiting value of UO_2 density that can be feasible. It resulted in the need for the increase in a number of fuel rods up to 6 pieces with the corresponding change in the inner displacer geometry. In case of the U9%Mo alloy, the ^{235}U loading is provided without a change in a number of fuel rods in a fuel assembly due to significantly higher fuel density.

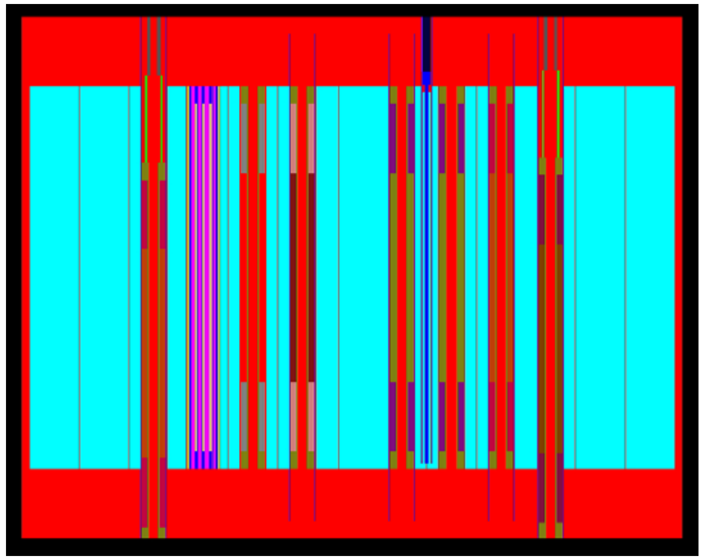
4. Neutronic calculations

To determine the HEU and LEU core characteristics, a detailed neutronic reactor model was developed by means of the MCU-RR2 code (Monte Carlo Universal – Research Reactor 2). The code is designed for calculation of neutron and photon flux functions in nuclear research reactors using a Monte Carlo method based on the estimated nuclear data without inserting any additional approximations into the description of geometry of a given system and physics of particles interaction with substance. Changes in the nuclide composition of fuel were calculated by means of the BURNUP software [2].

Figure 5 presents the reactor core model calculated by MCU (cross- and axial sections of the core).



Cross-section of the core



Axial section of the core

Figure 5 – Core model calculated by MCU

Table 2 presents the comparative characteristics of HEU and LEU cores obtained by the calculations.

Table 2 Comparative characteristics of HEU and LEU cores

<table>
<tr><th rowspan="2">Parameter</th><th colspan="3">Value</th></tr>
<tr><th>HEU UO_2</th><th>LEU UO_2</th><th>LEU U9%Mo</th></tr>
<tr><td>Average fuel burnup in the core, %
✓ at the beginning of the reactor run
✓ at the end of the reactor run</td><td>
29.5
33.3</td><td>
34.5
37.3</td><td>
33.8
36.6</td></tr>
<tr><td>Reactivity loss rate, 10^{-3} % Δk/k/MW*d</td><td>4.26</td><td>3.22</td><td>2.91</td></tr>
<tr><td>Safety rods efficiency, % Δk/k</td><td>28.7</td><td>28.3</td><td>27.4</td></tr>
<tr><td>Reactivity margin in the unpoisoned state, % Δk/k</td><td>13.0</td><td>12.8</td><td>12.6</td></tr>
<tr><td>Experimental FA power vs. neighboring FAs power in the unpoisoned state, rel. un.</td><td>0.70</td><td>0.69</td><td>0.68</td></tr>
</table>

The data presented show that the conversion to LEU fuel is accompanied by the increase in the average fuel burnup due to the increase in the fuel cycle duration. Decrease in the reactivity loss rate is conditioned by the increased density of LEU fuel. In so doing, safety rods efficiency and reactivity margin change within 3-4%. The last parameter that characterizes a possibility to

provide the required power in the loop channel owing to the power of neighboring FAs changes insignificantly and it doesn't worsen the experimental capacities of the reactor.
Table 3 presents average annual characteristics.

Table 3 Average annual characteristics

Parameter	Value		
	HEU UO_2	LEU UO_2	LEU U9%Mo
Average number of FAs unloaded at the end of the reactor run, pcs.	3.9	2.6	2.7
Average burnup of unloaded FA, %	50.5	54.4	53.1
Annual demand in FAs	62.4	41.6	43.2
Average consumption of, kg ✓ ^{235}U ✓ U	 21.8 24.2	 19.1 97.0	 19.9 100.9
Annual fluence of fast neutrons (E>0.1MeV) on a VVER fuel rod cladding in cell 3-10 in the core central plane, 10^{21} cm^{-2}	3.65	3.50	3.42

It should be noted that the conversion to LEU fuel is accompanied by a significant decrease in the annual demand in FAs by 30-33% and annual consumption of ^{235}U by 8-12%. The total U consumption increases by ~4 times. Fast neutron fluence (one of the reference parameters) is observed to decrease by 4-6%.

5. Thermohydraulic calculations

Thermohydraulic calculations were performed in order to justify thermophysical parameters of the reactor safe operation. For this purpose, the following was calculated:

- distribution of heat flows from the fuel rods surface;
- distribution of temperatures of fuel rod surfaces, temperatures of the fuel-to-cladding contact and maximal fuel temperatures along the core height;
- departure from nuclear boiling ratio and margin to heat transfer crisis.

A thermohydraulic model of the core is developed by means of the MIR software that allows calculating thermohydraulic parameters of coolant and temperature fields in an FA consisting of tubular fuel rods located co-axially. To evaluate the temperature of the onset of surface boiling, Bergles-Rhosenow [3] and Forster-Greif [4] formulas were used. The critical thermal flux density value was calculated by Mirshak correlation [5].
Since, according to the operational procedure, the maximal capacity of a standard FA may achieve 3.2MW under the maneuvering mode, all the thermohydraulic parameters were calculated with the account of this value. In so doing, the coolant temperature at the inlet to FAs was taken equal to 40°C and the coolant flow rate was taken equal to 70 m^3/h.
Temperature field distribution in the most stressed (outer) fuel rod for FAs with HEU and LEU is presented in figures 6-8, respectively.

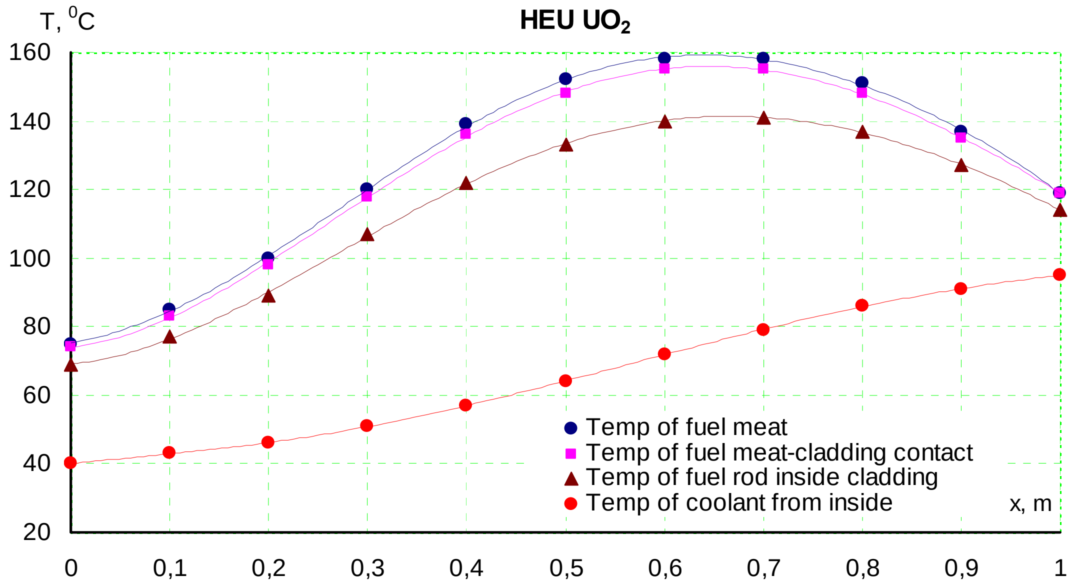


Figure 6 – Temperature distribution for HEU fuel

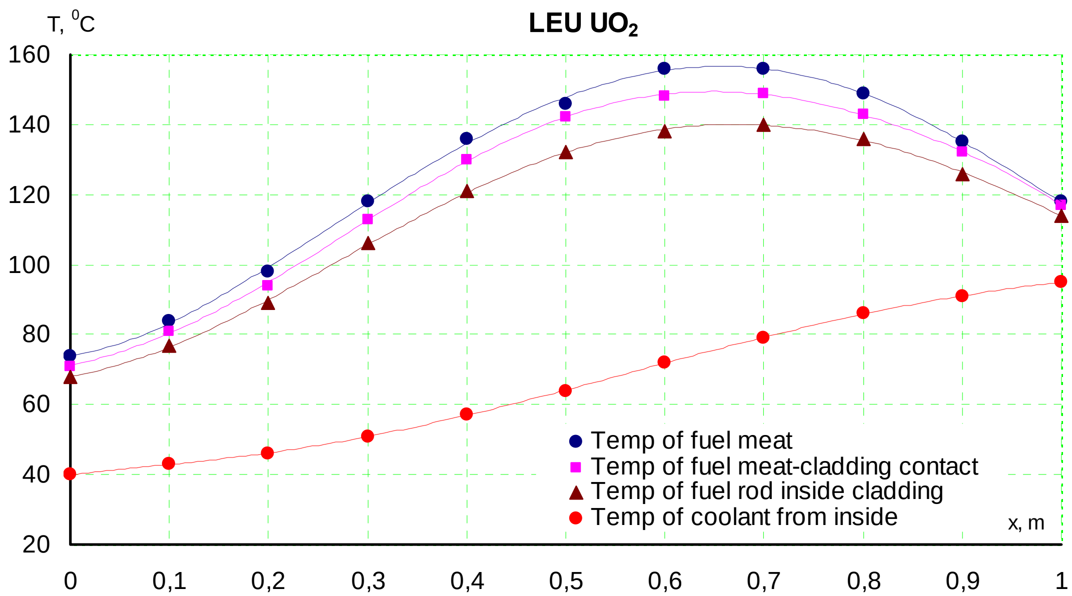


Figure 7 – Temperature distribution for LEU fuel

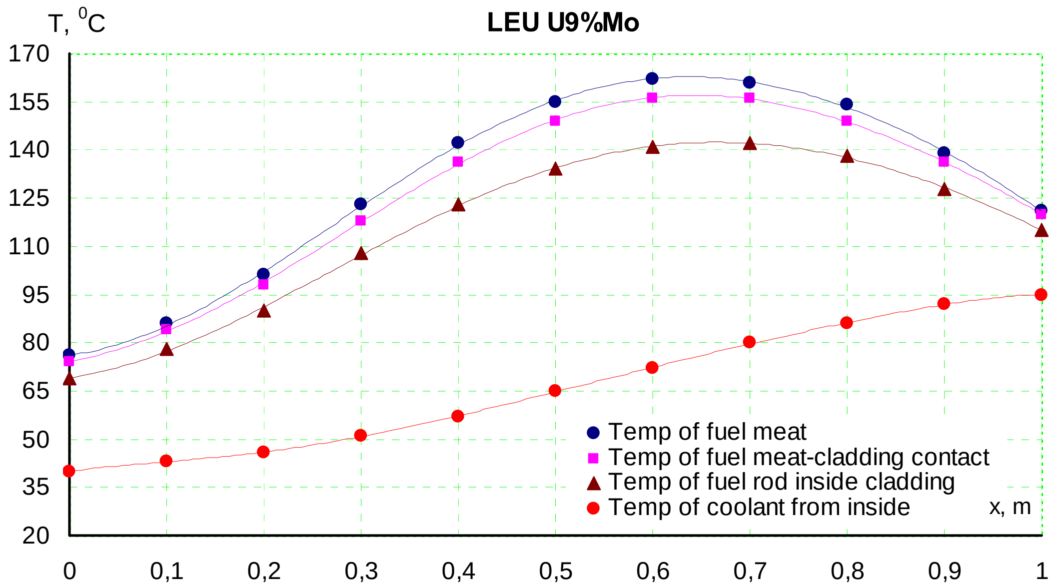


Figure 8 – Temperature distribution for LEU fuel

Table 4 presents maximal temperatures of the cladding and fuel meat for each fuel type.

Table 4 Maximal temperatures

Parameter	Value		
	HEU UO_2	LEU UO_2	LEU U9%Mo
Maximal cladding temperature, ^{0}C	141	140	142
Maximal fuel meat cladding, ^{0}C	158	156	162

In addition to temperature distribution, thermophysical margins (see Table 5) were calculated.

Table 5 Thermophysical criteria of the reactor safe operation

Parameter	Value		
	HEU UO_2	LEU UO_2	LEU U9%Mo
Thermal flux, kW/m^2	4002	3449	4042
Coolant velocity in the gap between fuel rods, m/s	9.1	7.2	9.1
Departure from nuclear boiling ratio • Bergles-Rhosenow formula • Forster-Greif formula	 1.45 1.58	 1.50 1.60	 1.44 1.57
Margin to heat transfer crisis	4.5	4.8	4.4

The data presented were obtained for a coordinate on a fuel rod with the maximal outside surface temperature. The analysis of the results shows no worsening of thermohydraulic characteristics when converting the reactor to LEU fuel.

6. Conclusion

Conversion to LEU fuel results in the following changes in the reactor characteristics:

1. Decrease in fast neutron flux density on the claddings of experimental fuel rods by 4-6%.
2. Decrease in a reactivity loss rate by 24-32%.
3. Increase in total U consumption by 4 times and of ^{235}U by 8-12%.
4. Increase in the annual consumption of FAs by 30%.
5. Increase in a number of fuel rods up to 6 pcs. in a FA with U9Mo.

It should be noted that the most important safety-related parameters, such as safety rods efficiency, departure from nuclear boiling ratio, margin to heat transfer crisis, etc., are observed to change with conversion by 5 % maximum.

Therefore, analysis of the calculation results shows it feasible to convert reactor MIR.M1 to LEU fuel without any significant changes of its experimental characteristics.

7. Acknowledgements

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8. References

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