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THE STATUS OF TESTING LEU U-Mo FULL-SIZE IRT TYPE FUEL ELEMENTS AND MINI-ELEMENTS IN THE MIR REACTOR.

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ABSTRACT

In April-May 2008, after achieving an average fuel burnup of ~ 40% testing of two IRT-type full-size fuel assemblies (FAs) with dispersed low-enriched U-Mo fuel was completed in the MIR reactor. One of the FAs has a tube design, while the second one is rod- type. Testing of other two FAs of the same design shall be continued in the MIR reactor to achieve an average fuel burnup of ~ 60%. The objective of the FAs testing is obtaining experimental data to license their use for the conversion of the VVER-SM reactor in Uzbekistan, as well as selection of an optimal FA design. Testing of the new batch of mini fuel elements with modified dispersed U-Mo fuel was completed after achieving a burnup of 50%, testing of the second batch is in progress.

1. Introduction

Within the framework of the RERTR program, in 2006 four IRT-type prototype full-size fuel assemblies (FAs) with dispersed low-enriched U-Mo fuel for the conversion of the VVER-SM reactor in Uzbekistan were fabricated at the Novosibirsk Plant of Chemical Concentrates. Two FAs have a tube design similar to that of the VVER-SM FAs, the other two FAs are of a rod-type, developed at the Bochvar Institute in cooperation with ANL [1]. In March-April 2007 testing of these four FAs was started in the MIR reactor [2]. In the first half of 2008, after achievement of the 40% burnup, one FA of each type were discharged from the reactor for cooling, PIE to be started at the end of 2008. Testing of other two FAs of the same design shall be continued in the MIR reactor to achieve an average fuel burnup of ~ 60%.

In order to investigate the behaviour of the modified U-Mo fuel compositions different in the degree of alloying, fuel particles coating and Si content in the matrix, testing of the rod-type mini fuel elements are being continued in the MIR reactor. By now, testing of the first batch of mini fuel elements with an average burnup of 50% is completed, testing second batch of mini fuel elements shall be continued to achieve an average fuel burnup of ~ 60%. The present report covers the results of the reactor testing of full-size IRT-type FAs and mini fuel elements as of September 15, 2008.

2. Technical characteristics of the FAs and mini fuel elements.

2.1. IRT-3M FA characteristics and design

The experimental IRT-3M fuel assembly (IRT-3M FA) contains six tubular fuel rods of square cross-section located concentrically, a head and a fixture. A fuel rod represents a three-layer tube 1.4mm long in total. Each fuel rod has outer and inner claddings, fuel column and end plugs. The minimal thickness of outer and inner claddings makes up 0.3mm. The main characteristics of IRT-3M FA are presented in table 1. The transversal cross-section of FA and its basic dimensions (mm) are presented in Fig.1.

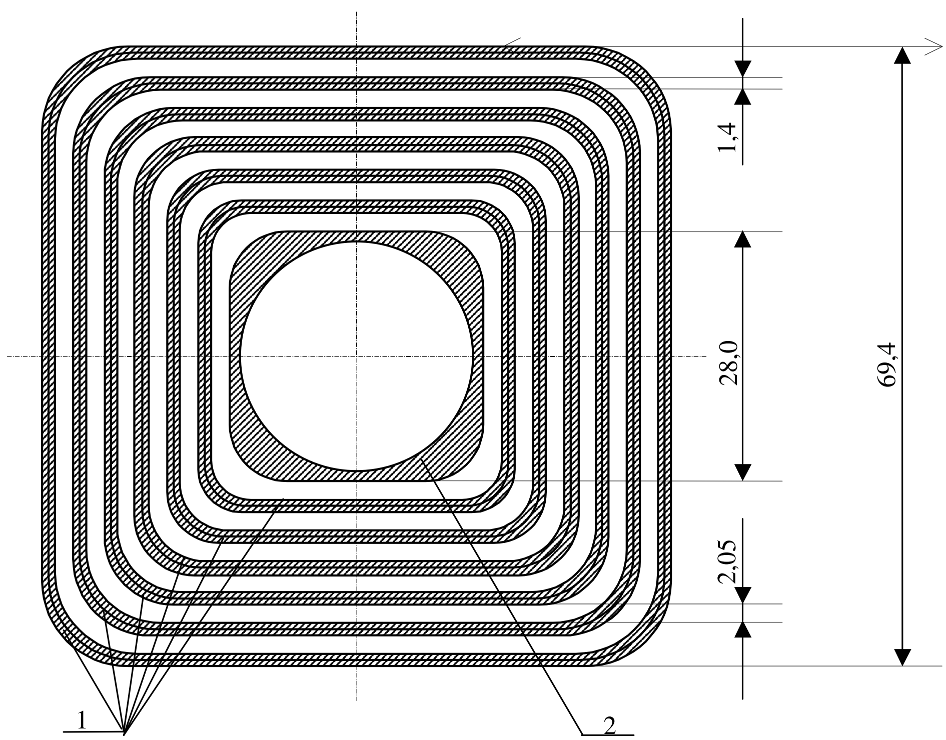


Fig.1. Cross-section of IRT-3M FA:

1-fuel tubes; 2-displacer

Table 1. Basic characteristics of IRT-3M FA

Characteristic	Value
Fuel tube cladding thickness, mm	0.31÷0.46
Fuel meet thickness, mm	0.5
Fuel tube thickness, mm	1.4
Length of fuel tube active part, mm	561÷609
Fuel material	U-8.8%Mo,U-9.4% Mo
Matrix material	PA-4
U density in the fuel meet, g/cm^3	5.3-5.4
Enrichment of ^{235}U, %	19.3÷19.9
Mass of U and ^{235}U in FA, g	1785 and 347
Volume of U-Mo in FA, cm^3	115.6
Number of fuel tubes in EFA, pcs	6
Cladding material	SAV-1

2.2 IRT-U EFA characteristics and design.

IRT-U EFA is non-dismountable and comprises a bundle of fuel rods of square cross-section and displacers connected by top and bottom spacer grids. The fuel rod bundle is located between two jackets. The transversal cross-section of IRT-U EFA and its basic dimensions (mm) are presented in Fig.2. A fuel rod is of square cross-section with ribs and consists of a cladding twisted around its axis with a pitch of 320mm and a right-directed helical line, two plugs and a column. The basic characteristics of IRT-U FA are shown in table 2.

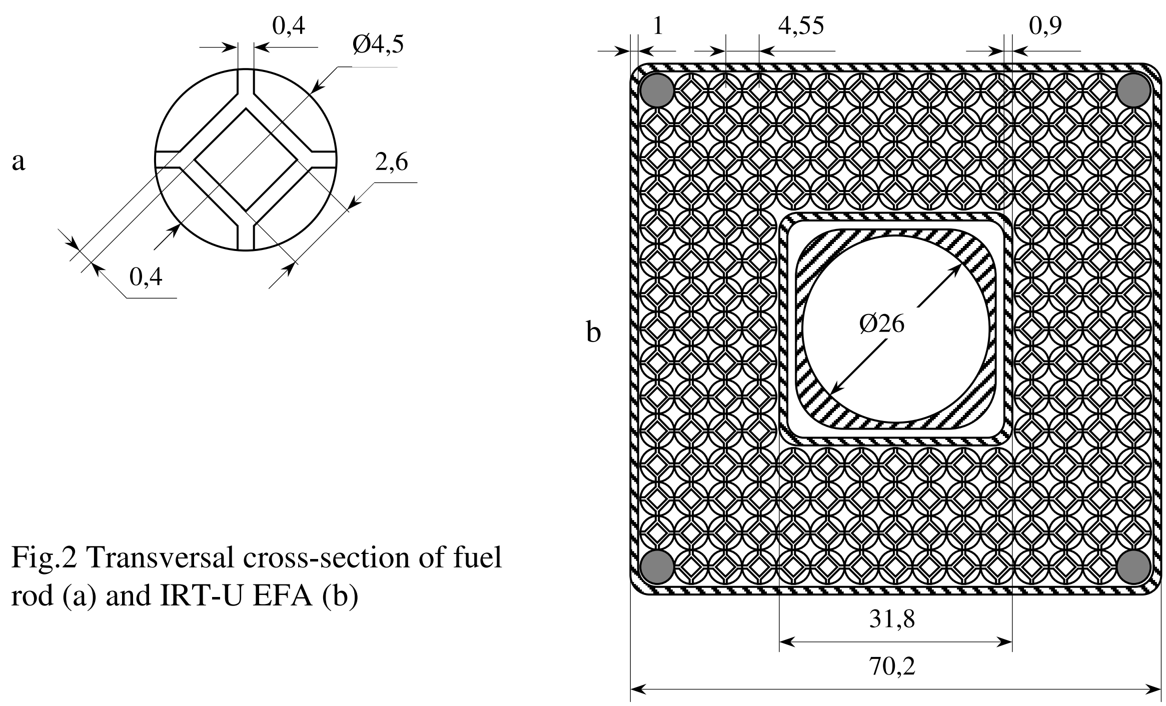


Fig.2 Transversal cross-section of fuel rod (a) and IRT-U EFA (b)

Table 2. Basic characteristics of IRT-U FA

Characteristic	Value
Fuel rod circumscribed diameter, mm	4.5
Fuel rod across-to-flat dimensions, mm	2.6
Fuel rod cladding thickness, mm	0.31÷0.46
Length of fuel rod active part, mm	620÷635
Fuel material	U-9.4 %Mo
Matrix material	PA-4
U density in the fuel meet, g/cm^3	6.0
Enrichment of ^{235}U, %	19.7
Mass of U in fuel rod and FA, g	10.7and 1842
Volume of U-Mo in FA, cm^3	119.4
Number of fuel rods in FA, pcs	172
Fuel rod cladding material	SAV-1,AMg2

The bearing element is the outer jacket 1mm thick that unites the head, fixture and spacer grids with fuel rods in FA by means of indents. Aluminum alloy SAV-1 is used as a material of jackets, head and fixture. The fuel rod claddings are made of aluminum alloys SAV-1 and AMg2.

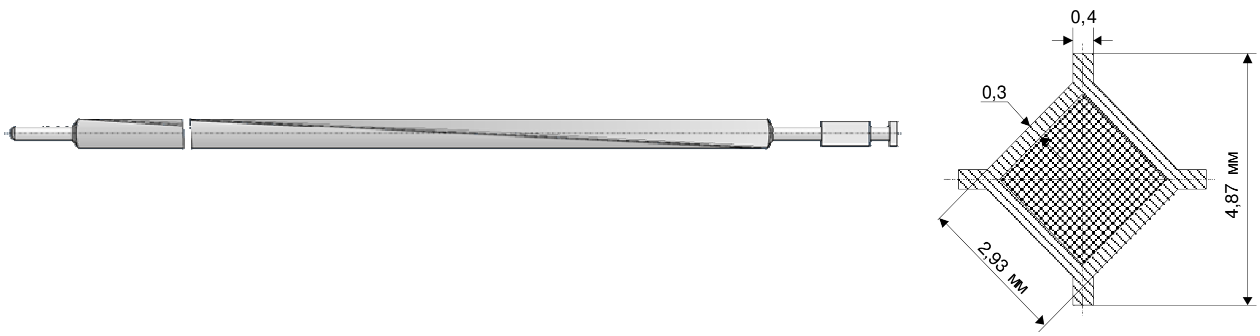
2.3 The mini fuel elements characteristics and design

Based on the results of the mini fuel elements testing [1] and the experience of the fuel development within the RERTR program, the foreign partners have developed mini fuel elements with modified U-Mo fuel compositions different in the degree of alloying, fuel particles coating, Si content in the matrix. Table 3 presents basic technical characteristics of the mini fuel elements.

Table 3. Basic characteristics of the mini fuel elements.

Characteristic	Value
Cladding material	SAV-6, alloy 99
Fuel	U-9.4 %Mo, 1-phase and 2-phase alloys
Coating of fuel particles	no coated, oxidized particles, ZrN
Matrix material	Al(PA-4); Al+2%Si; Al+5%Si; Al+13%Si
Fuel rod circumscribed diameter, mm	4.5
Fuel rod across-to-flat dimensions, mm	2.6
Enrichment of ^{235}U, %	19,7
Uranium density in the fuel meat, g/cm^3	6.0.
Mass of ^{235}U in MFE, g	0.57
Fuel meat length, mm	180-200

In order to test mini fuel elements there has been made two irradiation devices that is installed in the standard operating channels of the MIR reactor. Irradiation device has a dismountable design that enables to carry out intermediate inspections or to replace mini fuel elements in the irradia-



tion device in the hot cell. Up to 36 mini fuel elements (6) can be mounted into the device. If necessary, the mini fuel elements could be replaced by displacers.
Schematic drawings and cross-section of mini fuel element are illustrated in figure 3.

Fig.3. Drawings and cross section of mini fuel element

3. The conditions and reactor testing results

3.1 The procedure of burnup and fission density calculation of

The distribution of fuel fission and burnup rate in FA is calculated by the MCU code that allows a neutron transfer equation to be solved by the Monte-Carlo method on the basis of the estimated nuclear data for 3D geometry systems. In all calculations, neutron interaction cross-sections are used in the energy range 1eV – 10.5MEv in a 26-group format of the BNAB constant system. Resonance characteristics of cross-sections are used in the form of sub-group parameters. In the thermal neutron area range 0 – 1eV, cross-sections are presented in a 40-group decomposition with an equal rate pitch. Differential spread cross-sections are calculated accounting chemical relations, crystalline structure and material temperature.

To calculate the change of the isotopic composition of the reactor materials during the reactor run, the BURNUP code is used [4]. Numerical models of the reactor core are made accounting the dimensions, forms and materials of fuel rods, FA structural components, control rods and components having significant effect on the physical properties.

The calculations also account the average neutron energy W_n released in the reactor due to neutron loss reactions per a fission. It can be calculated by a formula:

$$W_n = (\overline{\nu}_f / k_{ef} - 1)\overline{W},$$

where:

$\overline{\nu}_f$ – average neutron number per a fission;

k_{ef} – effective neutron breeding factor in the conditionally critical task;

$\overline{W}$ – weighted average energy released in neutron-nuclide reactions, MEv;

$$\overline{W} = \sum_r \delta_r W_r / \sum_r (1 - n_r)\delta_r \ ;$$

δ_r – portion of neutrons participating in an *r*-reaction, except for the fission reaction;

W_r – energy released in an *r*-reaction and as a result of decay of its products (negative for an endothermic reaction);

n_r – number of secondary neutrons resulted from an *r*-reaction.

The specific loss of heavy nuclides - ^{235}U and nuclides fissioned by thermal neutrons - is considered as a characteristic of the change of the fuel nuclide composition. The specific loss of heavy nuclides is characterized by the loss and accumulation of ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu nuclei FP. Thus, the loss of fissile nuclides is equal to the difference of fissile materials mass sums at its starting and final points. Fissile materials decrease due to the fission reactions and radiation capture and replenish due to the conversion of ^{234}U into ^{235}U and accumulation of ^{239}Pu and ^{241}Pu from ^{238}U. The calculation data are approximated by the least-squares method by the flowing formulas:

$$\frac{M_{U5}(0)-M_{U5}(Q)}{Q}=A_{U5}-B_{U5}Q;$$

$$\frac{M_F(0)-M_F(Q)}{Q}=A_F-B_FQ,$$

where:

Q – power generation of FAs;

$M_{U5}(Q)$, $M_F(Q)$ – mass of ^{235}U and fissile nuclides in FA;

A_{U5}, B_{U5}, A_F, B_F – constants characterizing absorption and fission of nuclides.

Power generation of FAs and elements in the experimental device is determined mainly by the ^{235}U and ^{239}Pu nuclear fission. Burnup of ^{235}U is determined as relative decrease of ^{235}U in % due to fission and radiation capture. This value is used as the characteristics of the fuel burnup in FA:

$B(\tau) = (MU5(0) - MU5(\tau))/ MU5(0)$

where:
B – fuel burnup in FA;
MU5(0), MU5(τ) – ^{235}U mass in FA in the initial condition and at time moment τ, relatively.

To determine fuel fission rate and density, both a number of ^{235}U and ^{239}Pu fissions in fuel particles or fuel meet are taken into account.

3.2 The main testing parameters and results

Table 4 presents main testing parameters of the IRT-U and IRT-3M FAs, the reactor testing of which were completed at an average ^{235}U burnup ~ 40%. According to the VVR-SM reactor design, an average ^{235}U burnup value amounts to 40%, therefore, after achievement of this value one FA of each type (tube- and rod-design) were discharged from the reactor for cooling and further investigations.

After the 3-month cooling in the storage basin of the MIR reactor, inspection of the FA external surfaces was performed using an underwater TV system. The inspection results showed satisfactory condition of the FA external surfaces. For the IRT-U FA, only end pieces and external casing are available for inspection, thus, these results are of no special interest. As for the IRT-3M FA, view of the external fuel tube with maximum values of fission rate and burnup was observed. No valuable defects of corrosion and mechanical nature were found at the element surface. There are some areas where corrosion film is different in color, 3-4 spots of Ø ~ 5 mm (pittings) were also found.

The FAs volumes were measured using hydrostatic method in the reactor storage basin and compared with analogous measurements before the testing. For the tubular IRT-3M FA, average increase of the fuel composition volume (swelling) made up 19.5 %, while for the rod-type IRT-U FA it was equal to 23.7 %, that agrees with the data of the RERTR-(4-7) and French group tests at the fission density within the range of $(2\text{-}3)\cdot 10^{21}$ cm^{-3}. A change in the average thickness of the tubular fuel elements in the IRT-3M FAs makes up ~ 30 µm respectively.
Average increasing of volume fuel elements on active par 2.6 % for the tubular IRT-3M FA and 3.5% for IRT-U.

Table 4. Main parameters of the IRT-U and IRT-3M FAs testing with a burnup of 40%.

Parameter	IRT-U № 19УИ0012006	IRT-3M № 100МИС38606
Heat power of EFA, kW - average - maximum	 503 722	 452 800
Inlet coolant pressure, MPa	1.08	1.08
Inlet coolant temperature, ° C	40-60	40-60
Coolant velocity, m/s	5.9	6.6
Heat flux, kW/m^2 - average - maximum	 688 988	 562 995
Temperature of cladding outer surface,° C - average - maximum	 81-101 95-115	 67-87 86-106
Temperature of fuel meat,° C - average - maximum	 88-108 105-125	 73-93 89-109
Maximum neutron flux E_n >0.1 MeV, 10^{14} $cm^{-2}s^{-1}$	2.1	1.6
Burn-up ^{235}U of EFA, % - average - maximum	 40.1 55.4	 40.3 48.7
Fission rate in fuel particles, 10^{14} $cm^{-3}s^{-1}$ - average, - maximum	 1.33 2.64	 1.24 2.65
Fission density in fuel particles, 10^{21} cm^{-3} - average - maximum	 2.68 3.72	 2.75 3.32
Duration of testing, days		

Parameter	IRT-U № 19УИ0012006	IRT-3M № 100МИС38606
- calendar, - on power	364 234	397 257
Average increasing of U-Mo volume (swelling), %	23.7	19.9
Average increasing of volume fuel elements on active part, %	3.5	2.6

Table 5 presents main parameters of the IRT-U FA №19УИ0022006 and IRT-3M FA №199МИС38706 testing as of September 15, 2008, reactor testing of which are being continued up to the achievement of an average ^{235}U burnup value of ~ 60%.

Table 5. Main parameters of the IRT-U and IRT-3M FAs testing.

Parameter	IRT-U № 19УИ0022006	IRT-3M № 199МИС38706
Heat power of EFA, kW - average - maximum	 293 661	 369 800
Inlet coolant pressure, MPa	1.08	1.08
Inlet coolant temperature, ° C	40-60	40-60
Coolant velocity, m/s	5.9	6.4
Heat flux, kW/m^2 - average - maximum	 401 904	 454 995
Temperature of cladding outer surface,° C - average - maximum	 68-88 91-111	 67-87 86-106
Temperature of fuel meat at BOL,° C - average - maximum	 72-112 101-121	 69-89 89-109
Maximum neutron flux E_n >0.1 MeV, 10^{14} $cm^{-2}s^{-1}$	1.3	1.6
Burnup of ^{235}U, % - average - maximum	 29.9 42.0	 42.2 48.1
Fission rate in fuel particles, 10^{14} $cm^{-3}s^{-1}$ - average, - maximum	 0.80 2.44	 1.06 2.63
Fission density in fuel particles, 10^{21} cm^{-3} - average - maximum	 2.03 2.85	 2.88 3.44
Duration of testing, days - calendar, - on power	 505 294	 534 314

Table 6 presents main parameters of testing of mini fuel elements with modified U-Mo dispersion fuel compositions. In the first column (Irradiation device#2) there are parameters of testing of mini fuel elements that achieved an average ^{235}U burnup ~ 50% and reloaded , in the 2nd one (Irradiation device#1) – parameters of testing as of September 15, 2008. Testing of mini fuel elements in irradiation device#1 shall be continued to achieve an average fuel burnup of ~ 60%.

The PIEs of mini fuel elements with modified U-Mo dispersion fuel compositions (Irradiation device#2) are planned to be started at the beginning of 2009.

Table 6. Main parameters of testing of mini fuel elements with modified U-Mo dispersion fuel compositions.

Parameter	I D#2	I D#1
Heat Power of EFA, kW - average - maximum	 45 86	 37 69
Inlet coolant pressure, MPa	1.08	1.08
Inlet coolant temperature, º C	40-60	40-60
Coolant velocity, m/s	2.7	2.7
Heat flux, kW/m^2 - average - maximum	 850 1624	 678 1265
Temperature of cladding outer surface ,º C - average - maximum	 88-107 122-143	 77-97 110-131
Temperature of fuel meat at BOL,º C - average - maximum	 96-116 136-156	 82-103 120-142
Maximum neutron flux E_n >0.1 MeV, cm^{-2}	2.1	1.6
Burn-up ^{235}U of EFA, % - average - maximum	 48.6 52.1	 53.0 56.4
Fission rate in fuel particles, 10^{14} cm^{-3}s^{-1} - average, - maximum	 3.0 6.2	 2.4 5.0
Fission density in fuel particles, 10^{21} cm^{-3} - average - maximum	 3.4 3.6	 3.6 3.9
Duration of testing, days -calendar, - on power	 182 130	 290 172

4. Conclusions

1. The testing of two full-size IRT FAs of tubular and rod-type design with low-enriched U-Mo fuel which achieved an average burnup of ~ 40% were completed in the MIR reactor. The PIEs are planned to be started at the end of 2008.
The testing of the other two analogous FAs is underway for the purpose of achieving a burnup of 60 %.

2. The rod-type mini fuel elements from the 1st batch based on modified dispersed U-Mo fuel compositions different in the degree of alloying, fuel particles coating, Si content in the matrix, were irradiated up the burnup of 50 % and discharged from the reactor for cooling. The PIEs are planned to be started at the beginning of 2009.
The testing of the analogous batch of mini fuel elements is underway for the purpose of achieving a burnup of 70 %.

3. At present, preparation for the testing of the irradiation device with rod mini elements of different types based on the monolitic U-Mo fuel is underway. The testing is planned to be started at the end of this year.

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