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CURRENT STATUS OF DEVELOPMENT OF HIGH DENSITY LEU FUEL FOR RUSSIAN RESEARCH REACTORS

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ABSTRACT

One of the directions of the Russian RERTR program is development and licensing of high density LEU fuel and fuel elements/FA on its base for conversion of Russian-built research reactors according to the international program of nuclear material non-proliferation. The development is carried out for both existing reactors and for new advanced designs of research reactors.

Two types of fuel are under development: dispersion and monolithic U-Mo fuel, as well two types of FA to use the dispersion U-Mo fuel: with tubular type fuel elements and with pin type fuel elements.

Many Russian organizations participate in this work: TVEL corporation, VNIINM, RDIPE, RIAR, IRM, NPCC.

The first stage of works was completed successfully. This stage included out-pile, in-pile and post irradiation examinations of U-Mo dispersion fuel in experimental tubular and pin fuel elements under parameters similar to operation conditions of Russian design pool-type research reactors.

The results obtained both in Russia and abroad have enabled to proceed to the next development stage which includes life-time tests of full-scale IRT pin-type and tube-type fuel assemblies with dispersion U-Mo fuel and development of ways to stabilize behavior of U-Mo fuel under high loads and burn-ups.

The paper gives the summary review of the results of U-Mo fuel development performed by now.

1. Introduction

Major direction of the Russian RERTR program is to develop and license high density LEU fuel and fuel elements/FA on its base intended to convert Russian-built research reactors. Both in Russia and abroad two fuel types on U-Mo alloy basis are developed: dispersion and the monolithic. Two FA designs with tubular and pin fuel elements are developed to use this fuel.

Many Russian organizations participate in this work: TVEL corporation, VNIINM, RDIPE, RIAR, IRM, NPCC as well as Argonne National Laboratory (USA) under the international RERTR program.

The first development stage was finished successfully. This stage included out-pile, in-pile and post irradiation examinations of U-Mo dispersion fuel in experimental tubular and pin fuel elements. The irradiation tests have been carried out in three Russian reactors (IVV-2M-Zarechny, MIR-Dimitrovgrad, VVR-M-Gatchina) under parameters similar to the operation conditions of Russian design pool-type research reactors. The results of the investigations have been presented in detail in papers and presentations at various conferences and meetings [1-10].

The results obtained in Russia as well as the analysis and summarizing of the data obtained abroad made it feasible to start the next stage of the development that includes two main directions:

1. License dispersion U-Mo fuel and production of IRT-type FA with this fuel.
2. Develop methods that ensure irradiation stability of U-Mo fuel at high loads and burn-ups.

2. Latest results

By now the following results were received in these two directions.

Lifetime tests of four full-size IRT-type fuel assemblies of tube-type and pin-type design with LEU dispersion U-Mo fuel were finished in the MIR reactor. The objective of the tests is to validate the serviceability of theses types fuel assemblies. The post-irradiation examinations of two fuel assemblies with pin type and tube type fuel elements that reached the average burnup of ~ 40% are in progress. The results of the lifetime tests and post-irradiation examinations will be used for fuel licensing as applied to research reactors using this type FA.

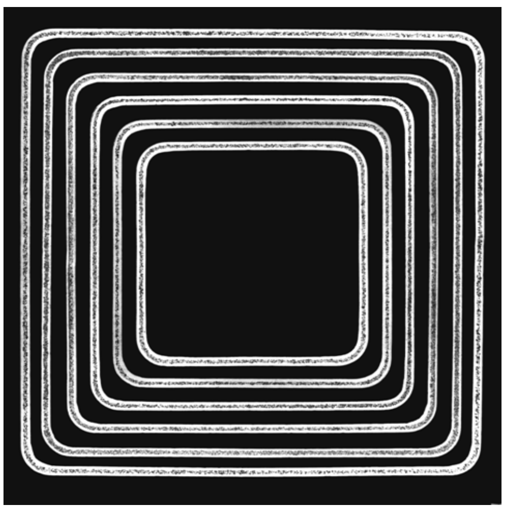
To prepare the lifetime tests a large set of the calculated, designed and technologic investigations has been performed in which TVEL, NPCC, RDIPE, VNIINM and RIAR participated. As a result two six-tube FAs and two pin FAs with U-Mo dispersion fuel have been fabricated at NPCC as well as four experimental channels to install FAs into the MIR reactor core have been fabricated at RIAR.

To fabricate fuel elements U-Mo powder was used that was produced at PEI and VNIINM by centrifugal atomization. The powder consisted of spherical particles of 60 to 160 microns. The U-Mo granules with oxide coating about 1 micron thickness were used in one (fourth from outside) fuel element of a six-tube FA.

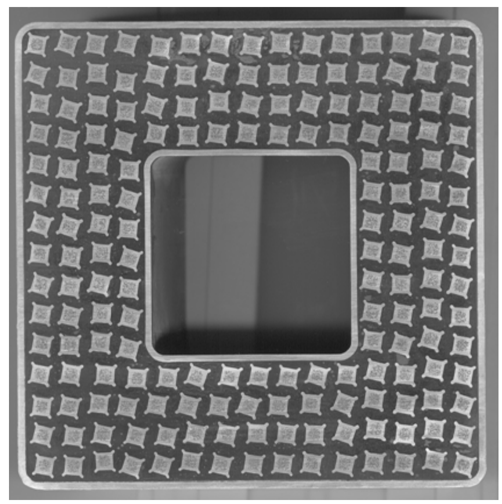
The basic characteristics of IRT FAs are given in Table 1. The FA designs are shown in Figure 1 [7].

Table 1. Main Characteristics of Experimental IRT-type fuel assemblies [4]

Parameter	Tube FA	Pin FA
Number of Fuel Elements (FE)	6	172
Cladding thickness, mm	0,45	0,4
Meat Length, mm	600	620
U^{235} mass per FA, g	351,6 ± 17,6	378,4 ± 17,2
U density, g/cm^3	5,4	6,0
Meat Material	U-9%Mo+Al	
Cladding material of FE	SAV-1	SAV-1, AMg2



a) Cross-section of six-tube FA



b) Cross-section of pin type FA

Figure 1. Cross-section of experimental IRT-type FA

The summarized parameters of FA tests are presented in Table 2.

Table 2. Parameters of FA tests [10]

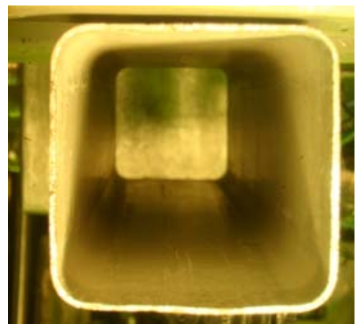
Parameter	Tube IRT type FA cell 3-16	Tube IRT type FA cell 2-10	Pin IRT type FA cell 2-8	Pin IRT type FA cell 3-13
Maximal power of FA, kW	700-810	750-820	650-720	480-660
Average rate of coolant, m/s	6,0-6,9	6,2-6,6	4,2-4,8	4,5-4,8
Maximal density of heat flux, kW/m^2	900-997	924-986	900-988	620-903
Maximal temperature of outer surface of fuel element cladding, ^{o}C	104	106	110	94
Maximal rate of fission, 10^{13} cm^{-3}s^{-1}	12,3-14,3	13,2-14,4	11,7-13,0	8,6-11,9
Average burn-up of U-235 (in FA/in max heated FE), %	52,1/58,7	40,3/48,7	40,1/46,4	41,2,6/47,9

The post-irradiation examinations of two IRT fuel assemblies with pin and tubular fuel elements that reached the average burnup of ~ 40% began in April 2009. Presently the non-destructive examinations have been completed and covered disassembling into the fuel elements, their visual-optical inspections and photographing, γ-scanning. The fuel elements were selected and samples were prepared for metallographic, planimetric and fractographic studies.

The first results of PIE are shown in fig. 2 - 6. Figure 2 illustrates the typical appearance of the irradiated tubular fuel element. Figure 3 presents the macrostructure of the cross-sections of the tubular fuel elements. Figure 4 shows the typical microstructures of the tubular fuel element meat.

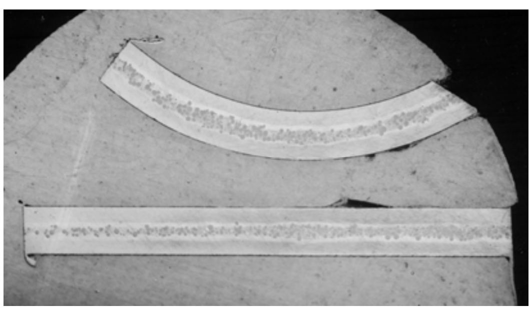
Figure 5 shows the appearance of the irradiated IRT pin type assembly. Figure 6 illustrates typical macro and microstructures of pin type meat. The post-irradiation examinations of the fuel elements are in progress.

a

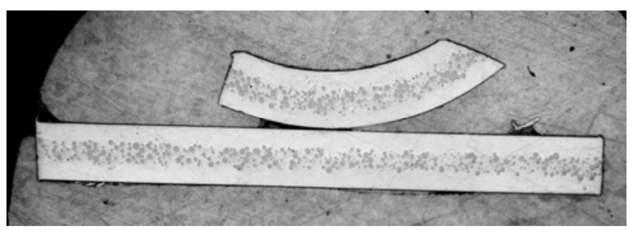


b

Figure 2. Irradiated tubular fuel element (on face side (a), on end part view (b)).

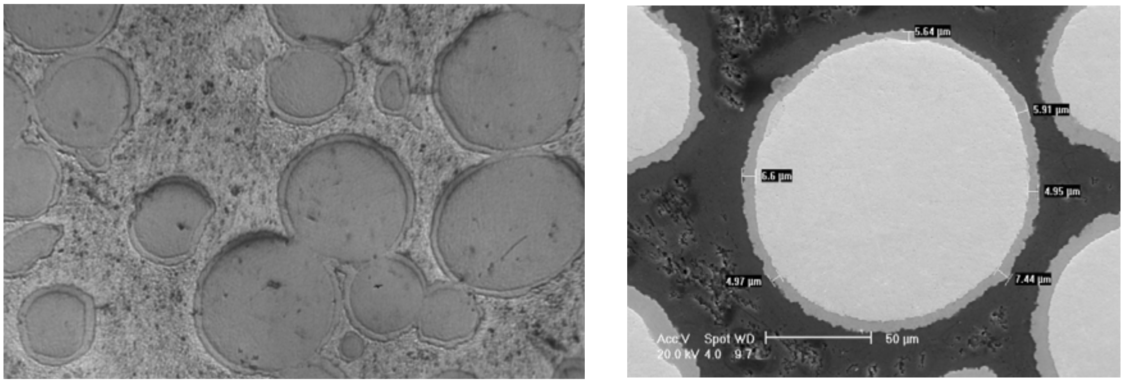


a



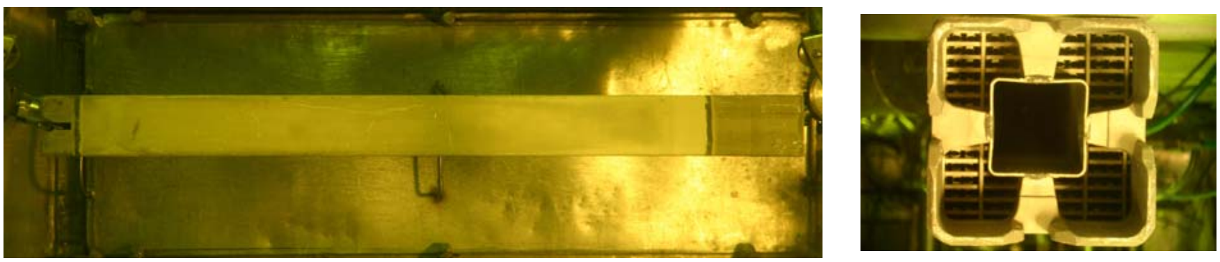
b

Figure 3. Macrostructure of cross-sections of first (a) and fourth (b) tubular fuel elements after irradiation.

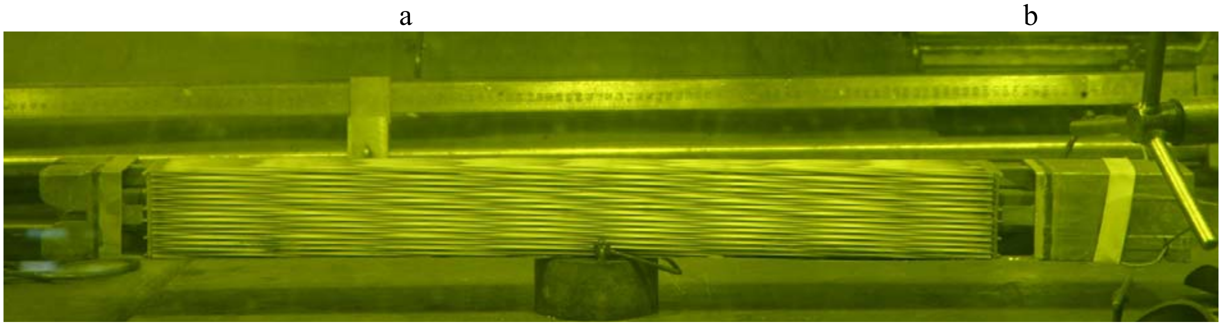


a b

Figure 4. Typical microstructure of meat of tubular fuel element.



a b



c

Figure 5. Appearance of irradiated IRT pin FA
(on face side (a), on end part side (b), after removal of shroud (c)).

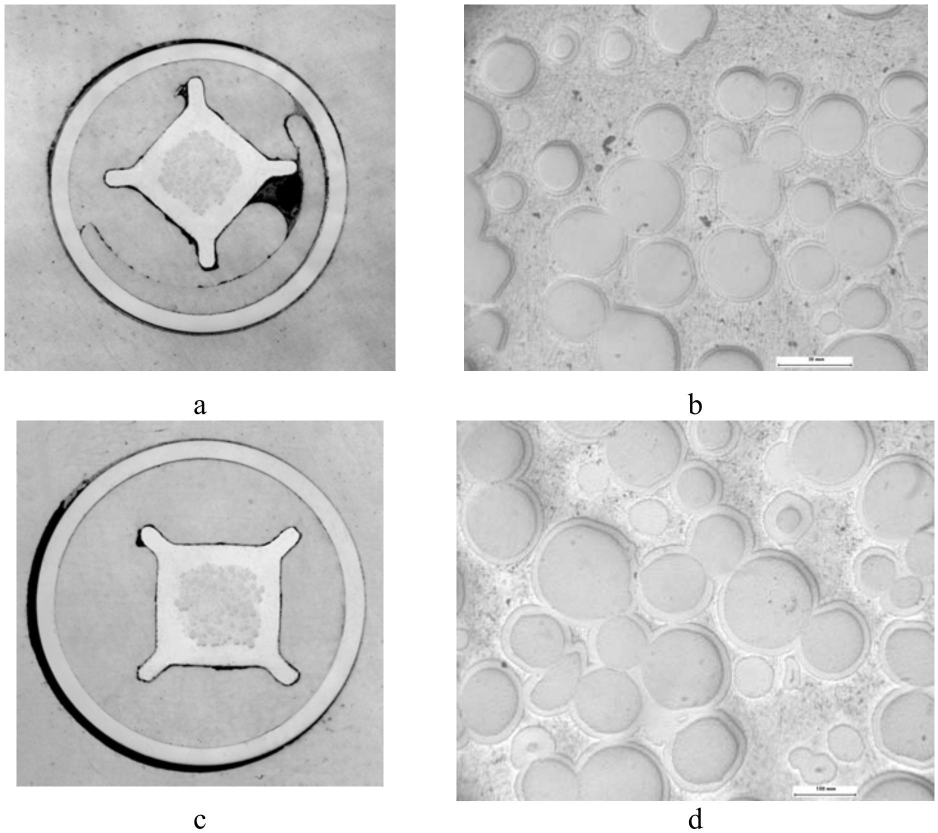


Figure 6. Macro (a) and microstructures (b) of pin type fuel element with minimal burnup; macro (c) and microstructures (d) of pin type fuel element with maximum burnup.

The available results show that:

- bundle of pin fuel elements remained integrity; neither distortion nor displacement of fuel elements are observed;
- state of the fuel element surfaces in tubular and pin fuel elements are quite good (the surfaces of the fuel elements have light silver color and oxide coat up to 15 µm thickness);
- interaction layer between fuel particles and an Al matrix makes up 6-10 µm;
- the meats haven't gas pores, however, porosity in the matrix in the meat of the tubular fuel elements is noticeable.

The second direction of our activity is development of ways that ensure the irradiation stability of U-Mo fuel at high load and burn-up. The investigations are performing in two directions: to modify dispersion U-Mo fuel and to use monolithic U-Mo fuel.

The irradiation stability of dispersion U-Mo fuel for Russian pool-type reactors has been confirmed by in-pile experiments. However, a higher irradiation resistance is needed for reactors having high heat flux and high burnup. To resolve this important problem the VNIINM experts use the results of the investigations that were obtained in the frame of the RERTR program as well as the experience of their own investigations [7].

First of all, it is the fuel composition modification via:

- alloying of matrix with different additions of silicon (2-13) %;
- using of different coatings for U-Mo fuel particles, e.g., zirconium nitride (ZrN).

In 2008 48 mini fuel elements with modified U-Mo dispersion fuel with the uranium density equal to 6.0 g/cm^{3}were fabricated at VNIINM to be tested in the MIR reactor. U-Mo alloy powder is fabricated at VNIINM by the method of centrifugal atomization. U-Mo granules were coated with zirconium nitride (ZrN) using the plasma-arc method developed by VNIINM. Thickness of coating is 1-3 microns. U-Mo granule surfaces were oxidized under the process developed by PEI. The oxide layer thickness on the granule surface is about 1-2 microns. The types of mini fuel elements with modified U-Mo dispersion fuel are given in Table 3. The main parameters of mini-fuel elements are given in Table 4.

Table 3. Types of modified U-Mo dispersion fuel

Quantity of samples	Characteristics of fuel element meat		Material of cladding
	State of U-9%Mo alloy powder	Matrix	
3	Single-phase	PA-4	SAV-6
3	Single-phase	PA-4	Alloy 99
4	Single-phase	Alloy Al+2%Si	SAV-6
3	Single-phase	Alloy Al+2%Si	Alloy 99
3	Single-phase	Alloy Al+5%Si	SAV-6
4	Single-phase	Alloy Al+5%Si	Alloy 99
3	Single-phase	Alloy Al+13%Si	SAV-6
4	Single-phase	Alloy Al+13%Si	Alloy 99
2	Two-phase	PA-4	SAV-6
5	Two-phase	PA-4	Alloy 99
3	Fuel granules with ZrN coating	PA-4	SAV-6
4	Fuel granules with ZrN coating	PA-4	Alloy 99
3	Fuel granules with oxide layer	PA-4	SAV-6
4	Fuel granules with oxide layer	PA-4	Alloy 99

Table 4. Main parameters of mini-fuel elements [8]

Parameter	Value
Length of mini-fuel element, mm	250
Length of meat, mm	200_{-20}
U_{235} Load, g	0,57±0,1
U density, g/cm^3	6,0
Enrichment by U_{235}, %	19,7±0,3
Powder fractional composition, micron	60-160

The irradiation test of two assemblies (each consisted of 24 mini fuel elements) [9, 10] were carried out to reach maximal burnup of 50 and 80 %. Table 5 shows the summarized parameters of tests of two assemblies.

Table 5. Test parameters of assemblies under the maximal power [9]

Parameter	Assembly No.1	Assembly No.2
Maximal power, kW	67	86
Maximal temperature of input/output in the channel, ^{o}C	52,0/56,6	58,1/63,4
Average rate of coolant, m/s	2,7	2,7
Maximal rate of fission, 10^{13} $cm^{-3}s^{-1}$	11,7	12,4
Maximal density of heat flux, kW/m^2	1265	1624
Maximal temperature of cladding outer surface, ^{o}C	122	133
Maximal burnup, %	80	50

Currently the irradiation test of the mini fuel elements has been finished. The PIE of the mini fuel elements that reached the maximal burnup of ~ 50 % are performing.

By now, non-destructive examinations that include visual-optical inspections and photographing mini fuel elements, gamma-scanning of fuel elements have been completed; 14 mini fuel elements were selected and specimens were prepared for further metallographic and planimetric examinations.

The first results of PIE are given in fig. 7- 8. Figure 7 illustrates the typical appearance of an irradiated mini fuel element; fig. 8 shows the macro-and micro-structures of the cross-sections of two investigated mini fuel elements having 13%Si-Al alloy and ZrN-Al alloy fuel compositions.

Figure 7. Typical appearance of irradiated mini fuel element

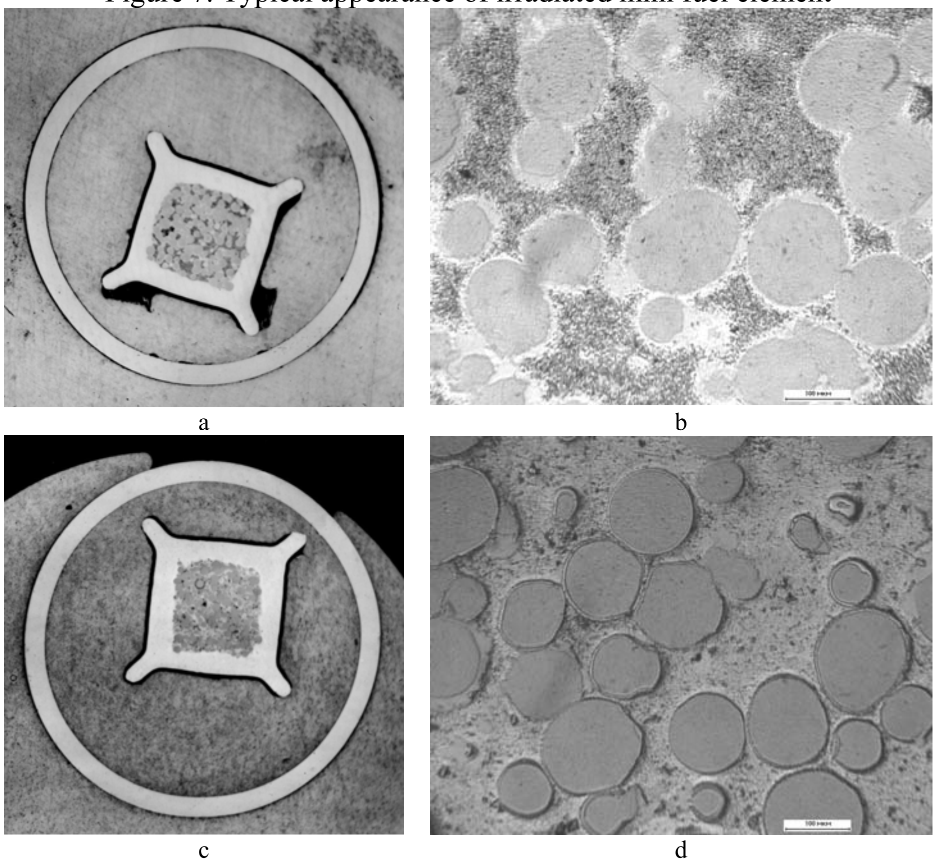
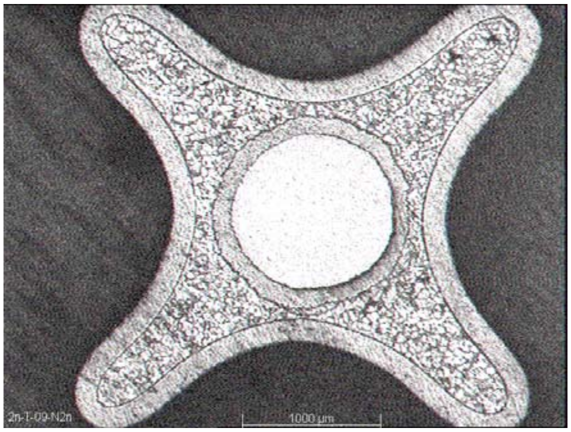


Figure 8. Macrostructure (a) and microstructure (b) of cross-section of mini fuel element having 13%Si+PA4 fuel composition; macrostructure (c) and microstructure (d) of cross-section of fuel element having ZrN+PA4 fuel composition. PA4 – standard Al alloy used to fabricate research reactor fuel. Cladding material is 99 Al alloy.

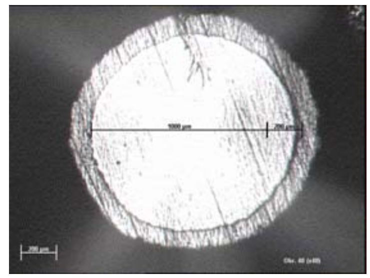
PIE of mini fuel elements is in progress. The results of PIE at the present moment show that:

- surface of all mini fuel elements have oxide layers ~50 μm thickness;
- the highest interaction between fuel particles and Al matrix is observed in the fuel composition, containing 2% Si, as the Si content in the matrix is increased the interaction layer is decreased;
- there is actually no interaction between fuel particles and Al matrix in fuel composition containing fuel particles with ZrN coating;
- oxide coating of fuel particles does not essentially affect the interaction;
- the meets of all the fuel elements investigated haven't gas pores.

The second direction of investigations is the use of monolithic U-Mo fuel. In 2008 at VNIINM mini fuel elements with monolithic U-Mo fuel and Zr cladding were designed and fabricated. The design of mini fuel element with monolithic U-Mo fuel is given in fig.9. The meat-cladding space is filled with Al allow by pressure casting in vacuum. 24 mini fuel elements are being tested in the MIR reactor since February 2009. The irradiation test is carried on until the maximum burnup of 80% is reached.



a) Cross section of mini fuel element



b) Monolithic U-Mo meat with Zr coating

Figure 9. Cross section of mini fuel element with monolithic U-Mo meat

3. Conclusion

To license the Russian U-Mo fuel 4 full-size IRT type FA (2 FA with tubular fuel elements and 2 FA with pin type fuel elements) having U-Mo fuel were fabricated at NPCC. The lifetime tests of the assemblies were carried out in MIR reactor. The PIE of them is in progress.

To reduce the interaction between U-Mo fuel particles and Al matrix mini fuel elements having modified U-Mo dispersion fuel have been fabricated and the irradiation test of mini fuel elements have been carried out. PIE of these fuels is in progress.

The novel design of a pin type fuel element with monolithic U-Mo fuel was developed. Mini fuel elements were fabricated and their irradiation test in MIR reactor is in progress.

Based on the results obtained by now on high density fuel development the following basic work is planned:

– Complete post-irradiation examinations of IRT-type FA of two designs with tube-type and pin-type fuel elements with dispersion U-Mo fuel. The work is scheduled to finish at the middle of 2010.

– Complete post-irradiation examinations of mini fuel elements with modified dispersion U-Mo fuel.

– Complete irradiation tests of mini fuel elements with monolithic U-Mo fuel and their post-irradiation examinations. The work is scheduled to finish at the end of 2010.

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