THE IRRADIATION TEST AND PRELIMINARY PIE RESULTS OF LOW ENRICHMENT U-MO PIN-TYPE FUEL

A.L. Izhutov, V.V. Alexandrov, N.G. Gataullin, A.Ye. Novoselov,
V.A. Starkov, G.V. Shevlyakov, A.A. Sheldyakov and V.Yu. Shishin
State Scientific Centre of Russian Federation
Research Institute of Atomic Reactors
433510, Dimitrovgrad, Ulyanovsk region, Russia.

and

I.V. Dobrikova, A.V. Vatulin, G.V. Kulakov and A.V. Morozov
State Scientific Centre of Russian Federation
A.A.Bochvar All-Russian Scientific Research Institute of Inorganic Materials
123060, Moscow, P. B. 369, Russia

ABSTRACT

In February 2005 in the MIR reactor the irradiation tests of LEU U-Mo pin-type mini fuel elements fabricated at the Bochvar Institute were completed within the framework of collaboration with ANL under RERTR program.
The fuel element cross-section represents a 2.98×2.98 mm square, cladding material is aluminum alloy SAV-1, height of the fuel element active part is ≤ 200 mm, uranium volume density in the fuel composition is ~ 4 and ~ 6 g/cm^3. Totally, 71 undersized pin-type fuel elements were tested including 13 different modifications that differed in the fuel composition characteristics. To obtain data on the fuel behavior at different burnups, several mini fuel element groups were irradiated up to different burnup values ranging from ~ 20% to ~ 70% of ^{235}U burnup.
This paper presents the main irradiation tests and PIE results that have been obtained by now.

1. Introduction

Soviet-production research and test reactors are known to use tube-type fuel elements of different geometry. As a rule, such a fuel assembly consists of several tubes of different dimension and, sometimes, shape, which are inserted co-axially one into another. One of the trends of the Russian RERTR program is to develop a unified pin-type fuel element with LEU U-Mo fuel to be used in future instead of tube-type fuel elements in the fuel assemblies of different design for pool-type research reactors.

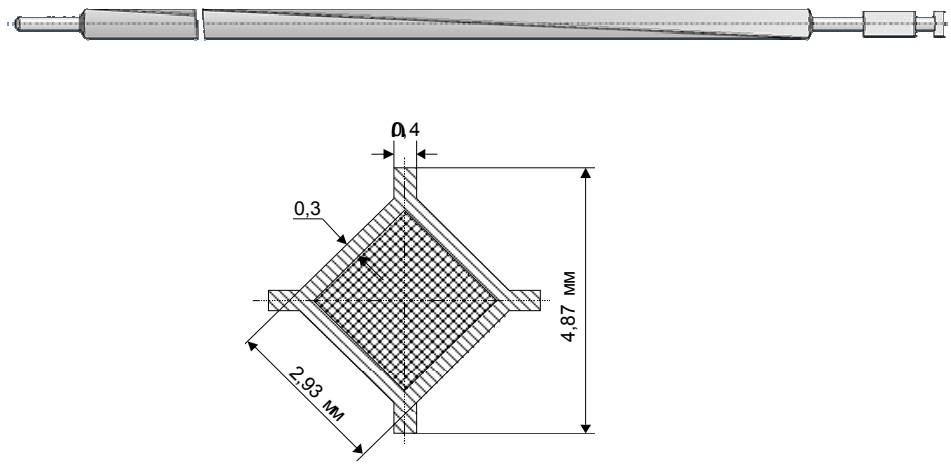
From August 2003 till February 2005 in the MIR reactor testing of pin-type mini fuel elements (MFE) with high-density LEU U-Mo fuel has been performed using dismountable irradiation devices up to the maximum burnup of ^{235}U in fuel achieving ~ 70%. 13 MFE were tested up to average burnup values of ^{235}U ranging (19.5 -22.9) %, 12 MFE – up to (49.0-52.8) %, 17 MFE – up to (57.9 –62.7)% and 29 mini fuel elements – up to (63.0 – 67.7)%. In the course of irradiation the cladding of one of the mini fuel elements of the OM-9.5 type has failed at average burnup of ~ 63%.

By now PIE of mini fuel elements with ~ 20% burnup have been completed and high-burnup mini fuel elements are being examined. The main attention is paid to the estimation of the general state of the mini fuel elements, change in the MFE dimensions and fuel meat swelling, analysis of the cladding and fuel material structure and their compatibility under irradiation.

2. Main technical characteristics of MFE

MFE have a square cross-section and ribs in the corners to provide spacing inside a fuel assembly. The cladding material is aluminum alloy SAV-1; fuel composition is U-Mo alloy particles dispersed in aluminum matrix. The uranium enrichment is ~19.7%; MFE length is ~ 250 mm and the fuel meat length is ~ (160- 200) mm. The mini fuel element and its cross-section are showed schematically in Fig. 1.

Fig. 1. Schematic representation of the mini fuel element and its cross-section.



All 71 fuel rods tested can be split into 13 groups differing in chemical composition, phase state, particles fabrication method and uranium density in the fuel composition. Table 1 and 2 present the main characteristics of the fuel alloys and data on the fuel loading in different MFE groups.

Table 1. Main characteristics of fuel alloys

Production method of alloy powders	Alloy designation	Alloy chemical composition, mass%								Alloy density ρ, g/cm^3
		U	Mo	Nb	Zr	Sn	Al	C	O_2	
Atomization	OM-9	90.2	9.2	–	–	–	–	0.04	–	17.23
	OM-6.5	91.63	8.0	–	–	–	–	0.04	–	17.43
	OM-6.5L1	92.38	7.4	–	–	–	0.2	0.04	–	17.36
	OM-6.5L2	91.94	7.0	–	–	–	0.4	0.04	–	17.02
	OM-6.5L3	92.11	7.1	–	–	0.2	0.2	0.04	–	17.21
	OM1.5	96.54	2.8	–	–	0.2	0.2	0.04	–	17.87
	ZrNb-10	91.12	–	4.3	6.0	–	–	0.041	–	16.50
Hydration - dehydration	OM-6.5L1	91.95	7.1	–	–		0.215	0.048	0.13	17.0
	OM-6.5L3	91.76	7.35	–	–	0.2	0.22	0.053	0.13	16.9

The particle size of the U-Mo alloy powders produced by the atomization method makes up ~ (100…140) μm and of those produced by the hydration-dehydration method – ~ (200...263) μm.

Table 2. The MFE groups fuel features

No.	Alloy characteristics		Uranium density in the fuel meat, g/cm^3	Designation of the MFE group
	Alloy designation	Alloy phase state		
1	OM-9$^{(A)}$	γ	4 ± 0,2	014N*
2	OM-9$^{(A)}$	γ	6 ± 0,3	016N*
3	OM-9$^{(A)}$	$\alpha + \gamma$	4 ± 0,2	024N*
4	OM-6.5$^{(A)}$	γ	4 ± 0,2	114N*
5	OM-6.5$^{(A)}$	γ	6 ± 0.3	116N*
6	OM-6.5$^{(A)}$	$\alpha + \gamma$	4 ± 0.2	124N*
7	OM-6.5L1$^{(A)}$	γ	4 ± 0.2	214N*
8	OM-6.5L1$^{(H)}$	γ	4 ± 0.2	234N*
9	OM-6.5L2$^{(A)}$	γ	4 ± 0.2	314N*
10	OM-6.5L3$^{(A)}$	γ	4 ± 0.2	414N*
11	OM-6.5L3$^{(H)}$	γ	4 ± 0.2	434N*
12	OML-1.5$^{(A)}$	α'	4 ± 0.2	514N*
13	ZrNi-10$^{(A)}$	γ	4 ± 0.2	614N*

Note: $^{(A)}$ – atomization method, $^{(H)}$ – hydration-dehydration method, N* – MFE No. in a specific group of mini fuel elements.

3. Irradiation testing conditions and results

Table 3 presents the main testing parameters of the mini fuel elements in the MIR reactor.

Table 3. Main testing parameters

Parameter	Value
Heat power of MFE, kW	1.3–1.9
Coolant pressure, MPa	1.1–1.3
Coolant temperature, ºC	40–60
Coolant velocity, m/s	2.3–3.0
Maximum heat flux, MW/m^2 - MFE with ~ 4 gU/cm^3 - MFE with ~ 6 gU/cm^3	 0.6 0.9
Maximum temperature of the cladding outer surface,º C - MFE with ~ 4 gU/cm^3 - MFE with ~ 6 gU/cm^3	 75–95 90–110
Maximum fuel temperature at the beginning of tests,º C - MFE with ~ 4 gU/cm^3 - MFE with ~ 6 gU/cm^3	 85–105 105–125
Maximum neutron flux E_n >0.1 MeV, cm^{-2}s^{-1}	$6 \cdot 10^{13}$
Maximum fission density in the fuel particles, 10^{14} cm^{-3}s^{-1} - MFE with ~ 4 gU/cm^3 - MFE with ~ 6 gU/cm^3	 2.8 3.1

The mini fuel elements were tested in two dismountable irradiation devices. To obtain data on the fuel state at different burnups, 13 MFE were tested up to average burnup values of ^{235}U (19,5 – 22,9)%, 12 MFE – up to (49,0 – 52,8)%, 17 MFE – up to (57,9 – 62,7)% and 29 MFE – up to (63,0 – 67,7)%.

Table 4 presents the main testing results of mini fuel elements from different groups regarding the fuel composition characteristics.

Table 4. Main testing results of the MFE from different groups regarding fuel composition.

No.	Fuel characteristics		Uranium density in the fuel meat, g/cm^3	Maximum ^{235}U burnup in fuel, %	Fission products accumulation in the fuel meat, g/cm^3
	Alloy designation	Phase state			
1	OM-9$^{(A)}$	γ	4 ± 0.2	67.7	0.45
2*	OM-9$^{(A)}$	γ	6 - 0.2	64.7	0.67
3	OM-9$^{(A)}$	$\alpha + \gamma$	4 ± 0.2	65.8	0.47
4	OM-6.5$^{(A)}$	γ	4 ± 0.2	66.2	0.48
5	OM-6.5$^{(A)}$	γ	6 - 0.2	63.4	0.68
6	OM-6.5$^{(A)}$	$\alpha + \gamma$	4 ± 0.2	65.1	0.47
7	OM-6.5L1$^{(A)}$	γ	4 ± 0.2	66.7	0.47
8	OM-6.5L1$^{(H)}$	γ	4 ± 0.2	66.8	0.48
9	OM-6.5L2$^{(A)}$	γ	4 ± 0.2	66.8	0.48
10	OM-6.5L3$^{(A)}$	γ	4 ± 0.2	66.6	0.48
11	OM-6.5L3$^{(H)}$	γ	4 ± 0.2	67.5	0.49
12	OML-1.5$^{(A)}$	α'	4 ± 0.2	67.6	0.47
13	Zr Nb-10$^{(A)}$	γ	4 ± 0.2	67.4	0.47

* In the marked group a MFE cladding has failed.

Upon achieving ~63% burnup and accumulation of fission products (~0.65 g/cm^3) in the fuel meat a failure of one mini fuel element from group 2 took place. The fuel of alloy OM -9(A) containing 9.1% Mo, uranium density in the fuel meat ~ 5.8 g/cm^3. It should be noted that MFE of this group were tested at relatively high values of power (0.9 MW/m^2) and fission product accumulation (0.65 g/cm^3) as compared to those of the mini fuel elements of the other groups, except group 5. On the other hand, several mini fuel elements from group 2 and group 5 achieved higher burnup but they have not failed. Hence, the reason of the cladding failure can be established only in the course of careful post-irradiation examinations.

4. Results of PIE

4.1. Results of visual inspection and gamma scanning of mini fuel elements

MFE of all 13 types with 20% burnup were chosen for the nondestructive examinations. No mechanical defects on the surface or deformation were revealed as a result of visual inspection of the mini fuel elements. The MFE surface acquired shade of grey color as compared to the initial white color. Small (~1 mm) spots of white and dark-grey color are observed. Fig. 2 presents a photo of MFE No.0148 that is characteristic of all mini fuel elements under test.

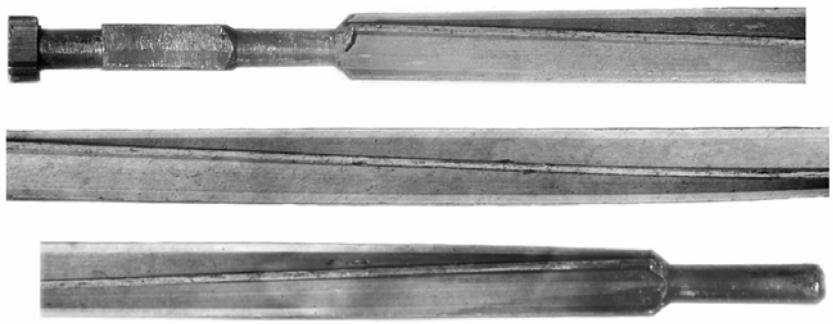
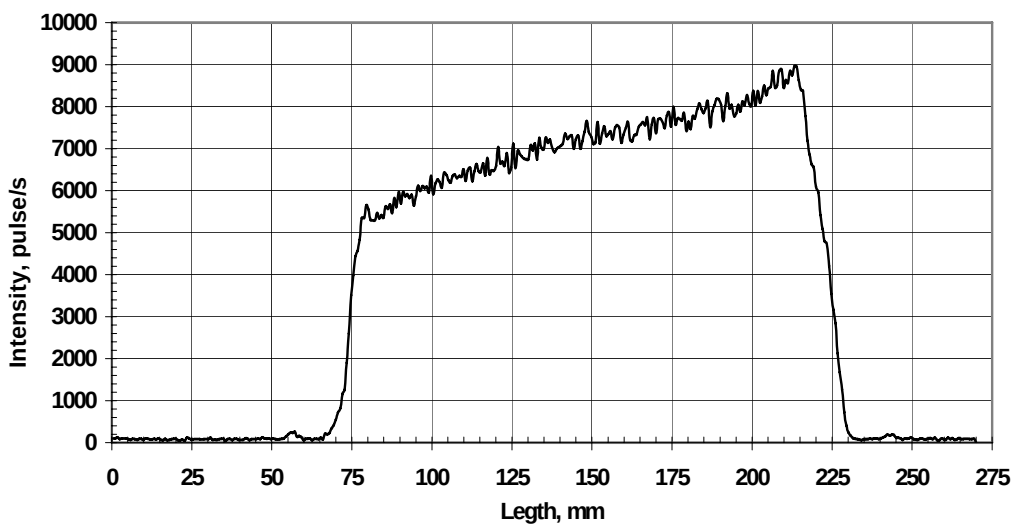


Fig.2. Photo of some areas of MFE No.0148

To define the distribution of fission products and heat flux along the MFE height, gamma-scanning of the mini fuel elements was performed in term of integrated and differential intensity of gamma-quanta. Fig. 3 shows the distribution of the integrated gamma-quanta intensity along the height of MFE No.0148 that is characteristic of other mini fuel elements. The distribution of the gamma-quanta intensity at low fuel burnup values (~20 %) actually corresponds to the distribution of fission products and heat flux along the fuel element height. The curve trend is determined by the neutron flux distribution along the irradiation device height in the reactor core. However, a significant difference is observed between the experimental and calculated heat flux curves at the ends of the fuel meat. It is manifested by the fact that the calculated curve, obtained under the assumption of a uniform fuel distribution along the height of the fuel meat, must have bursts of heat flux on the ends of fuel meat. The experimentally obtained distribution is possible only if at the ends of fuel meat a significant decrease in the fuel density occurs. The curves show that the areas with the fuel density decrease achieve (15-25) mm. The relative fuel distribution in the central part of the mini fuel elements is rather uniform and meets the technical requirements.



top bottom

Fig.3. Distribution of the gamma-quanta integrated intensity along the height of mini fuel element No. 0148.

4.2. PIE results of the MFE structure

Two mini fuel elements were chosen for destructive examination: MFE No.0148 (group 1, OM-9(A) with uranium density of ~ 4 g/cm^3) and MFE No. 0163 (group 1,OM-9(A) with uranium density of ~6 g/cm^3). 4 specimens were cut out from each mini fuel element for metallographic and electron microscopic examinations. One specimen from each MFE was also cut out (from the central part) to be

tested in the mechanical impact machine at liquid nitrogen temperature to obtain fracture; these specimens then were subjected to fractographic examination of the fracture surface.

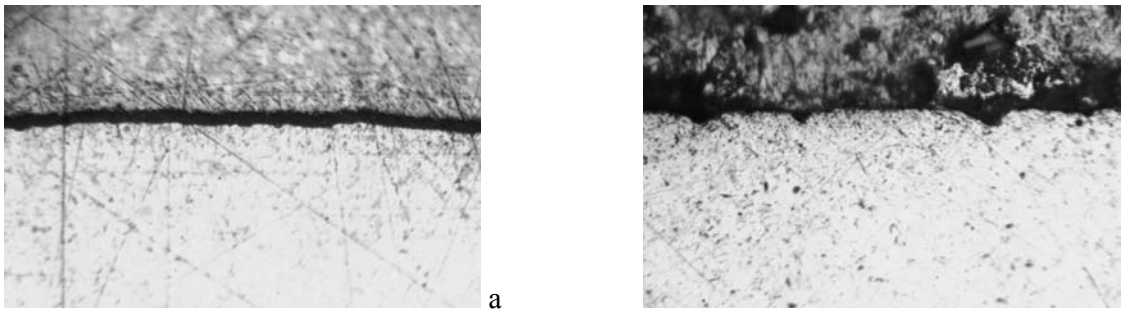
Figures 4 (a) and (b) present the typical appearance of the MFE cross sections: the claddings retained their integrity and there is a tight contact of the cladding with the fuel meat. Fig. 5 presents the microstructure of the MFE claddings. It is obvious that no traces of uniform corrosion are available on the outer surface of both mini fuel elements. Insignificant pitting (Fig. 5b) is observed in some regions of the outer surface of both mini fuel elements, assumingly it were caused by the corrosion pitting peeling or by some mechanical effect during PIE.

Fig. 6. presents the microstructure of the fuel-cladding contact area. The quality of the contact is obviously to be satisfactory, however, separate fuel particles pressed into the claddings are observed (Fig. 6a).

Fig. 7 presents the fuel meat microstructure. An interaction layer is revealed between the fuel particles and the matrix.

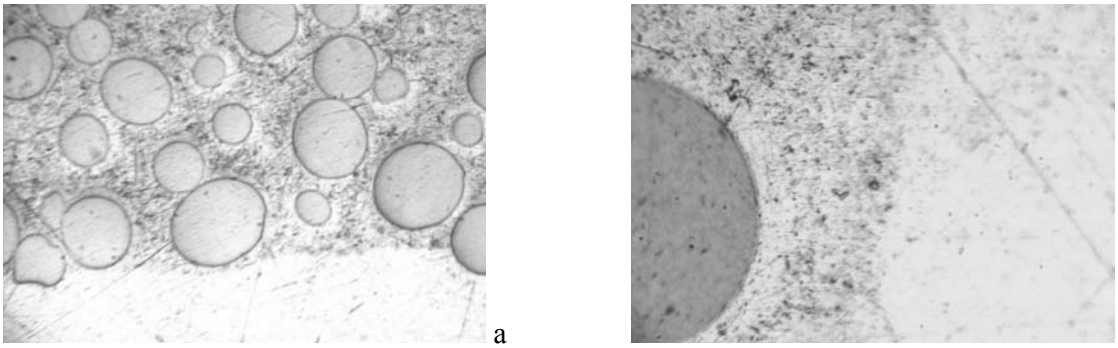
a b

Fig.4. Macrostructure of the cross-sections of MFE No.0163 (a), and No. 0148 (b): 130 mm from the bottom.



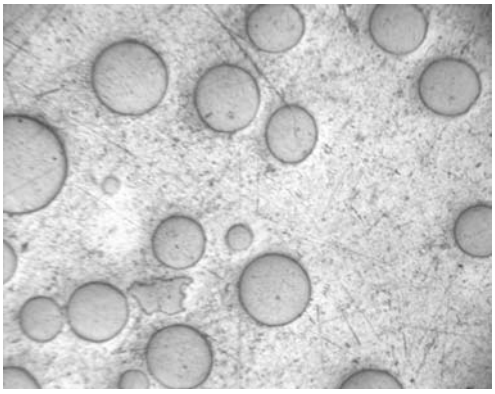
a b

Fig.5. Cladding microstructure of MFE No. 0163 (a,) and No.0148 (b), ×400



a b

Fig.6. Microstructure of the “fuel-cladding” boundary of MFE No.0148 (a) and No. 0163 (b) at magnification ×100 (a) and ×400 (b)


a

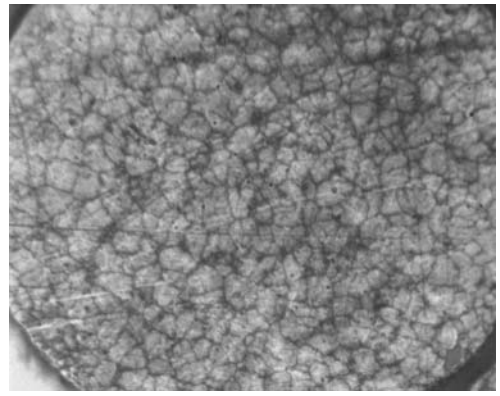

b

Fig.7. Fuel composition microstructure of MFE No. 0163 at magnification ×100 (a), ×600(b)

4.3. Cross-section plane geometry of the mini fuel elements

Geometric characteristics of the MFE cross-sections were measured from the photo images of polished specimens (Fig. 4). The measurement methods [2] allow the definition of the cross-section area of the mini fuel element (for outer cladding surface) and fuel meat (for inner cladding surface); across-the-ribs and across-the-flats dimensions as well as other dimensions within the cross-section presented on the polished specimen.

Table 5 presents the measurement results of the MFE cross-section areas (S_{TB}), across-the-ribs (D) and across-the facet dimensions (d), and also their relative changes $\Delta STB/STB_0$., $\Delta D/D0$ and $\Delta d/d_0$. The dimensions of the cross-sections without fuel meat are considered to be initial MFE dimensions (STB_0, D_0, d_0). For MFE No.0148 this cross-section is 197 mm from the bottom of the mini fuel element, for MFE No.0163 – 223 mm from the bottom.

Table 5. Geometrical characteristics of the mini fuel elements

MFE No.	Height from the MFE bottom, mm	D, mm	$\Delta D/D_0$, %	d, mm	$\Delta d/d_0$, %	S_{mfe}, mm^2	$\Delta S_{mfe}/S_{mfe}^0$, %
0148	30	4.82	0.71	2.96	2.46	9.26	2.52
	120	4.81	0.52	2.95	2.15	9.18	1.59
	177	4.80	0.40	2.94	1.70	9.12	0.93
	197	4.79	0.00	2.89	0.00	9.03	0.00
0163	30	4.88	2.95	2.95	1.06	9.38	3.61
	120	4.86	2.36	2.94	0.58	9.28	2.47
	198	4.83	1.92	2.93	0.27	9.16	1.12
	223	4.74	0.00	2.92	0.00	9.06	0.00

Note: dimensions D and d presented in the table are averaged for two ribs and for two facet

The data of Table 5 show that the irradiation gave rise to an increase in the dimensions of MFE as compared to the area without fuel composition. The dimensions increased both with regard to ribs and facet, correspondingly; the cross-section areas of the mini fuel elements have increased either. On the whole, such an increase corresponds to the accumulation of fission products in the respective cross-section of the mini fuel element.

4.4. Electron microscopic examination results of the mini fuel elements

Fig. 8 presents the results of the electron microscopic examination of the polished specimens of MFE No. 0163 and No. 0148.

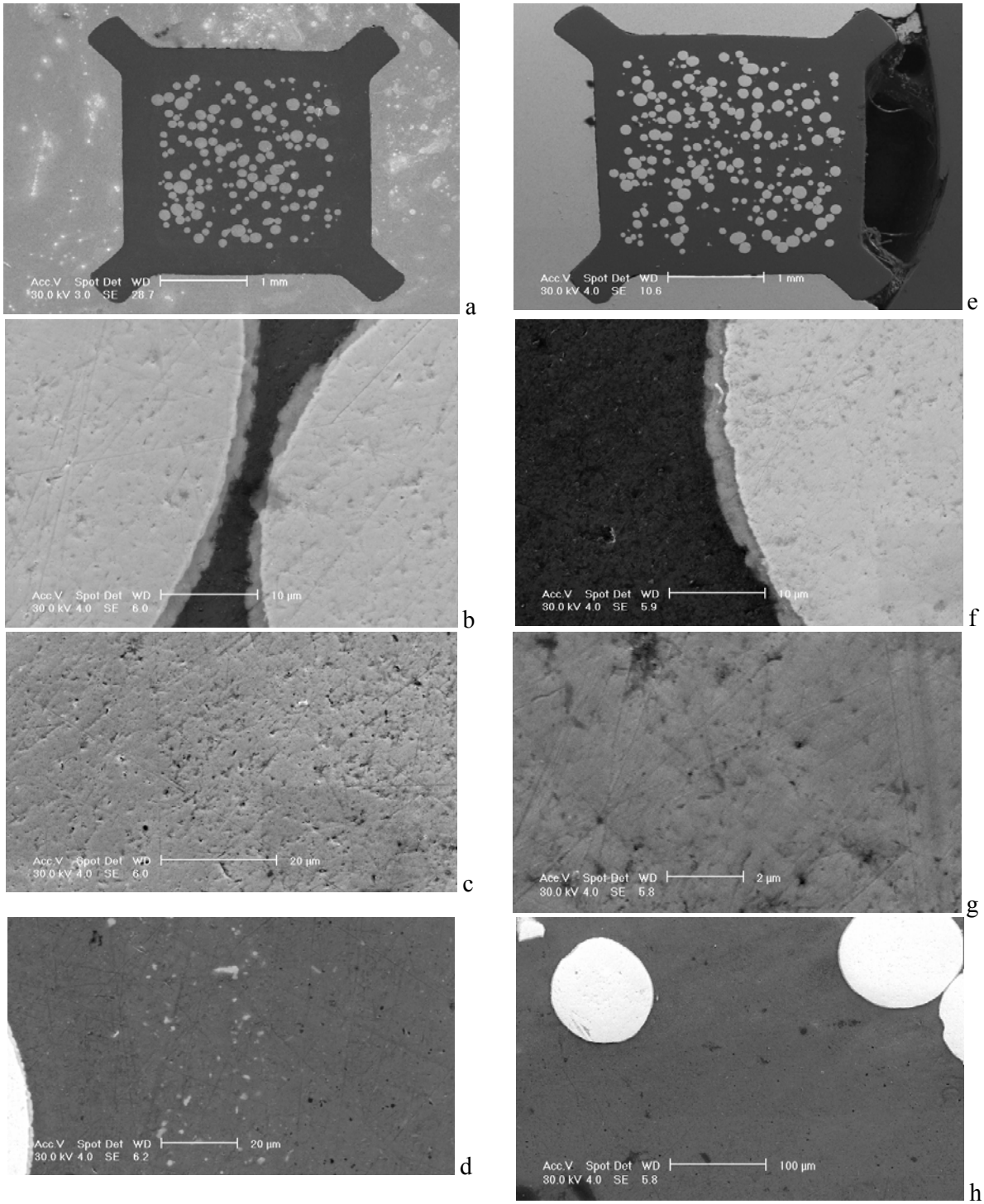


Fig. 8. Results of the electron microscopic examination of the polished specimens of MFE No. 0163(a-d) and No.0148 (e-h).

The fuel particle distribution over the MFE cross-sections is non-uniform (Figs. 8a и 8b). However, it seems likely that their volume fractions (content per volume unit) do not differ very much. An interaction layer between a fuel particle and the matrix (Fig. 8 b, f), fine-dispersed precipitates of an unknown

phase at the boundary between the fuel meat and cladding are observed in MFE No. 0163 along the entire boundary perimeter (Fig. 8 d).

The analysis of the electron microscopic images of impact testing specimens (Fig. 9) shows that the damage of fuel particles is brittle (Fig. 9 a, e). The fuel particles and interaction layer between a fuel particle and the matrix are clearly observed (Fig. 9 f). Multiple pores are located along the fuel particle grain boundaries of both mini fuel elements (Fig. 9 c, g). The cladding and matrix damage has a ductile transgranular nature (Fig. 9 d, h).

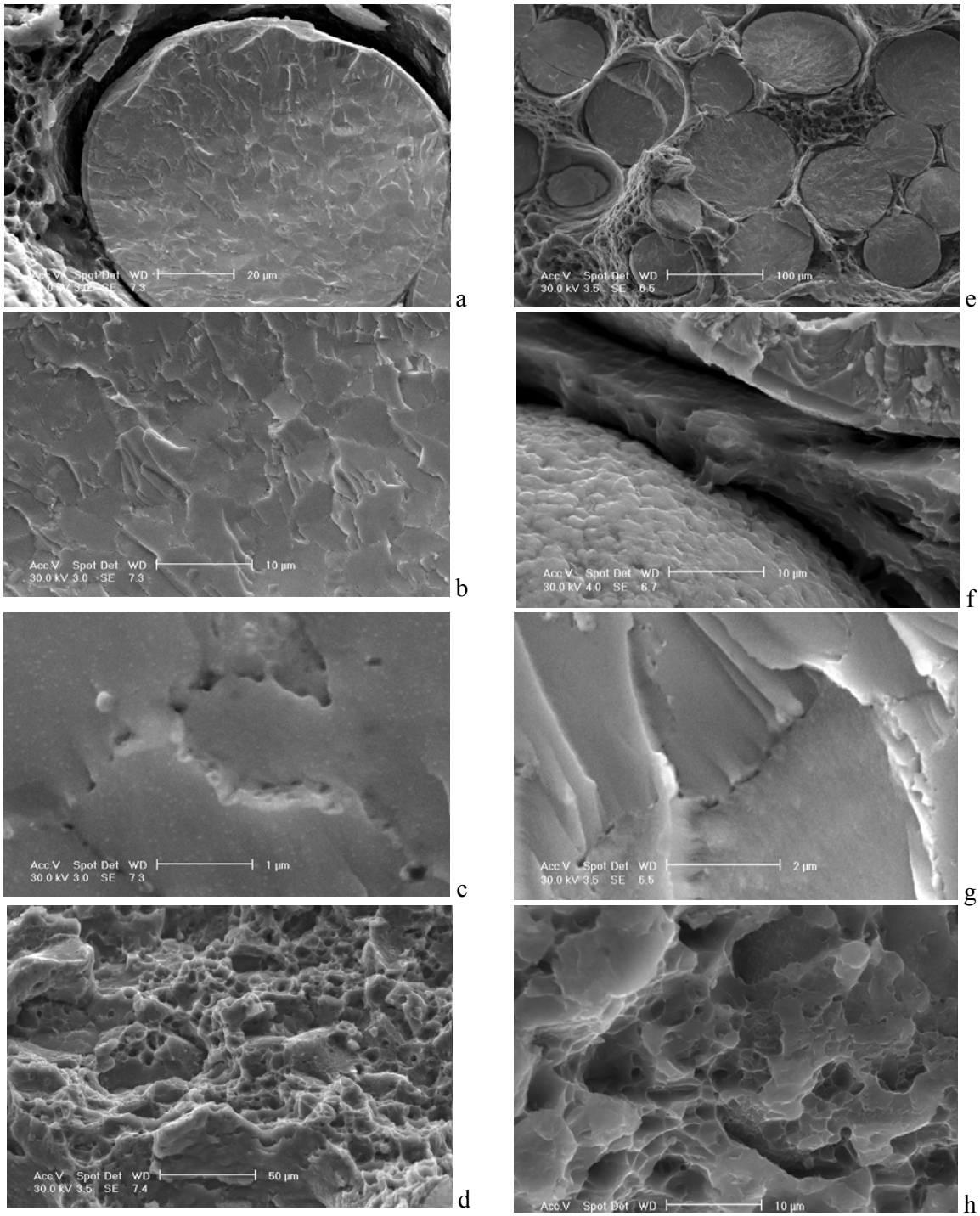


Fig 9. Results of electron microscopic examination of the fracture of MFE No. 163(a-d) and No.0148(e-h)

5. Conclusion

In the MIR reactor the testing of mini fuel elements of the pin-type (MFE) has been performed. They incorporated high-density low-enrichment U-Mo fuel of 13 different modifications with regard to composition, phase state and uranium density in the fuel meat up to the maximum value (~ 70%) of ^{235}U burnup.

Upon achievement of ~63% burnup and fission products accumulation in the fuel meat (~0.65 g/cm^3), a failure of one mini fuel element from group 2 took place. The fuel of alloy OM -9(A) containing 9.1% Mo, uranium density in the fuel meat achieving 5.8 g/cm^3. It should be noted that fuel pins of this group were tested at relatively high values of power (0.9 MW/m^2), fission product accumulation (0.65 g/cm^3) as compared to those of MFE of the other groups, except group 5, hence, the cladding failure can be related to this reason. On the other hand, several mini fuel elements from group 2 and group 5 achieved higher burnup but they have not failed. The damage reason of the mini fuel element failure can be established only in the course of further examinations.

Post-irradiation examinations of the mini fuel elements with ~20% burnup have been performed. The mini fuel elements retained their shape; no mechanical or corrosion damage of the claddings was observed; the tight contact between the fuel meat and the cladding is retained, no interaction between them is revealed. There is an interaction layer of ~ 2 μm between the fuel particles and the matrix.

6. References

1. A.L. Izhutov, N.G. Gataulin, M.N. Svyatkin et al. “Conditions and preliminary results of low enrichment U-Mo pin type fuel testing in the MIR reactor” Proceedings of the 2003 International Meeting on Reduced Enrichment for Research and Testing Reactors”, Chicago, USA, October 5-10, 2003.
2. The measurement methods of geometry parameters of products and material structure, registration No. 535. SSC RIAR Register, Dimitrovgrad, 2000.