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Main results of the development of dispersion type IMF at A.A. Bochvar Institute

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ABSTRACT

At A.A. Bochvar Institute a novel conception of IMF to burn civil and weapon's grade Pu is currently accepted. It consists in the fact, that instead of using pelletized IMF, that features low serviceability and dust forming route of fuel element fabrication, the usage is made of dispersion type fuel element with aluminium or zirconium matrices.

Dispersion fuels feature a high irradiation resistance and reliability; they can consequently reach high burnups and be serviceable under transient conditions.

Three basic fuel element versions are under development in VNIINM for both thermal and fast reactors.

The first version is a fuel element with a heterogeneous arrangement of fuel (PuO_2 or YSZ granules) within an Al or Zr matrix. The second version of a fuel element has a heat conducting Al or Zr alloy matrix and an isolated arrangement of PuO_2 in a fuel minielement more fully meets the 'Rock Fuel' requirements. According to the third version a porous meat of zirconium metallurgically bonded to a fuel cladding is formed through which a PuO_2 powder is introduced. All the versions are technologically simple to fabricate and require minimal quantities of process operations related to treating MA and Pu. Preliminary in-pile tests of IMF prototypes are presented.

1. Introduction

For the incineration of excess Pu using existing LWRs, inert matrix fuels (IMF) have been proposed for use in a 'Once Though Then Out' (OTTO) concept. Inert matrix Pu fuels do not contain uranium; hence, during in-reactor use almost no Pu is generated [1]. The same approach can be proposed for burning MA in fast reactors.

As an inert matrix use is made of various ceramic materials – spinel, YSZ, Mg_2O, etc. [2]. Fuel element designs traditionally have the form of IMF pellets. They have no metallurgical bond between cladding and meat which aside from raising the temperature in the centre of a fuel element, degrades its serviceability, particularly, in transients [2]. The low irradiation resistance is the main factor that restricts the application of IMF.

2. Development of dispersion type IMF concept with metal matrix and metallurgical cladding – fuel bond

IMF elements contain a small volume fraction (not more than 15%) of a fissionable element (PuO_2). This specific feature makes it possible to use as a IMF element dispersion type fuel elements with metal matrices that as distinct from the traditional pelletized fuel elements have a number of advantages [3–6]. They are a low temperature of a fuel centre, high irradiation resistance, feasibility of extended burnups (100 MW d/kg U and higher). Technologic merits also involve the applicability of PuO_2 powder as an initial one or YSZ or PuO_2 granules to manufacture dispersion fuels not resorting to subsequent dust-forming operations of pellets manufacturing, such as granule crushing, powder filtration, powder blending, pressing, sintering, grinding. Dispersion fuels have specific structural features and differ in both the fuel composition, primarily, the material of a matrix, and the fabrication process. When developing novel types of IMF elements we were guided by the following criteria:

1. Under steady-state and in transients fuel elements should be serviceable at the maximal burnup of up to 100 MW d/kg U in thermal reactors, and up to 200 MW d/kg U in fast reactors.
2. Reliability and safety of a fuel element, high irradiation and corrosion resistances that comply with the requirements for 'Rock-fuel' making direct geologic disposal of spent fuel feasible.
3. Simple technology, i.e., minimal number of operations used to process plutonium fuel.
4. The design of fuel-grade plutonium element should have analogues that were subjected to in-pile tests and proved their serviceability.

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5. Further fuel modifications and substitution of an inert matrix for uranium alloys of high performance and serviceability are feasible to be applied in fast reactor fuel rods.

3. Choice of process to fabricate fuel element and matrix materials

Arbitrarily two ways of dispersion fuel element fabrication might be assumed.

1. Pressing or extrusion of fuel meat.
2. Impregnation with a molten matrix material of an internal volume of fuel cladding pre-loaded with fuel particles (Fig. 1a).

The second option of dispersion fuel fabrication viz., impregnation, has been commercially mastered, provides the uniform distribution of fuel along the height and across a fuel element as well as a metallurgical bond between cladding and meat (no gap available) (Fig. 1) [6,7]. However, it restricts to some extent the properties of a matrix material. Technologically (in terms of compatibility between fuel element components) the temperature of impregnation as it has been shown experimentally has not to exceed 950 °C. That is why, only aluminium alloys are used for this objective (copper alloys are not suited because of their neutron capture, magnesium – because of a low aqueous corrosion resistance and zirconium – because of its high melting temperature of 1860 °C). Therefore, for zirconium to be used as a matrix for impregnation technology a novel class of its alloys was designed that have low melting point temperatures (690–860 °C) [6–9].

In various reactor types under different irradiation conditions preliminary in-pile tests and post-irradiation examinations were carried out using prototypes of fuels and fuel compositions in which PuO_2 was substituted by UO_2 (Table 1) [3,5,8–9].

Both aluminium and zirconium matrix fuel rod prototypes 250–1000 mm long clad in zirconium alloy E110 and fueled with UO_2 granules were successfully in-pile-tested under conditions VVER-440, VVER-1000 and RBMK without loss of tightness or volume changes [3,8–9]. Aluminium matrix fuels reached the burnup of 100 MW d/kg U and the burnup of zirconium matrix fuels made up 60 MW d/kg U.

Specimens of fuel compositions with zirconium matrices and steel claddings were irradiated to the burnup of 0.8 g frag/cm^3 which as calculated for the VVER-1000 standard fuel rod makes up 100 MW d/kg U without loss of tightness or changes in fuel meat dimensions. The heat flow at the surfaces of the fuel specimens amounted to 2.0 MW/m^2.

Intricately shaped fuel element prototypes clad in austenitic stainless steel having a zirconium matrix with PuO_2 fuel placed in a fuel minielement (an isolated fuel arrangement) were successfully in-pile tested in the steam superheating loop of MIR (RIAR) at the steam temperature of 550–600 °C and the cladding temperature <750 °C up to the burnup of 1.5 g frag/cm^3 under the fuel cladding and 3.0 g frag/cm^3 inside the fuel minielement [8,9].

The implemented tests evidence the promising character of similar designs and the materials used as IMF.

It is to be noted that the process of impregnating with aluminium alloys has been mastered commercially while the process of impregnating with zirconium matrix alloys is rather complicated. Therefore, the zirconium matrix fuel element option has been modified. Basing on the capillary properties of the novel zirconium matrix alloys both the fuel composition fabrication process and the structure of the high uranium content fuel compositions were updated. Instead of impregnating the internal space of a fuel element with molten Zr alloy in the novel process the mixture of fuel and zirconium matrix granules is loaded into a fuel cladding and then heated to a temperature 50 °C higher than the melting temperature of the alloy [6,8] (Fig. 2). Under the action of capillary forces the molten zirconium alloy coats the fuel granules and the cladding and moves into the gaps between the fuel granules and the cladding to form so-called bridges which provides for the high thermal conductivity of the fuel meat.

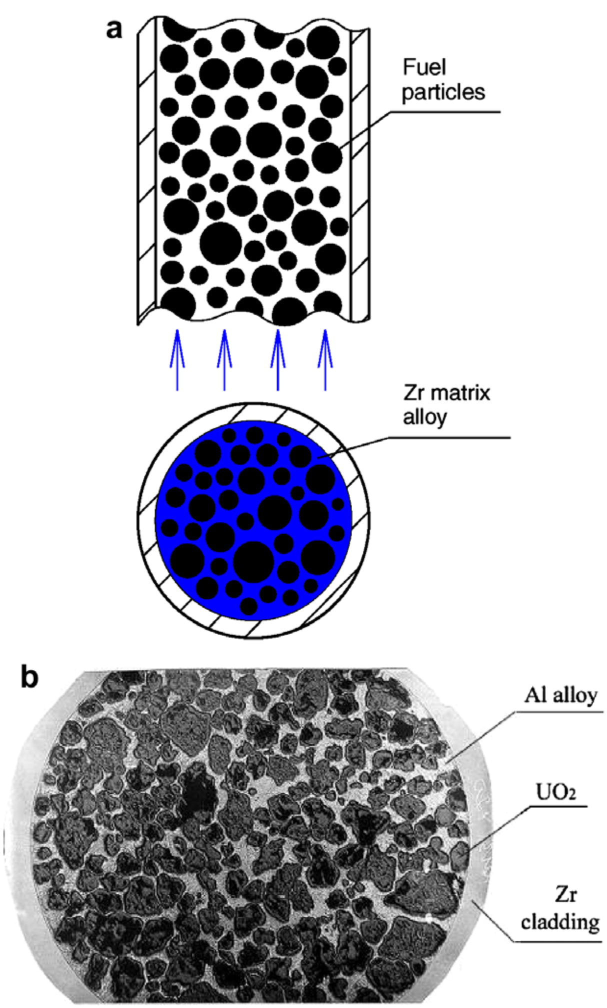

Fig. 1. Schematic presentation of dispersion fuel element fabrication via impregnation (a) and microstructures of UO_2 dispersion compositions with Al–Si alloy (b) [3–6]. The arrows show the motion direction of the molten matrix alloy in the fuel element fabrication process.

Table 1
In-pile testing uranium dioxide fuel elements prototypes [3,8–9].

Fuel	Temperature clad/fuel, °C	Fuel element type	Burnup	
			g frag/cm^3	MW d/kg U
UO_2 + Al alloy	350/470	VVER	0.8	100
UO_2 + Al alloy (UO_2 in minifuel)	350/470	Special	0.8	100
UO_2 + Zr alloy	300/500	Fuel composition	0.8	100
UO_2 + Zr alloy	330/500	RBMK	0.4	55
UO_2 + Zr alloy	330/440	VVER-440	0.45	60
UO_2 + Zr alloy (UO_2 in minifuel)	600/750	Special	1.5	200

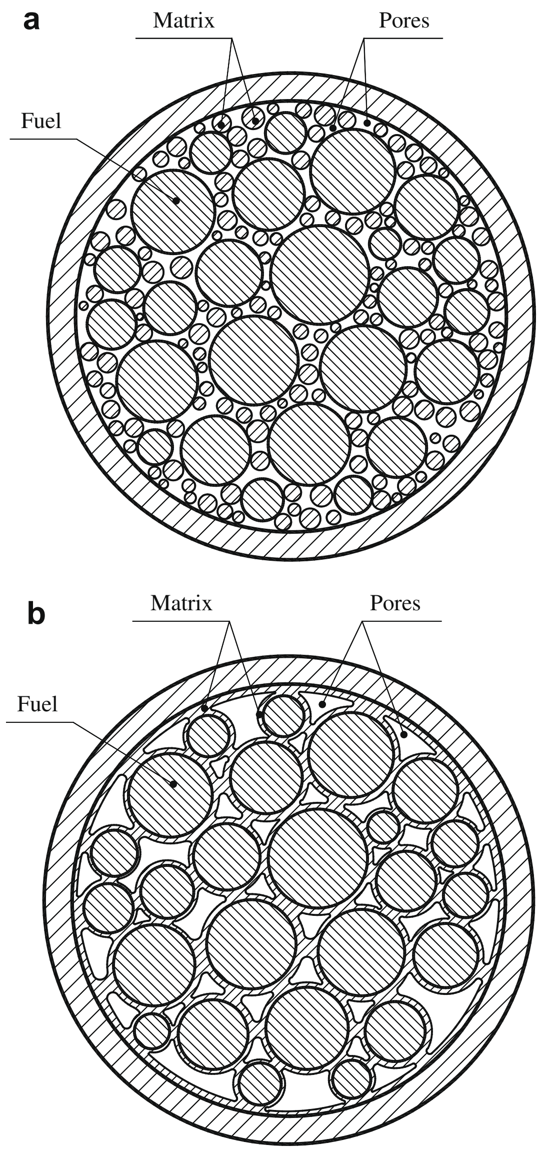

Fig. 2. Schematic cross-section presentation of fuel element fabricated by capillary impregnation method (a) as vibroloaded; (b) as capillary impregnated [6,8].

4. Inert matrix fuel elements under development

At A.A. Bochvar Institute three basic fuel element versions are under development. The first version of a fuel element having a heat conducting metal matrix and an isolated arrangement of PuO_2 in a fuel minielement [3–6]. The second version is a fuel element with a heterogeneous arrangement of fuel [3–6]. According to the third version a porous meat of zirconium metallurgically bonded to a fuel cladding is formed through which a PuO_2 powder is introduced [9]. All the versions are technologically simple to fabricate and require minimal quantities of process operations related to treating MA and Pu. The general schema of fuel element designs, fabrication processes and materials used are illustrated in Fig. 3.

4.1. Fuel element with isolated fuel arrangement

This fuel element version is a mostly unified one. It is technologically simple to fabricate, allows the use of both aluminium and zirconium matrices and more fully meets the "Rock Fuel" requirement and it might be used in both thermal and fast reactors.

The main distinction and advantage of such a fuel element consist in the fact that PuO_2 is separately arranged in fuel minielements that in their turn are placed inside a fuel element. The space between the fuel minielements and the fuel cladding is filled with an Al alloy matrix or a Zr matrix alloy. Fig. 4 schematically presents a fuel element inside which an accommodator might be also placed to accommodate fuel swelling.

The advantage of this design lies in the fact that the number of the main dust-forming operations in the fuel element fabrication is reduced to a single one, viz., filling minielements with powder or granules. The other operations, viz., minielement sealing (second end welding), fuel element assemblage, impregnation with a matrix alloy, are carried on in clean zones. Aside from this, the fuel-free space of a minielement served to accommodate swelling of fuel. The fuel of a minielement is protected against the interaction with a matrix and with a coolant.

4.2. Fuel element with heterogeneously arranged fuel

In this design PuO_2 particles are distributed within a heat conducting Al alloy matrix that is metallurgically bonded to a zirconium cladding or a zirconium cladding. The general cross-section of a fuel element with a heterogeneous fuel arrangement is illus-

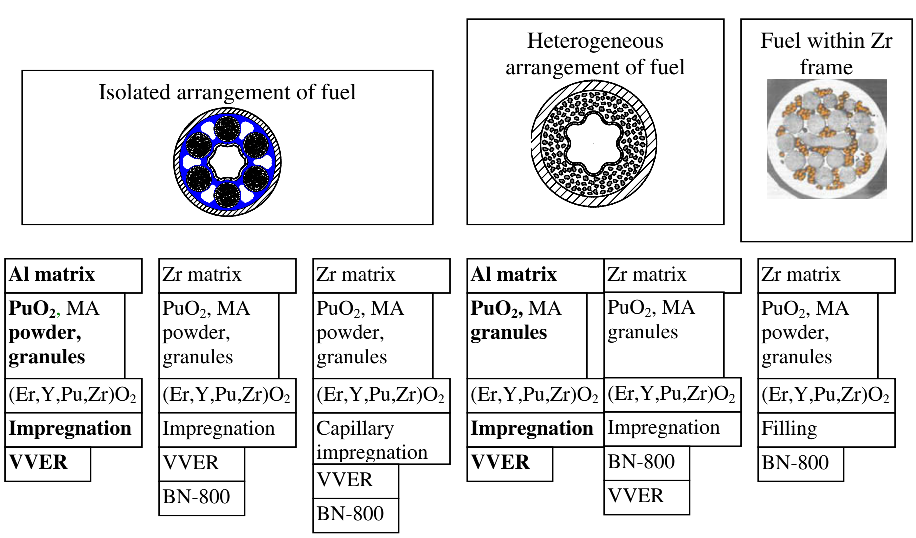

Fig. 3. General schematic presentation of dispersion fuel element designs with IMF under design at VNIINM (bold type points out versions of fuels fabricated for in-pile tests).

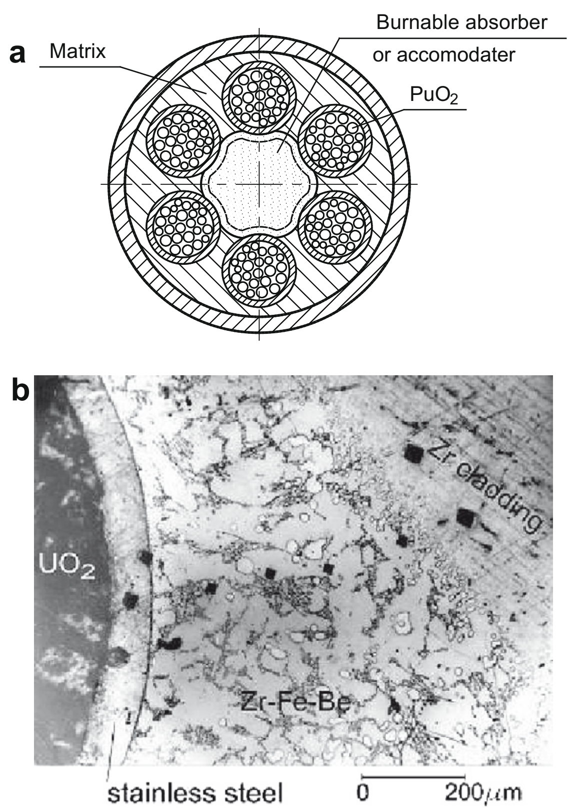

Fig. 4. Cross-section of fuel element – plutonium burner containing fuel minielements with burnable poison or accommodator of swelling, with an Al alloy matrix or a Zr matrix alloy fabricated by impregnation method (a), and microstructure of fuel element with Zr matrix (b) [3–6].

trated in Fig. 5, and Fig. 1(b)–(c) shows the microstructure of a fuel element with Al and Zr matrices and PuO_2 fuel [3–6].

In the above shown fuel element design in place of pure PuO_2 also $(Er,Y,Pu,Zr)O_2$, microspheres might be used.

4.3. Fuel element with heterogeneous fuel arrangement within pores of heat conducting zirconium frame

In the third version at first a porous metallurgically bonded to fuel cladding zirconium meat is formed through which PuO_2 powder is introduced. The fabrication of a fuel element comprises two stages. At the first stage by capillary impregnation method using a Zr powder (Fig. 6a) or Zr granules (Fig. 6b) a heat conducting zirconium frame metallurgically bonded to a cladding is fabricated. It is technologically feasible to produce a precision porosity of 20–40% [6,9]. At the second stage PuO_2 or MA powder manufactured by a pyrochemical or other method is introduced into the frame pores. In this way the quantity of process operations related treating MA is reduced. An extra advantage is that in the capillary impregnation process the fuel cladding becomes coated with the zirconium matrix alloy that protects the cladding from their interaction with fission products and Cs induced corrosion [9].

This fuel element version is promising to burn Pu or MA in fast reactor fuels. It is technologically possible using this method to form a frame not only from an inert matrix but also from U-alloys of UMo, UZr, etc. systems. In this case it is feasible to produce novel promising combined U–PuO_2 fuel basing on a dispersion type fuel element having a high conversion ratio [9].

5. Fabrication of lead fuels for reactor tests

To validate the applicability of dispersion type designs for IMF elements to burn plutonium in LWR at RIAR in cooperation with A.A. Bochvar Institute the PuO_2 fuel elements of the VVER-1000 type were fabricated that will be subsequently in-pile tested.

Two fuel element designs having isolated and heterogeneous arrangement of fuel is fabricated (Fig. 7). To produce fuels use was made of Zr alloy (E110) claddings 9.1 mm in the diameter and pyrochemically prepared reactor-grade crystalline powder of PuO_2 of 50–100 μm fraction. Aluminium alloy is used as a matrix. The fuel element length is 250 mm; the quantity of fuel elements makes up 12.

Late in 2010 according to the schedule the fabricated fuels will be loaded into a reactor to be tested under the VVER-1000 operating conditions.

Using IMF elements the planned burnup shall be 100 MW d/kg U as recalculated for the standard VVER-1000 fuel element.

The fabrication of PuO_2 fuel elements of other options is scheduled for future.

6. Conclusion

At A.A. Bochvar Institute a novel concept of IMF to burn civil and weapon's grade Pu is now accepted. It consists in the fact, that instead of using pelletized IMF that features low serviceability and dust-forming fabrication route, the usage is made of dispersion type fuel element with aluminium or zirconium matrices fabricated by different processes.

Dispersion fuels feature a high irradiation resistance and reliability; consequently, they might reach high burnups and be serviceable under transient conditions.

Three basic fuel element versions are under development in VNIINM both for thermal and fast reactors.

The first version is a fuel element with a heterogeneous arrangement of fuel (PuO_2 or YSZ granules) within an Al or Zr

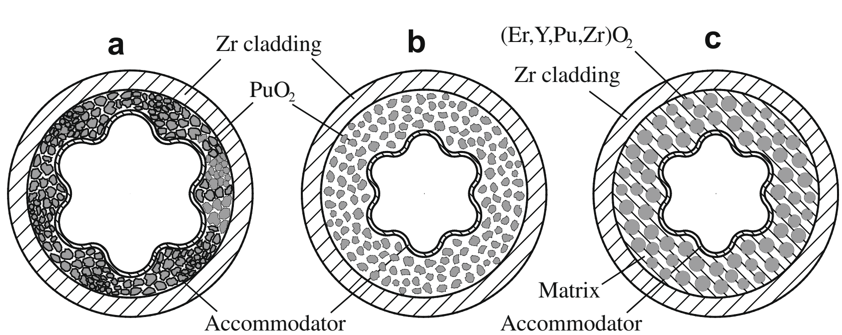

Fig. 5. Cross-section of fuel element with heterogeneous arrangement of fuel in Al matrix alloy: (a) PuO_2 volume fraction 60%, (b) PuO_2 volume fraction 30% and (c) $(Er,Y,Pu,Zr)O_2$ microspheres volume fraction 60% [3–6].

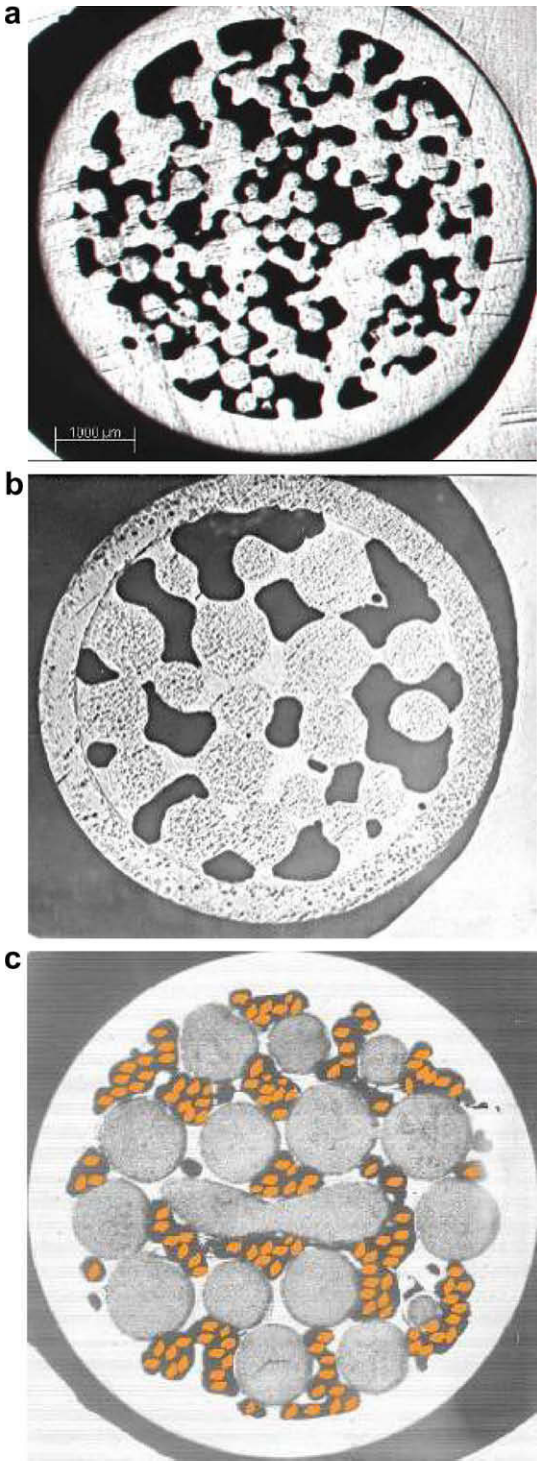

Fig. 6. Microstructure of Zr porous meat fabricated by capillary impregnation from Zr powder (a), Zr granules (b) and (c) U–PuO_2 dispersion combined fuel (PuO_2 in pores is shown schematically) [9].

matrix. The second version of a fuel element has a heat conducting Al or Zr alloy matrix and an isolated arrangement of PuO_2 in a fuel minielement, which comply with the requirements for 'Rock Fuel' to a large extent. In the third version a porous metallurgically bonded to a fuel cladding meat of zirconium is formed through which PuO_2 powder is introduced. All the versions are technologically simple to fabricate and comprise the minimal quality of process operations related to treating MA and Pu.

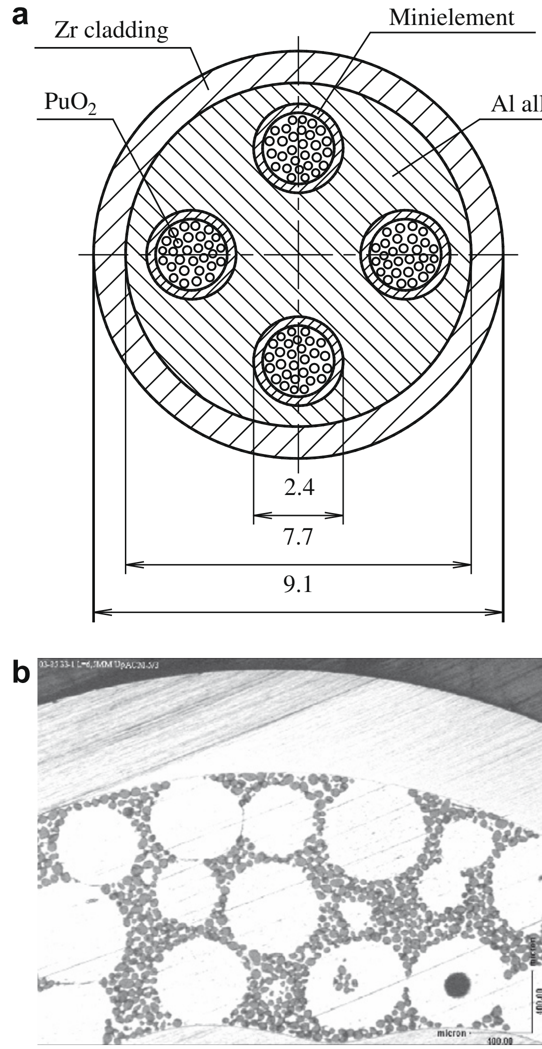

Fig. 7. Cross-section of fuel element having isolated arrangement of Pu to be in-pile tested (a) and microstructure of fabricated fuel element prototype having heterogeneous arrangement of PuO_2 in Al matrix (b) [4].

Fuel element simulators of similar designs with inert aluminium matrix, in which UO_2 was used in place of PuO_2 were successfully in-pile tested under PWR conditions up to the burnup of 100 MW d/kg U and fuel element simulators with inert zirconium matrix clad in stainless steel reached the burnup of 200 MW d/kg U with the temperature of steam up to 600 °C, which makes their use promising in both thermal and fast reactors.

Currently a lead IFM assembly has been fabricated with two versions of fuels with an Al matrix; use was made of a crystalline powder of fuel-grade PuO_2 prepared by the pyrochemical method. At the end of the year we are planning to commence in-pile testing under PWR conditions. The anticipated burnup is 100 MW d/kg U.

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