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Inert matrix fuel in dispersion type fuel elements

A.M. Savchenko *, A.V. Vatulin, A.V. Morozov, V.L. Sirotin, I.V. Dobrikova,
G.V. Kulakov, S.A. Ershov, V.P. Kostomarov, Y.I. Stelyuk

A.A. Bochvar All-Russia Research Institute of Inorganic Materials (VNIINM) 123060, P.O. Box 369, Rogova Street, 5A, Moscow, Russia

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Abstract

The advantages of using inert matrix fuel (IMF) as a dispersion fuel in an aluminium alloy matrix are considered, in particular, low temperatures in the fuel centre, achievable high burn-ups, serviceability in transients and an environmentally friendly process of fuel rod fabrication. Two main versions of IMF are under development at A.A. Bochvar Institute, i.e. heterogeneous or isolated distribution of plutonium. The out-of-pile results on IMF loaded with uranium dioxide as plutonium simulator are presented. Fuel elements with uranium dioxide composition fabricated at A.A. Bochvar Institute are currently under MIR tests (RIAR, Dimitrovgrad). The fuel elements reached a burn-up of 88 MW d kg^{-1} (equivalent to the burn up of the standard uranium dioxide pelletized fuel) without loss of leak-tightness of the cladding. The feasibility of fabricating IMF of these particular types with plutonium dioxide is considered with a view to in-pile irradiation.

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1. Introduction

Fuel element designs for burning civil and weapon's grade plutonium traditionally take the form of pellets made of inert matrix fuel (IMF). Currently, several versions of dispersion type fuels and isolated fuel made of aluminium alloy matrix are also under consideration [1–5].

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

In developing novel types of IMF elements we considered the following criteria to be relevant:

1. Serviceability of a fuel element under steady-state and transients for burn-ups up to 100 MW d kg^{-1}.
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 fuel feasible.
3. Simple technology, i.e. minimal number of operations used to process the plutonium fuel.
4. The design of fuel-grade plutonium element should have analogues that were subjected to in-pile tests and have established their serviceability.

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* Corresponding author. Tel.: +7 095 1908985; fax: +7 095 1964075.
E-mail address: sav@bochvar.ru (A.M. Savchenko).

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2. Characterization of design features of aluminium inert matrix fuels under development

At the A.A. Bochvar Institute two basic fuel element designs are under development that are planned to undergo in-pile testing in the future. The first design is a fuel element with a heterogeneous arrangement of fuel within an Al matrix. In this design PuO_2 particles are distributed within a heat conducting Al alloy matrix that is metallurgically bonded to a zirconium cladding [1,2,5].

The second design is a fuel element having a heat conducting Al alloy matrix completed by an isolated arrangement of PuO_2 in a fuel minielement [1,3,4].

The results of the investigations given here refer to inert matrix fuel element simulators in which UO_2 was used in the place of PuO_2.

Both fuel element designs are fabricated at the A.A. Bochvar Institute using the developed and industrially applied process in which UO_2 fuel granules are impregnated within a cladding using a molten Al alloy [3,6]. As a result, a metallurgical bond is formed between the cladding and the fuel component leading to a lower operating temperature in the fuel element centre, which makes the fuel element serviceable under transient conditions.

2.1. Fuel element with heterogeneously arranged fuel

The general cross-section of a fuel element with a heterogeneous fuel arrangement is illustrated in Fig. 1 [1,3].

In this design the fuel volume fraction is dependent on the shape and sizes of fuel particles and is usually about 50–65%. When UO_2 is replaced by PuO_2 the volume of the fuel has to be less, i.e., not more than 10–15%. Consequently, two methods are applied to reduce the volume fraction. In the first one an empty volume is produced so that the total content of PuO_2 in a fuel element is reduced to the required amount (Fig. 1(a)) [1]. This way is most effective since it also allows for fuel swelling and a temperature decrease in the fuel element centre.

In the second method, PuO_2 is diluted with aluminium which increases the thermal conductivity of the fuel component (Fig. 1(b)).

The most interesting design of a heterogeneous fuel element is the version where $(Er,Y,Pu,Zr)O_{2-x}$ microspheres (prepared by internal gelation process such as at PSI) are used instead of plutonium dioxide (Fig. 1(c)) [7,8]. Aside from the purely technological advantages, the process of impregnation with a dilute Al alloy is improved and the $(Er,Y,Pu,Zr)O_{2-x}$ microspheres comply with the non-proliferation requirements and with the 'Rock-like Fuel' criterion more than PuO_2. When the microspheres are used in the suggested fuel element design, the mole fraction of PuO_2 in $(Er,Y,Pu,Zr)O_{2-x}$ has to exceed 10%.

The thermal conductivity of the fuel component is dependent on the volume fraction of UO_2 and was experimentally determined by flow heat method (Fig. 2). The temperature distribution within the fuel of the element at volume fraction of 30 and 60% PuO_2 was calculated using the heat elementary balance method (control volume finite-elements method for heat transfer) and is illustrated in Fig. 3. Because of the high thermal conductivity the maximum fuel temperature does not rise to higher than 693 K. The thermal design was implemented for the fuel

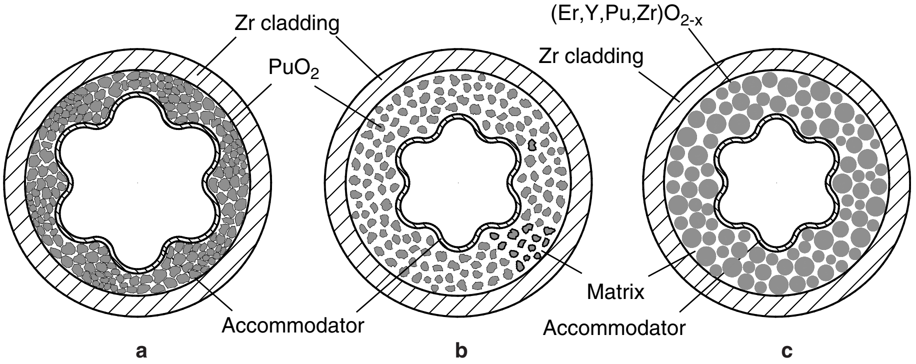

Fig. 1. Cross section of fuel element with heterogeneous arrangement of fuel: (a) PuO_2 volume fraction ~60%, (b) PuO_2 volume fraction ~30% and (c) volume fraction of $(Er,Y,Pu,Zr)O_{2-x}$ microspheres ~60%.

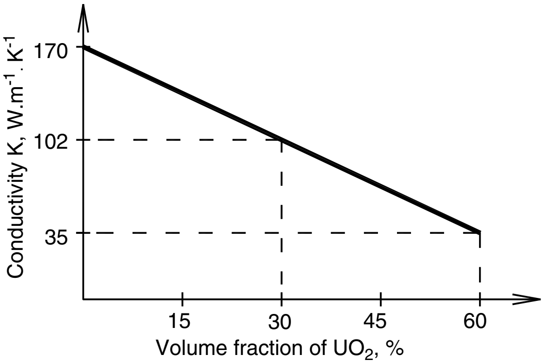

Fig. 2. Thermal conductivity of Al containing fuel component versus volume fraction of UO_2 at 723 K.

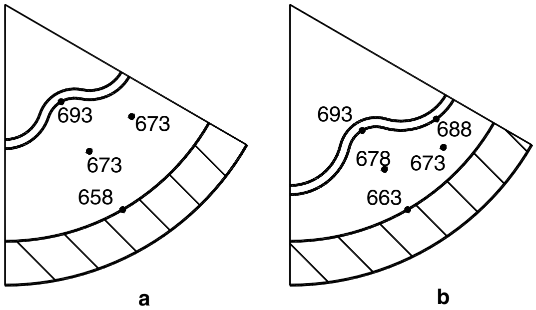

Fig. 3. Temperature (K) distribution of part of fuel element with heterogeneous fuel arrangement at PuO_2 volume fraction of 30% (a) and 60% (b) at linear heat generation rate of 450 W cm^{-1}.

element linear heat rate of 450 W cm^{-1} which corresponds to the highest power density conditions of the VVER-1000 operation.

The long-term (800 h) compatibility tests of the fuel element components at 773 K did not lead to an increased interaction with the aluminium matrix alloy [1].

2.2. Fuel element with isolated arrangement of fuel

Another fuel element design that meets the 'Rock-like Fuel' requirement more completely is a fuel element that has an isolated arrangement of the fuel. The main distinction and advantage of such a fuel element stems from the fact that PuO_2 is arranged in fuel minielements that are placed inside a fuel element. The space between the fuel minielements and the fuel cladding is filled with an Al alloy matrix [1,3,4]. Fig. 4 schematically presents a fuel element inside which an accommodator might be also placed to accommodate fuel swelling [1].

Fuel minielements have the following functions:

1. to prevent fuel from interaction with the matrix as well as providing protection against corrosion in leakers;
2. as a barrier against fission product releases;

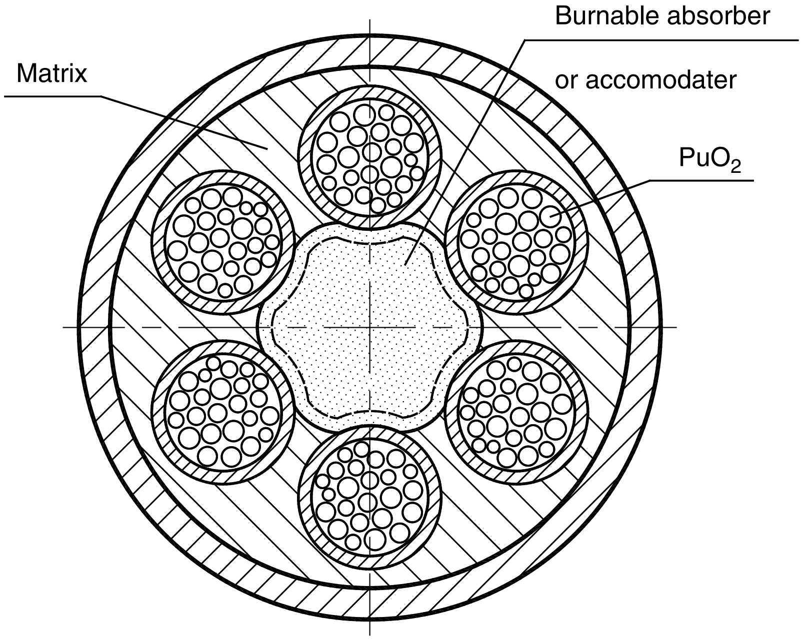

Fig. 4. Cross section of fuel element – plutonium burner having fuel minielements [1].

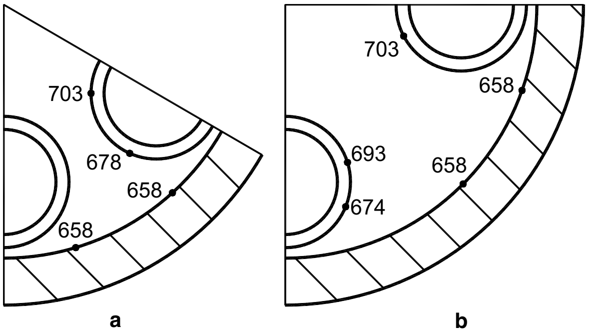

Fig. 5. Distribution temperature (K) in fragment of fuel elements with 6 (a) and 4 (b) fuel minielements respectively, 2.0 × 0.2 mm in diameter at linear heat generation rate of 450 W cm^{-1}.

3. to accommodate fuel swelling;
4. to regulate content of Pu material.

An extra advantage of this design arises from the fact that PuO_2 powder may be used as fuel immediately after the PUREX process. This reduces the number of dust producing processes with plutonium. Aside from this, the $(Er,Y,Pu,Zr)O_{2-x}$ solid solution microspheres might be used and are an intermediate product in producing pellets of fuel having a ZrO_2 base inert matrix.

Fig. 5 shows the distribution of temperatures in the fuel elements with 4 and 6 fuel minielements (2.0 mm diameter), respectively. The temperature calculations used the heat elementary balance method (control volume finite-elements method for heat transfer). The maximum temperature of PuO_2 in the minifuel centre does not exceed 1173 K. The temperature of the aluminium alloy matrix is not higher than 703 K, which is below the onset temperature of the interaction between the aluminium alloy (silumin) and the Zr cladding of the fuel minielement.

The in-pile tests (up to 20000 h) of fuels of several designs in which the temperature of the Zr-aluminium alloy contact was at the level of 703 K have revealed that the interaction layer did not increase in comparison to the original one.

3. Analysis of inert matrix fuel element behavior under emergency conditions

It has already been pointed out that the proposed designs of the Al alloy matrix fuel elements provide for the reliable operation of fuels under nominal conditions. However, under emergency conditions the fuel component temperature might exceed the melting temperature of the aluminium matrix and this has to be analyzed and investigated.

As the preliminary investigations have shown, the main interaction should take place between the aluminium alloy matrix and the Zr alloy (the fuel element cladding, minielement cladding and accommodator).

The analysis reveals that due to the large and developed surface of zirconium per unit volume of the Al matrix, a self-regulation process takes place under emergency condition. It comes from the fact that when zirconium alloy dissolves in the molten Al alloy, the latter changes its composition such that there is a sharp rise in its melting temperature to 1773 K.

Fig. 6 illustrates the variations in the composition of the aluminium alloy matrix and its melting

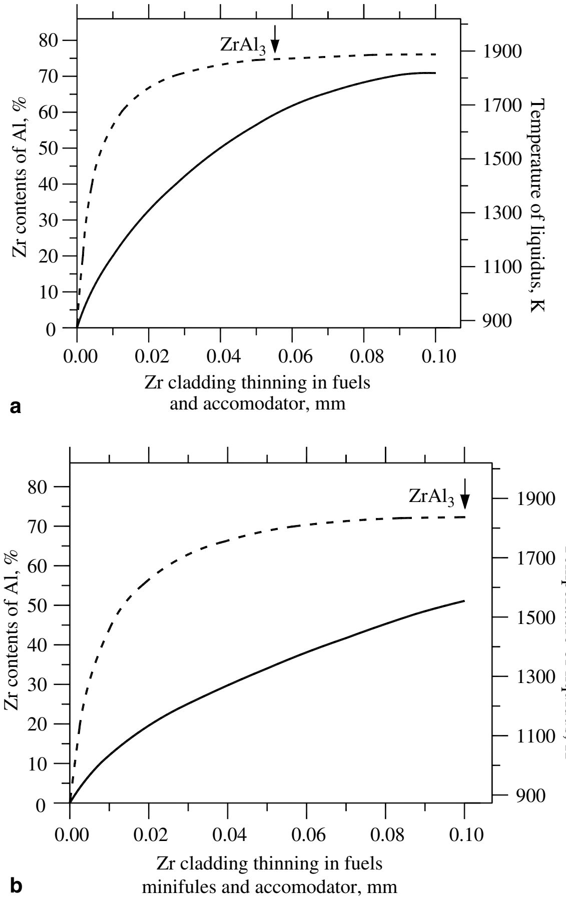

Fig. 6. Variations in aluminium alloy composition and its melting temperature versus quantity of dissolved zirconium, solid line – variation in chemical composition of Al alloy, dashed line – variation in melting temperature: (a) heterogeneously arranged fuel element and (b) fuel element with isolated arrangement of fuel.

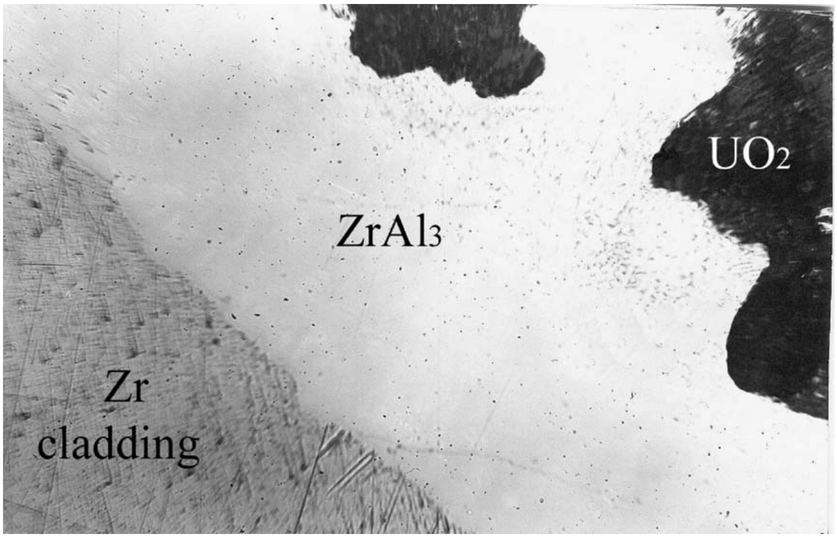

Fig. 7. Microstructure of sample of heterogeneously arranged fuel element with UO_2 in Al alloy matrix after anneal at 1273 K for 30 min.

temperature, depending on the amount of zirconium dissolved in aluminium, as applied to the fuel elements having heterogeneous (Fig. 6(a)) and isolated (Fig. 6b) fuel arrangements. It is evident from Fig. 6 that for the heterogeneous fuel design at a 100 μm thinning of the cladding, the mass content of zirconium in aluminium makes up 72% while in the design with the isolated fuel arrangement it is 51%. If one takes into account the fact that the intermetallic compound $ZrAl_3$ that forms during the interaction contains 55% mass zirconium and its melting temperature is 1853 K, then under emergency conditions a fuel composition of the CERCER type is forming in which the aluminium phase is completely unavailable. This has been corroborated by the preliminary tests of fuel element simulators at 1273 K for 30 min. The fuels remained leak-tight. The fuel element volumes did not essentially change. The microstructure of a sample of the fuel simulator is shown in Fig. 7.

4. In-pile tests of UO_2 fuel element simulators

Fuel element analogues with fuel minielements (isolated arrangement of fuel) were tested in-pile under conditions close to those of VVER-1000. The design of the fuels differed a little from that being considered here, since the claddings of the fuels and fuel minielements were fabricated from stainless steel and UO_2 was used in place of the

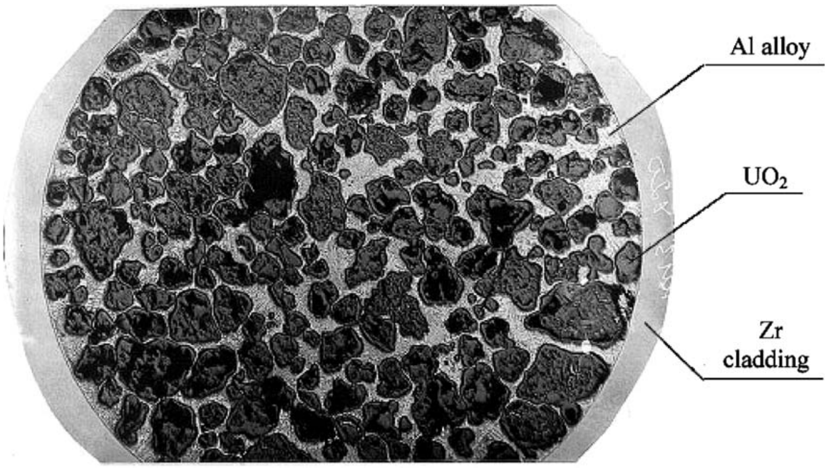

Fig. 8. Microstructure of UO_2 fuel element sample that is under MIR reactor test [2,6].

PuO_2 powder. The fuel element was cross-shaped [3]. The local maximum burn-up was 100 MW d kg^{-1} directly adjacent to the fuel element cladding as calculated for the standard VVER-1000 fuel rod. This extended burn-up was achieved without cladding failure of the fuel element. This allows a qualitative judgment of the reliability and serviceability of this design type.

Analogues of the heterogeneously arranged fuel elements were tested in-pile tested in the MIR reactor (Dimitrovgrad). Their design was close to that of the VVER-1000 fuel rod. A range of different cladding designs with diameters from 6 to 9 mm and with UO_2 used in stead of PuO_2. The microstructure of one of the fuel elements currently undergoing in-pile testing is illustrated in Fig. 8 [2,6].

The irradiation conditions were as follows:

Maximal heat flow from fuel element surface 1.3 MW m^{-2}
Coolant temperature 563 K
Coolant pressure 12.5 MPa

Currently the fuel elements have reached a burn-up of 88 MW d kg^{-1} as calculated for a standard VVER-1000 fuel element. The fuels with accommodators did not essentially change their diameters. The tests are in progress.

5. Conclusion

An aluminium alloy inert matrix fuel element with either a heterogeneous or an isolated distribution of the fuel features the following advantages:

- low temperatures in the fuel component centre;
- feasibility of high burnup;
- fuel element serviceability under transient conditions;
- environment-friendly process of fuel element fabrication.

Currently work is underway to optimize the design of the IMF elements. After the end of the fuel element prototype tests, the PuO_2 fuel elements are planned to be fabricated and reactor irradiated under VVER-1000 operating conditions.

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