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Dispersion type zirconium matrix fuels fabricated by capillary impregnation method

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Abstract

Several novel dispersion fuel compositions with a high uranium content fuel (U9Mo, U5Zr5Nb, U_3Si) and a zirconium alloy matrix with low melting point (1063–1133 K) have been developed at A.A. Bochvar Institute using a capillary impregnation fabrication method. The capillary impregnation method introduces fuel granules and granules of a zirconium alloy into a fuel element followed by a short-term anneal at a temperature above the melting temperature of alloy. The alloy melts down and under capillary forces moves into the joints between the fuel element components to form metallurgical bonds. The volume ratios between the components are: 55–65% fuel, 10–20% matrix, and 15–30% pores. Fuel elements produced by capillary impregnation method have a high uranium content (9–10 g cm^{-3}) and a high thermal conductivity (18–22 W m^{-1} K^{-1}), which, when used as PWR or BWR fuels allow the fuel temperature to be lowered to 723–773 K. They also feature porosity to accommodate swelling. The metallurgical fuel–cladding bond makes the fuel elements serviceable in power transients. The primary advantages for PWR, BWR and CANDU use of these fuels elements, would be the high uranium content, low fuel temperature and serviceability under transient conditions. Consideration is given to their applicability in Floating Nuclear Power Plants (FNPP) as well as for the feasibility of burning civil and weapon grade plutonium.

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1. Introduction

There are several approaches to improve fuels for PWR and BWR reactors including the increase in the uranium content of the fuel, lower temperatures in the fuel element centre, the extension of the burnup and the serviceability of fuel elements operating under transient conditions. High uranium content fuel (U9Mo, U5Nb5Zr, U_3Si alloys or intermetallic) and Zr alloys that meet to a larger extent the above requirements matrices are currently under development at the A.A. Bochvar Institute [1–3]. They are produced by the impregnation with a molten alloy within the inner space of a fuel element with fuel granules arranged inside it [1,2,4]. For this process several classes of novel zirconium matrix alloys with the melting temperatures 1063–1133 K have been designed [2–4].

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The uranium content in such fuel compositions is 8.5–9.5 g cm^{-3}. The fuel compositions have a high thermal conductivity (22–26 W m^{-1} K^{-1}), are compatible with high uranium content fuel up to 1023 K and are serviceable under transient conditions due to the metallurgical bonding to the cladding [2–4]. Preliminary in-pile tests of these fuel compositions demonstrated their serviceability for the PWR and BWR reactors [6]. The further perfection of this type of dispersion fuel is in progress, both to improve the fuel design (controllable porosity to accommodate swelling) and to modify the fabrication process. Using the capillary properties of the zirconium matrix alloys, a method of capillary impregnation is being developed [3–5]. It consists in co-introducing zirconium matrix alloy and fuel granules into a fuel element. Upon a subsequent anneal of the matrix alloy above its melting temperature it moves into the joints between the fuel element components to form metallurgical bonds.

This paper addresses the properties of the fuel fabricated by the capillary impregnation method and the feasible ways of the application of these fuels.

2. Method of capillary impregnation

The impregnation method has been worked out by taking into account the capillary properties of the melted zirconium alloys. It comprises two stages and is schematically presented in Fig. 1 [2–5].

- *Vibroloading* of mixed fuel and matrix granules into cladding (Fig. 1(a) and (b)). Coarse granules of fuel and fine granules of a zirconium alloy matrix (zirconium brazing alloy) are used. Fuel and matrix granules might be loaded into the fuel element cladding either simultaneously or consecutively, viz., first coarse fuel granules and after that between them fine matrix granules (infiltration route, Fig. 1(b)). The volume ratios of the fuel components are:

The fuel forms a skeleton	55–65%
The matrix within the interstices of the skeleton	10–22%
The pores	16–30%

  The ratios between the diameters of the fuel and matrix granules range from 3:1 to 10:1.
- *Vacuum* anneal above the melting temperature of the matrix alloy (*capillary impregnation* Fig. 1((c) and (d)). While melting down the zirconium matrix alloy fills the joints between fuel particles and the joints between fuel and cladding to form the so-called bridges under the action of capillary forces, which increases the thermal conductivity of the fuel composite.

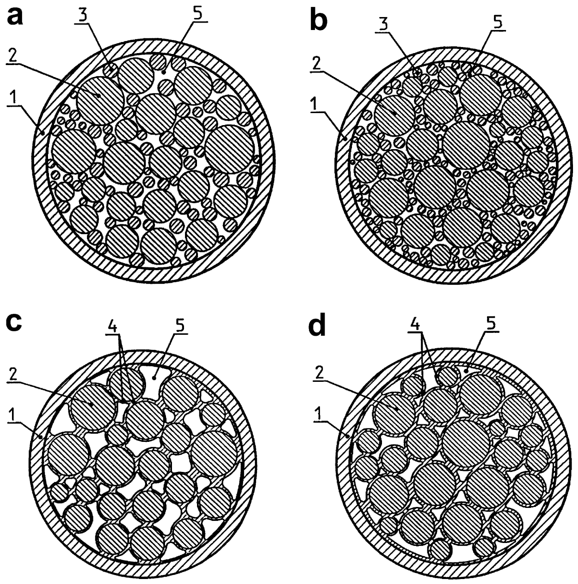

Fig. 1. Schematic cross-section representation of fuel element fabricated by capillary impregnation method [2–4]; (a) and (b) as vibroloaded; (c) and (d) as capillary impregnated, (1) fuel element cladding, (2) fuel granules, (3) Zr alloy matrix granules, (4) 'bridges' and matrix alloy coats on fuel granules after heating and cooling, (5) pores. Conditions: Cladding diameter 5.8 mm, thickness 0.5 mm, fuel granules 0.6–1.2 mm, matrix granules 0.15–0.5 mm in (a) and 0.06–0.2 mm in (b).

Although it is easier to use fuel in the form of granules the capillary impregnation method might also be used for fuel particles produced by grinding (UO_2 and U_3Si in Fig. 2).

Fig. 3 illustrates the appearance of the fuel composition (without cladding) and the macrostructure of the fuel. Fig. 4(a)–(d) show micrographs of a fuel element fracture and cross section as well as the fuel microstructure.

Figs. 3 and 4 clearly reveal the occurrence of metallurgical bonding via the alloy between individual fuel granules and between the fuel granules and the cladding. The fuel granules at the inner surface of the cladding are coated with a zirconium matrix alloy layer 3–10 μm thick.

The process flow sheet used to fabricate fuel elements for BWR, PWR, CANDU and FNPP is presented in Fig. 5.