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U–Mo alloy fuel for TRU-burning advanced fast reactors ☆

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ABSTRACT

The use of U–Mo instead of U–Zr as the base alloy fuel for transuranics (TRU)-burning advanced fast reactors is assessed in several aspects. While the replacement of Zr with Mo involves no significant differences in terms of neutron physics (core design), U–TRU–Mo does provide advantages. U–TRU–Mo has lower TRU migration to cladding because of its simpler phase diagram, is advantageous in safety margin due to its higher thermal conductivity and better fuel-cladding-chemical-interaction resistance. High fuel swelling data, obtained at low temperatures, available in the literature are not directly applicable to the TRU-burning advanced fast reactors. The potential high swelling can also be controlled when strong cladding and degassing are used as are adopted for typical U–Pu–Zr fuel. Results and detailed analysis are presented in this paper, indicating the benefits of U–Mo base alloy fuel in TRU-burning advanced fast reactors.

1. Introduction

One of the candidate base fuels for transuranics (TRU)-burning fast reactors is U–Zr alloy, where TRU refers to transuranic elements such as Np, Pu, Am, and Cm. U–Zr alloy fuel is characteristic of constituent redistribution by which radial zones of different composition and microstructure are formed in the fuel, and as a result fuel performance is affected. The addition of TRU in the fuel enhances constituent redistribution, which also further activates TRU migration to the fuel surface. The significance of TRU migration to the fuel surface is that these elements are more reactive with cladding than uranium, causing a number of unfavorable performance issues such as reduction in cladding melting temperature, cladding wall thinning, and fuel eutectic formation. In addition, the TRU reactions with cladding represent a complication to used fuel reprocessing.

Constituent redistribution in a U–Zr or U–Pu–Zr alloy is a result of the associated poly-phase fields in the irradiation temperature distribution [1,2]. The solubility of the solute atoms in the solvent changes over the phase fields, so more precipitation occurs in a phase field than the adjoining phase field. This results in a different solute concentration in the continuous phase, and as a result, diffusion occurs. Meanwhile, the fuel's thermal gradient produces a concentration gradient of the solvent in the continuous phase, which also yields diffusion. The heat flux associated with the thermal gradient is balanced by the movement of atoms, which is quantitatively measured by the phenomenological property of heat of transport.

Fig. 1 shows how constituent migration and zone formation in the fuel affect the TRU migration. The Am profile is nearly flat, but more large spikes appear near the fuel surface, a hint of migration to the surface. The large spikes indicate that Am is included in precipitates. The large pores typically contained in this region may facilitate precipitation of Am and in general its migration. While fine pores are formed in the higher temperature regions near the fuel center, large pores at the fuel periphery are formed through a different swelling mechanism associated with the phase in that outer region. The Np profile shows no obvious sign of migration, which is similar to behavior of Pu while other fuel constituents migrate.

Contrary to U–Zr alloy fuel, U–Mo alloy fuel should have much less constituent migration in typical fuel operating conditions. Consequently, if U–Mo is to be used as a base fuel form, less TRU migration is also expected than in the U–Zr base fuel. The use of U–Mo alloy fuel also offers several other advantages relative to U–Zr such as better thermal properties, higher γ-phase stabilizing power, and better resistance to fuel-cladding chemical interaction, which are discussed in detail in the following section. In addition, U–Mo alloy has a slight advantage over U–Zr from the reprocessing point of view.

This paper presents the results of an assessment that explores the potential of using U–Mo as an alternative fuel to U–Zr in TRU-burning advanced fast reactors. In this paper, U–TRU–Zr and U–Pu–Zr are in some cases used interchangeably on the assumption that the minor actinide concentrations are relatively lower than that of Pu in typical TRU burning reactors.

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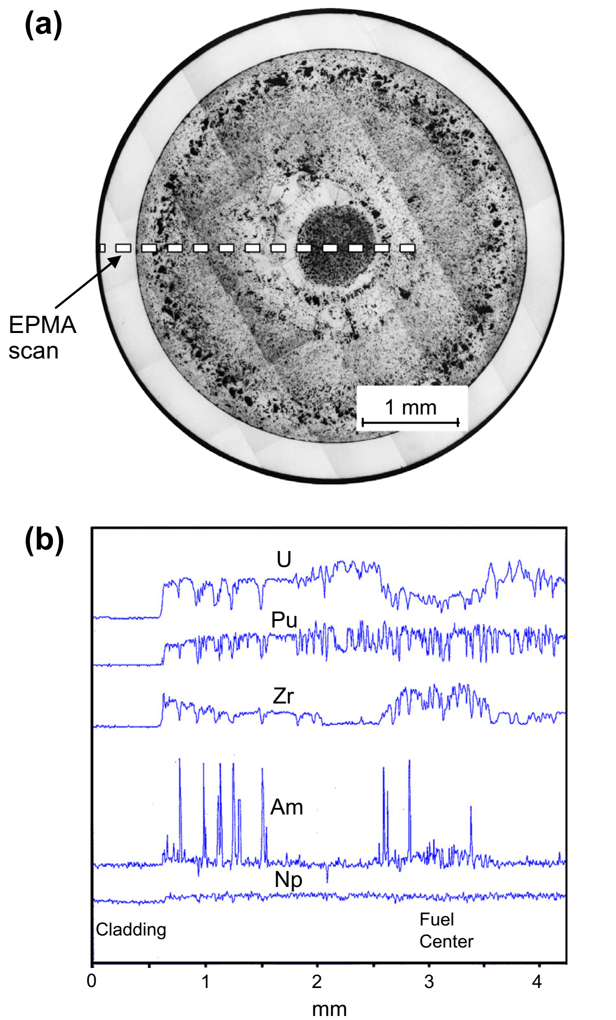

Fig. 1. Concentration profiles of elements along the electron probe microanalysis (EPMA) scan (broken line in (a)) in G582 from X501 test irradiated to ~6 at% burnup. The as-fabricated fuel composition was U–20.2Pu–9.1Zr–2.1Am–1.3Np (wt%).

2. Comparison between U–Mo and U–Zr

2.1. Phase diagram

U–19 wt.%Pu–10 wt.%Zr (U–19Pu–10Zr), which had been tested extensively in the EBR-II, extends over three phase fields in the typical metallic fuel temperature range in fast reactors, 550–750 °C. Two of the phase fields are two-phase mixtures, and one comprises three phases (Fig. 2). The single phase (γ-U) exists only at high temperatures. For typical operating temperatures, the number of phase boundaries that the fuel faces is three.

U–Pu–Mo is composed of a single phase, γ-phase, in the typical range of fuel operation temperatures (see Fig. 3). Within this phase, constituent migration is only driven by the thermal gradient, which is smaller than the chemical-potential-gradient driven migration. In this case, much less constituent migration is expected, which is a major advantage of U–Mo alloy fuel in TRU-burning systems. By inference, migration of TRU across the fuel is also expected to be small.

2.2. Thermal properties

The thermal properties of U–19Pu–10Zr and U–19Pu–10Mo are mostly similar. U–Mo base alloy has better thermal properties: U–19Pu–10Mo has a higher thermal conductivity and a lower thermal expansion. However, it has a slightly lower melting point. Both alloys have similar heat capacities. A comparison of the thermal properties between these two alloys is given in Table 1.

From the safety standpoint, the higher thermal conductivity of U–Pu–Mo is advantageous because it improves the reactor response to off-normal reactor conditions by providing faster heat removal. Lower fuel temperatures associated with higher fuel thermal conductivity might compensate for the reduction in melting point.

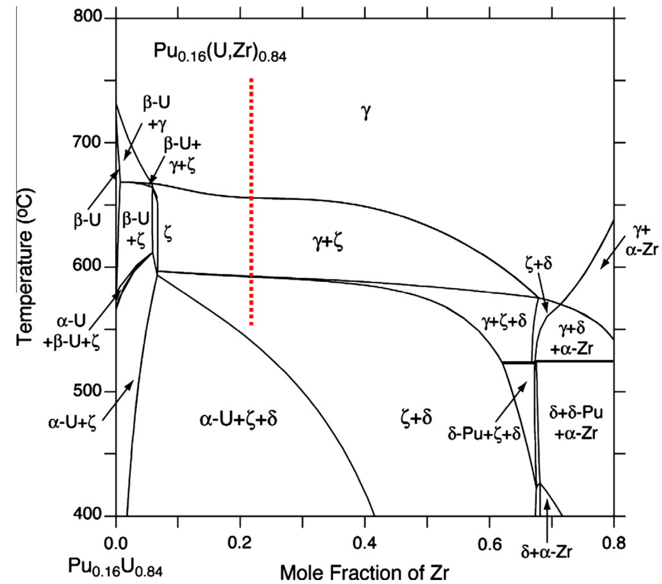

Fig. 2. U–19Pu–10Zr pseudo-binary phase diagram [1]. The vertical broken line indicates the phase field of U–19Pu–10Mo in typical reactor operations.

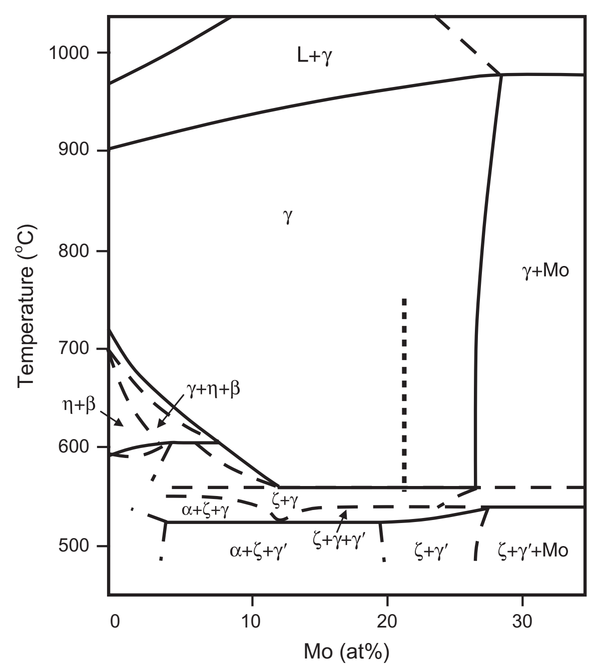

Fig. 3. Isopleth of U/Pu = 3. The vertical broken line indicates the phase of U–19Pu–10Mo in typical reactor operations [3].