Progress in Nuclear Energy 72 (2014) 119–125

Contents lists available at ScienceDirect

Progress in Nuclear Energy

journal homepage: www.elsevier.com/locate/pnucene

Peculiarities of fuel cycle with advanced composite fuel for thermal reactors

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ARTICLE INFO

Article history:
Received 2 October 2013
Accepted 7 October 2013

PACS:
28.41.Bm
81.05.Zx
81.05.Rm
81.30.Bx

Keywords:
Composite fuel
Fuel cycle
Zr matrix

ABSTRACT

The use of dispersion type fuel elements, with high uranium content such as, U–Mo, U–Nb–Zr, U_3Si, with a Zr alloy matrix (“advanced metmet”), is considered instead of a UO_2 base type fuel for thermal reactors. Such fuels were fabricated and post-preparation analysed. In addition, composite, (U,Th)–PuO_2 fuels were considered based on depleted uranium (or uranium, thorium alloy) and dioxide plutonium powder as the dispersion phases (a “cermet” analogue of heterogeneous MOX). Such fuel elements could be used in thermal reactors as low temperature fuels.

Subsequently, a novel reprocessing strategy for composite fuel is proposed. This would allow the separation of ***uranium*** from burnt ***plutonium*** as well as the newly generated fissile plutonium from the burnt portion without chemical processes, with repeated use in CANDU/RBMK reactors. This would simplify the closure of the nuclear fuel cycle. By sequential use of the composite fuel, the generated Pu in spent fuel could be recycled in a more pragmatic way, reducing drastically the waste flow.

1. Introduction

Generation II Light Water Reactors (LWRs) are the dominant world commercial nuclear power plant. Currently, 90% of the installed reactors worldwide operate on a once-through nuclear fuel cycle, utilising uranium dioxide fuel (Legergerber, 2006; United States Department of Energy strategic plan, DOE/CF-0067, May 2011). While closing the fuel cycle is proven to be more sustainable and has been the general aim for several decades, progress towards that goal has been slow (Ledergerber et al., 2010). To optimize the fuel cycle MOX fuel has been considered for thermal reactors (Arslan et al., 2009a,b), although some limitations exist. The two most relevant are:

1. the Pu isotopic vector degrades. The Pu fissile content drastically decreases from cycle to cycle as shown in Table 1. Using MOX for one cycle can reduce by 18% the need to enriched uranium (Arslan et al., 2009b; Savchenko et al., 2007, 2010a; Degueldre and Paratte, 1999). MOX fuel can be used in one fuel cycle, the second cycle is more demanding (requiring extra driving).
2. The insufficient fissile uranium density limits burn-up and the conversion ratio; this requires enrichment of more than 5% ^{235}U (Feng et al., 2011).

We suggest replacing the container design fuel rod, for which possibilities are practically exhausted, by dispersion type fuel elements (Savchenko et al., 2006, 2010b). The dispersion type fuel is known to have a high irradiation resistance and better thermal conductivity, hence low operating temperatures and high burn-ups can be achieved (Ledergerber et al., 2010; Bonnet et al., 2001; McKeown et al., 2013).

The other disadvantages of pelletized uranium-oxide fuel are the high operating central temperature and the low serviceability under transients. All these problems encourage us search for other types of fuel taking into consideration novel fuel developments as well as fuel designs.

2. Experimental

Structurally the proposed dispersion fuel meat consists of uniformly distributed higher density fuel granules of U–Mo, U–Nb–Zr or U_3Si alloys that are metallurgically bonded to each other and to the fuel cladding made of specially developed Zr-based matrix alloys (Savchenko et al., 2006; McKeown et al., 2013) with 790–860 °C melting temperatures. The fuel material maintains a

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http://dx.doi.org/10.1016/j.pnucene.2013.10.007

Table 1
Fuel fissile isotope (^{239}Pu + ^{241}Pu) fraction change over the fuel cycles (Arslan et al., 2009a,b).

	Initial	First cycle	Second cycle
UOX	0.0%	68%	
Initial MOX after reprocessing	68%	55%	45%
Advanced metmet	–	75%	
Cermet U/PuO$_2$	0%/68%	75%/42%	82%/53%

porosity ranging from 14 to 22% in order to accommodate fuel swelling (Fig. 1).

This type fuel element can be produced by the capillary impregnation method (Savchenko et al., 2007, 2010b, 2012). Fuel and matrix granules are loaded into the fuel cladding and then heated to a temperature 500 °C higher than the melting temperature of the matrix alloy. The matrix melts and under capillary forces moves into gaps between the fuel components to form metallurgical bonds, which promote a high thermal conductivity for this fuel form. The properties of this composite fuel are presented in Table 2 and microstructures in Fig. 1 and 2.

3. Results

The use of advanced composite fuels has been studied at the conceptual level. Results from implementing such composite fuels are presented below.

3.1. Advantages of uranium composite (metmet) fuel for use in thermal reactors

The proposed metmet fuels offer various advantages when used in VVER type reactors. The uranium content (9.5–12.9 g cm^{-3}) in the fuel element is 25–50% higher than the uranium content of standard PWR, BWR and VVER-1000 fuel rods. This allows a reduction in the uranium enrichment or an increase in burn-up. It also improves the neutronics characteristics and reactor safety (Feng et al., 2011; Savchenko et al., 2010b, 2012). The use of the proposed novel composite fuel increases the breeding ratio. The higher density fuel reduces the hydrogen-to-“heavy metal” ratio in the light water reactor which results in a relatively harder spectrum for which breeding is more effective (Feng et al., 2011). This is illustrated in Fig. 3 where the dependence of reactivity versus burn-up for a PWR assembly using standard pelletized oxide fuel is compared with this composite fuel (Takada and Shimazu, 2010). It is clearly seen that:

1. Composite fuel refers to the fuel of higher density and higher reactivity.
2. Low temperature of the fuel, which satisfies the requirements of colder fuel.
3. The porosity in the fuel microstructure will allow the accommodation of swelling up to the burn-up of 1.0 g-*fiss* cm^{-3}, which in terms of the standard VVER-1000 fuel rod corresponds to 120 MW d kg^{-1}.
4. Metallurgical bond between fuel and cladding makes fuel elements serviceable under severe transients that leads to optimization of Nuclear Plant operation conditions and improvements in their operation reliability and safety.

These advantages of the novel generation fuel might result in increased economic efficiency and a corresponding decrease in the cost of electric power. When used in thermal reactors the novel fuel will have much better neutronics characteristics that will eventually reduce the costs of energy production. So, the advantages of such a fuel form are: high irradiation resistance, high thermal conductivity, pore region for swelling, metallurgical bond between fuel and cladding.

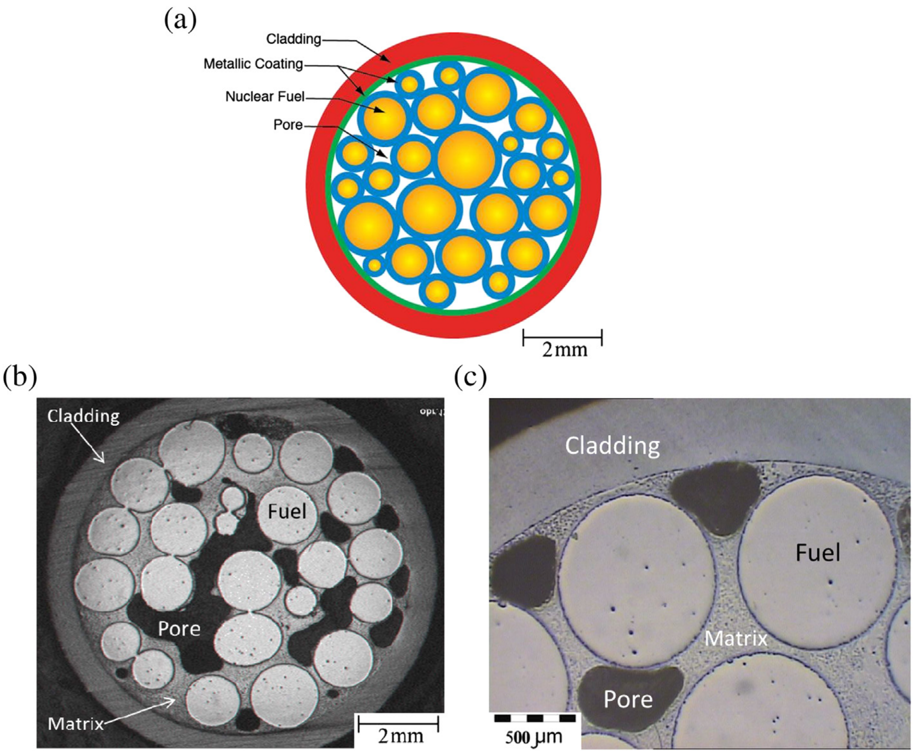

Fig. 1. Schematic presentation of composite fuel (a); micro and macrostructures of composite fuel (b) U–Mo + Zr matrix alloy; (c) U–Zr–Nb + Zr matrix alloy. Conditions: $t = 850$ °C and $\tau = 60$ s, fuel column length: 1200 mm.