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Characterization of metallic fuel for minor actinides transmutation in fast reactor

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ABSTRACT

The METAPHIX programme is a collaboration between the Central Research Institute of Electric Power Industry (CRIEPI, Japan) and the Joint Research Centre - Institute for Transuranium Elements (JRC-ITU) of the European Commission dedicated to investigate the safety and effectiveness of a closed nuclear fuel cycle based on Minor Actinides (MA: Np, Am, Cm) separation from spent fuel, incorporation in metal alloy fuel and transmutation in fast reactor.

Nine Na-bonded experimental pins of metal alloy fuel were prepared at ITU and irradiated at the Phenix reactor (CEA, France) achieving 2.5 at.%, 7 at.% and 10 at.% burn-up. Four metal alloy compositions were irradiated: U-Pu-Zr used as fuel reference, U-Pu-Zr + 5 wt.% MA, U-Pu-Zr + 2 wt.% MA + 2 wt.% Rare Earths (RE: Nd, Y, Ce, Gd), and +5 wt.% MA + 5 wt.% RE, respectively. RE reproduce the expected output of a pyrometallurgical reprocessing facility.

Post Irradiation Examination is performed using several techniques, covering properties ranging from the macroscopic morphology of the fuel matrix to the microanalysis of phases and elemental redistribution/segregation. The irradiated fuel is characterized by many phases occurring along the fuel radius. The fuel underwent large redistribution of the fuel constituents (U, Pu, Zr) and many secondary phases are present with a variety of compositions. The distribution of phases in the irradiated fuel containing minor actinides and rare earths is essentially similar to that observed in the basic ternary alloy fuel.

1. Introduction

Advanced nuclear reactors and closed nuclear fuel cycles are important options to achieve sustainable nuclear energy supplies to satisfy future demands while reducing the long-term radiotoxicity of high level waste (GIF, 2002; GNEP, 2007; Funasaka and Itho, 2007; Haas et al., 2009; JRC-EASAC, 2014). Spent fuel reprocessing and the subsequent recycling of U and Pu as fuel and transmutation of Minor Actinides (MA) Np, Am, Cm in fast reactors are necessary steps to achieve this goal (Yokoo et al., 1996; Inoue et al., 1991; Ohta et al., 2005).

Fast reactors brings different advantages compare to thermal reactors in term of transmutation of actinides. Hereafter the main reasons are reported from OECD/NEA, (2012):

- A favourable neutron balance, which allows to introduce MA of any type and in significant amounts, without perturbing the reference performances of the corresponding core without MA.
- A neutron spectrum which allows fissions to dominate captures for all TRUs. This feature allows limiting with respect to thermal reactors the build-up of higher mass nuclei, e.g. the build-up of 252 Cf during TRU multi-recycle.
- The flexibility to burn or breed fuel, or to be iso-generator (a system that has a zero net production of TRU constituents in the fuel).
- The possibility to benefit from the favourable characteristics indicated above, whatever the Pu vector, the type of fuel (oxide, metal, nitride, carbide) and the type of coolant (sodium, heavy liquid metal, gas).

The METAPHIX programme is a collaboration between the Central Research Institute of Electric Power Industry (CRIEPI, Japan) and the Joint Research Centre-Institute for Transuranium Elements

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Table 1
Average composition (wt.%) of the fuel alloys as fabricated (impurities content < 0.3 wt.%).

El	U-Pu-Zr	U-Pu-Zr 2MA-2RE	U-Pu-Zr 5MA	U-Pu-Zr 5MA-5RE
U	71.00	66.85	66.30	63.50
Pu	18.93	19.80	19.35	19.75
Zr	10.19	9.46	8.97	8.19
MA	0.03	2.08	4.74	4.78
Np	0.03	1.23	2.97	3.04
Am		0.67	1.45	1.52
Cm		0.18	0.32	0.31
RE	–	1.73	–	3.40
Y		0.12		0.31
Ce		0.20		0.45
Nd		1.25		2.30
Gd		0.16		0.32

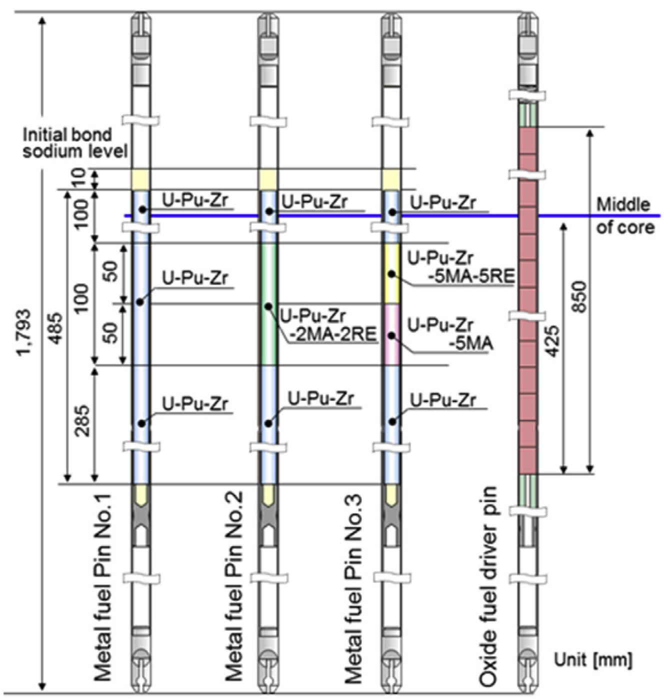

Fig. 1. Schematic view of the 3 different fuel pins irradiated in PHENIX reactor. The top of the fuel pin is approximately at the middle of the PHENIX core.

(JRC-ITU) of the European Commission with the support of the Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA, France). It is dedicated to the study of the safety and effectiveness of a closed nuclear fuel cycle based on MA separation and irradiation in metallic fuel using fast reactor. In this context, three assemblies containing nine Na-bonded experimental pins of metal alloy fuel prepared at ITU (Kurata et al., 1999) were loaded in the Phénix reactor in 2003 and irradiated at three different burnups, 2.5 at.% (METAPHIX-1), ~7 at.% (METAPHIX-2) and ~10 at.% (METAPHIX-3).

Extensive metal fuel irradiation tests were conducted in the USA in the Integral Fast Reactor (IFR) program (Carmack et al., 2009; Chang, 1989; Till and Chang, 1991) both on U-10 wt.%Zr binary alloy fuel and on U-Pu-10 wt.%Zr ternary fuel. Of these test pins, the highest burnup achieved for the U-19 wt.%Pu-10 wt.%Zr fuel without pin breach was more than 19 at.% (Crawford et al., 2007).

The first irradiation of MA-bearing metal fuel was conducted in the X501 test assembly in EBR-II up to 7.6 at.% burnup (Meyer et al., 2009; Kim et al., 2009). Preliminary post irradiation examinations revealed that the macroscopic behavior in pile of MA-bearing metallic fuel is similar to the basic alloy metallic fuel.

The main objective of the PIE studies on the irradiated METAPHIX fuel is to study the safety of this concept during irradiation. The presence, distribution and behavior of the various phases in the fuel is a key aspect of these investigations. The possible effects investigated include abnormal behavior of secondary phases (e.g. in terms of thermal stability, fuel-cladding chemical interaction, etc.). The present paper describes some of the recent findings in this campaign of studies. In particular, it focuses onto the distribution of phases as evidenced by the PIE. This examination is part of a broader effort aimed at confirming the safety of the fuel during irradiation and the achievement of effective transmutation rates.

2. Materials and methods

Post Irradiation Examination (PIE) is performed at JRC-ITU. Nondestructive examinations and fission gas analysis showed that MA-bearing fuel pin behavior during irradiation was in line with that of the base alloy (Papaioannou et al., 2012; Ohta et al., 2011, Rondinella et al., 2010). Destructive examinations, including optical microscopy, scanning electron microscopy (SEM) and electron probe micro analysis (EPMA) are ongoing for METAPHIX-1 and

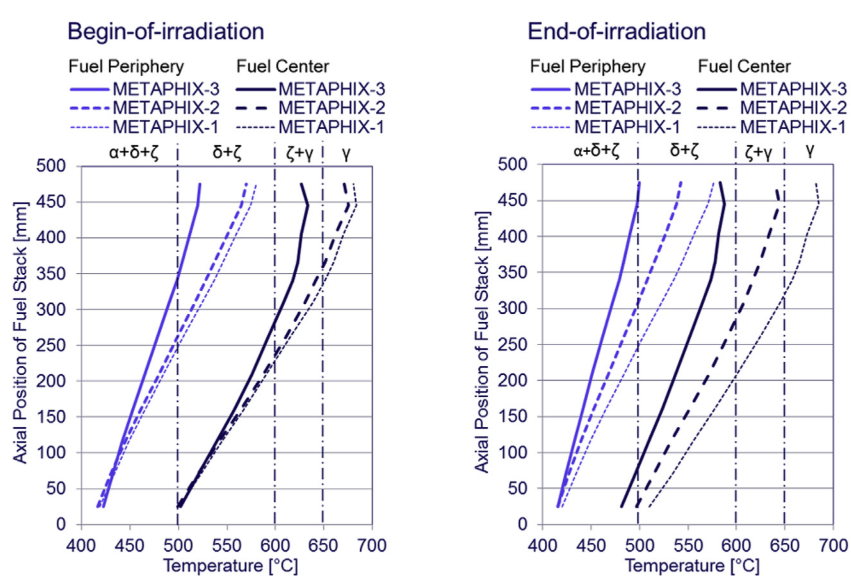

Fig. 2. Temperature axial distribution in the metallic fuel alloys at the beginning of irradiation and end of irradiation for the 3 different burn-ups and for fuel centre and periphery (Ohta et al., 2015a,b).