Journal of Nuclear Materials 512 (2018) 214–226

Contents lists available at ScienceDirect

Journal of Nuclear Materials

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

Outcomes of the PELGRIMM project on Am-bearing fuel in pelletized and spherepac forms

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HIGHLIGHTS

- PELGRIMM: a European Project carried out from 2012 to 2017 between 12 partners.
- New step in development of Minor Actinide-bearing fuels for transmutation.
- Spherepacked and pelletized fuels for homogeneous and heterogeneous recycling modes.
- R&D on fabrication, behaviour under irradiation, modelling, simulation, neutronics.

ARTICLE INFO

Article history:
Received 28 May 2018
Received in revised form
28 September 2018
Accepted 9 October 2018
Available online 11 October 2018

Keywords:
PELGRIMM
Transmutation
Americium
Homogeneous recycling
Heterogeneous recycling
Spherepac
Fabrication
Fuel behaviour under irradiation
Experiments
Simulation
MARIOS
SPHERE
MARINE
Core design
Safety coefficients
Accidental situations

ABSTRACT

The PELGRIMM project was a FP7-European project (funded by the European Commission, Grant Agreement No. 295664), carried out from 2012 to 2017. It was devoted to the investigation of spherepacked and pelletized fuel forms for Minor Actinide transmutation in homogeneous and heterogeneous recycling modes. PELGRIMM aimed at constituting a new step in the long term process in the assessment of Minor Actinide-bearing fuel, initiated within the European projects ACSEPT, F-BRIDGE, CP-ESFR and FAIRFUELS. The present paper provides an overview of the main technical outcomes gained within PELGRIMM. The developments of alternative processes in order to simplify synthesis routes and to limit secondary waste streams for Minor Actinide-bearing fuel preparation are detailed. The first results of behaviour under irradiation of spherepacked and pelletized fuel forms are provided from Post-Irradiation Examinations on (U,Pu,Am)O_2 and (U,Am)O_2 fuels respectively irradiated during SPHERE and MARIOS experiments, along with the description of the latest irradiation experiment, MARINE. In parallel, the capabilities of existing models and calculation codes have been improved to describe Minor Actinide-bearing fuel behaviour under irradiation in a more reliable way, and their predictive results have been compared to available Post-Irradiation Examinations. Finally, to start linking fuel behaviour with core neutronic problematics, a preliminary design of a Sodium-cooled Fast Reactor core loaded with spherepacked (U,Pu,Am)O_2 fuels was built and correlated preliminary safety assessments have been performed.

1. Introduction

The PELGRIMM project [1] stands for PELlets versus GRanulates: Irradiation, Manufacturing and Modelling. It was a FP7-European

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https://doi.org/10.1016/j.jnucmat.2018.10.016
0022-3115/

project (7th Framework Program for funding of European research projects started between 2007 and 2013, funded by the European Commission, Grant Agreement No. 295664) carried out from 2012 to 2017 which was devoted to the investigation of spherepacked and pelletized fuel forms for Minor Actinide (MA) transmutation. PELGRIMM aimed at constituting a new step in the long term process of the MA-bearing fuel testing rationale, initiated within the European projects ACSEPT (2008–2012), F-BRIDGE (2008–2012), CP-ESFR (2008–2013) and FAIRFUELS (2009–2015) [2–5]. In addition, the PELGRIMM and ASGARD [6] projects, implemented in parallel within FP-7, were able to bridge fuel developments to back-end of the fuel cycle.

Within PELGRIMM, a total of 12 partners from research laboratories, universities and industries, collaborated to share and leverage their skills, progress and achievements, covering a comprehensive set of investigations. The present paper intends to make an overview of the main technical outcomes gained within PELGRIMM, which has addressed all the key R&D items relative to fuel developments for testing, for both homogeneous and heterogeneous recycling modes and for both spherepac and pellet fuels: fuel synthesis developments, analytical (separate-effect) and semi-integral irradiations of MA-bearing fuels and their Post Irradiation Examinations (PIE), irradiation behaviour modelling and predictive code developments, preliminary safety performance assessment.

In section 2, the project context, the motivation and the technical items under consideration are firstly summarized: a brief state of the art is presented, related to the developments on MA-recycling in homogeneous and heterogeneous mode at the beginning of the PELGRIMM project; the main developments on spherepac fuel are also summarized as they highlight this type of fuel as an attractive concept for MA-bearing fuels. The extension of MA-bearing fuel preparation processes to alternative routes in order to limit secondary waste streams and simplify the steps is described in section 3. Section 4 presents the results of the PIE on SPHERE and MARIOS pins and fuels, which provide respectively a comparison between spherepacked and pelletized $(U,Pu,Am)O_2$ fuel performances and the very first results on helium behaviour in $(U,Am)O_2$ fuels. It also addresses the next step in the $(U,Am)O_2$ fuel safety testing rationale with a new irradiation test, MARINE, implemented in the High Flux Reactor (HFR). The progresses in the capabilities of existing models and calculation codes to describe the MA-bearing fuel behaviour under irradiation are presented in section 5. Finally, section 6 draws the main conclusions regarding a preliminary design of a Sodium-cooled Fast Reactor (SFR) core loaded with spherepacked $(U,Pu,Am)O_2$ fuels and the correlated preliminary safety assessment.

2. Summary description of project context and objectives

2.1. State of the art summary on MA-bearing oxide fuels developments for Gen-IV systems before PELGRIMM

High activity wastes are currently vitrified and planned to be stored in deep geological repositories. In order to reduce the radiotoxic inventory of vitrified wastes and the footprint of deep storage [7], research concerning solutions that could separate the most radiotoxic and long-lived elements from spent fuel and transmute them into non-radioactive or short-lived ones in nuclear reactors is being carried out on an international level. Transmutation being only reasonably applicable for Minor Actinides (MAs), (chiefly americium, neptunium, and curium) and the best transmutation performance being obtained in fast neutron reactors, MA incorporation into the fuel has become a prerequisite for Generation IV reactors to bring benefits in the disposal requirements by reducing the MA content in the high activity wastes [8–10]. Based on historical experience and knowledge, oxide fuels have emerged in Europe as the solution to meet the Generation IV assigned performances and reliability goals. Two main MA-recycling options have been under consideration within PELGRIMM:

- the homogeneous recycling mode, or Minor Actinide Driver Fuel (MADF) concept, where MAs are diluted in $(U,Pu)O_2$ standard driver fuel at a low enough content (<3%) to limit the MA impact on the performance of the fuel and on the core safety as well as on the fuel cycle facilities, as far as possible;
- the heterogeneous recycling mode of UO_2 fuel located in radial core blankets, or Minor Actinide Bearing Blanket (MABB) concept, where MAs are concentrated in UO_2 based fuels at a content of ~10% into the radial breeder blankets of Sodium-cooled Fast Reactors (SFRs) core in order to limit the neutron impact on the core physics; in this concept, the use of the UO_2 matrix as a support for MAs should ease developments as UO_2 behaviour under irradiation as well as UO_2 reprocessing, are well known.

Regarding the first option, national and international R&D programs have been conducted for 25 years [11,12] and many issues have been addressed by previous irradiations such as SUPERFACT [13–16], Am1 [17–19] or US DOE - AFC-2C&2D [20]. For the second option, operation of MABB in the reactor under very specific conditions has raised many questions and experimental data were scarce at the beginning of the PELGRIMM project, with the unique SUPERFACT irradiation [14,15]. A comprehensive R&D program of MABB fuel testing campaign started in 2008, including, as a first stage, two separate-effect irradiation tests: MARIOS, manufactured and irradiated within the FAIRFUELS project, and DIAMINO, implemented within the French national nuclear program [21,22]. Table 1 and Table 2 give an overview of the irradiation tests already done, in progress or in preparation, related to homogeneous and heterogeneous recycling mode, at the beginning of the PELGRIMM project (i.e. in 2011).

One of the main issues still under consideration in both kinds of MA-bearing oxide fuel investigations is the high helium production during (and after) irradiation: this is a well-known specificity of fuel containing MAs since the amount of helium produced is all the more significant as the ^{241}Am content is high. For MADF, the helium release could induce additional fission product release, as helium is expected to be totally released at high temperatures, thus leading to enhanced Fuel Cladding Chemical Interactions (FCCI). For MABB, the high to huge helium production, combined with low temperatures of MABB fuel, could enhance the fuel gaseous swelling and correlated Fuel Cladding Mechanical Interaction (FCMI).

In addition, the impact of introducing MAs in the fuel remains a major concern for fuel plants. The high neutron emission and the high thermal power of americium and especially curium generate significant technological challenges to limit radiation exposure of staff, criticality risks, etc. Fuel preparation must be carried out in shielded cells with remote handling, which means that the processes need to be revised for simplification as well as for implementation of relatively dust-free steps in the prospect of an industrial production [23].

These two issues have led to consider the spherepac technology as an attractive alternative to classical pelletized fuel forms for MA-bearing fuels.

2.2. State of the art summary on spherepacked fuels developments before PELGRIMM

Even though pelletized fuel forms have been preferred so far, the spherepac technology, consisting of filling a pin with dense