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To cite this version:

A. Gallais-During, F. Delage, S. Béjaoui, S. Lemehov, J. Somers, et al.. Outcomes of the PELGRIMM project progress in the development of Am-bearing fuel under pelletized and spherepac forms. Journal of Nuclear Materials, 2018, 512, pp.214-226. 10.1016/j.jnucmat.2018.10.016 . cea-02339767

HAL Id: cea-02339767

https://cea.hal.science/cea-02339767v1

Submitted on 5 Nov 2019

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Accepted Manuscript

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PII: S0022-3115(18)30738-4

DOI: 10.1016/j.jnucmat.2018.10.016

Reference: NUMA 51255

To appear in: *Journal of Nuclear Materials*

Received Date: 28 May 2018

Revised Date: 28 September 2018

Accepted Date: 9 October 2018

Please cite this article as: A. Gallais-During, F. Delage, S. Béjaoui, S. Lemehov, J. Somers, D. Freis, W. Maschek, S. Van Til, E. D'Agata, C. Sabathier, Outcomes of the PELGRIMM project on Am-bearing fuel in pelletized and spherepac forms, *Journal of Nuclear Materials* (2018), doi: https://doi.org/10.1016/j.jnucmat.2018.10.016.

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ACCEPTED MANUSCRIPT

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

A. Gallais-During[1°], F. Delage[1*], S. Béjaoui[1*], S. Lemehov[2*], J. Somers[3*], D. Freis[3*], W. Maschek[4*], S. Van Til[5], E. D'Agata[6], C. Sabathier[1]

°corresponding author: annelise.gallais-during@laposte.net
*on behalf of the PELGRIMM consortium
[1]*CEA/DEN-DEC, 13108 St Paul Les Durance, France,*
[2]*SCK●CEN - Belgium,* [3]*JRC/DirG – Germany,* [4]*KIT – Germany,* [5]*NRG – Netherlands*
[6]*JRC/IET - Netherlands*

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 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 project (7th Framework Program for funding of European research projects started between 2007 and 2013) 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 spherical fuel beads by vibro-compaction, could be attractive regarding MA-bearing fuels.

Actually, the potentially better accommodation of solid swelling of spherepac fuels (compared to pellets) through the re-arrangement of the free inter-particule areas under irradiation could ultimately lead to better safety management of the helium generated during irradiation; this point, to be demonstrated, would be a significant advantage of spherepac fuels. Additionally, the preparation process could be significantly simplified thanks to the elimination of some process steps such as milling and grinding, that involve fuel powders and dust.

From a general point of view, the properties of granulated fuel behaviour under irradiation are quite similar for spherepac fuels (spherical beads) and VIPAC fuels (angular shards) [24], which take benefit from an extended experience as they have been operated in Russia for about forty years [25]. Their advantages mainly are their behaviour at high temperature, which is similar to that of pellet fuels (formation of a central hole, columnar grains, etc.) after an initial stage of sintering of the areas of the fuel submitted to high temperature, as well as a good accommodation of power transients thanks to the lower cohesion of the fuel structure. Nevertheless, among the issues to be dealt with in a safety demonstration, are lower melting margins compared to pellet fuels (due to a lower thermal

conductivity) and a risk of loss of fissile granules to the coolant in case of cladding failure.

Within European projects frameworks, developments on granulated fuels were performed quite recently within F-BRIDGE (2008-2012) and FAIRFUELS (2008-2015). Within F-BRIDGE, the investigations were dedicated to the potential applicability of granulated fuels to Generation IV systems [3] while within FAIRFUELS, the objective included the design, the manufacturing and the irradiation of the SPHERE experiment [26].

Consequently, regarding the developments on spherepac fuels, the following points have emerged for building the PELGRIMM project: the need to perform the PIE of the SPHERE irradiation in order to better understand the behaviour under irradiation of spherepac fuel and the need to follow efforts initiated within previous initiatives regarding spherepac fuel preparation process, irradiation behaviour and performance, as well as to extend the investigation to an exploratory analysis of an SFR core loaded with spherepac Am-bearing fuels.

2.3. Overview of the PELGRIMM technical items

The key points mentioned in the previous sections were combined and used as basis for the PELGRIMM project, described in details in [1]. Close connections exist within and between each set of investigations: experiments on MABB and MADF; pelletized versus spherepacked fuel behaviour; spherepac preparation through several technologies; experimental activities and modelling-simulation; and finally spherepac MADF pin behaviour under normal operating conditions and problematics of core physics under normal and off-normal conditions.

To reflect the fuel safety approach followed throughout the project, this paper gives an overview of the main outcomes gained within PELGRIMM, as follows: investigations of alternative synthesis routes for spherepac fuels, analytical (separate-effect) and semi-integral safety testing irradiations of MA-bearing fuels and their PIE, modelling and simulation of fuel behaviour under irradiation and preliminary assessment of safety performance for spherepac fuels.

3. INVESTIGATIONS IN ALTERNATIVE FUEL SYNTHESIS ROUTES

Powder metallurgy flowsheets used to supply $(U,Pu)O_2$ or standard fuels at industrial scale can be used at lab-scale to prepare Am-bearing fuel samples, such as the MARIOS disks (see [27] and section 4.2). However, the major drawback to application to Am-bearing fuels is the difficulty in managing fine powders (dust) at all stages of the process (dosing, milling, mixing, granulation, grinding, sieving, press filling, etc.). This compromises the use of metallurgical processes for industrial production of Am-bearing fuel.

Dust-free routes and simplified flowsheets are essential to scale-up the Am-bearing fuel preparation processes. In this prospect, the spherepac technology is attractive, as it would lead to a significant simplification of the preparation process through elimination of some process steps, such as milling and grinding that involve fuel powders and dust. Moreover, the resulting process would be more compact and simple than the pelletizing process.

3.1. Sol-gel processes and MARINE AmBB fuel preparation

The main advantages of sol–gel processes involve the easy shaping during the gelation stage, thanks to the fluidity of the initial solution. In particular, they allow a controlled synthesis of dense or porous microspheres depending on their subsequent use such as spherepac fuel beads or pelletized fuel made by pressing the beads. Once optimized, the technique allows spherical particles of homogeneous composition to be obtained after washing, drying and calcination resulting in condensation of the heavy metals involved [28].

Already, within FAIRFUELS, the SPHERE $(U,Pu,Am_{0.03})O_{2-x}$ beads were prepared by infiltration of porous $(U,Pu)O_2$ precursor beads prepared by sol-gel gelation, with americium nitrate solutions (see [26] and section 4.1). The MARINE irradiation [29] is part of the second step in the testing of $(U,Am)O_2$ fuels (separate-effect tests like MARIOS belonging to the first step). MARINE is equivalent to SPHERE as it includes 2 mini-pins of pelletized and spherepacked fuels, but differs in fuel composition: $(U_{0.15}Am_{0.85})O_{2-x}$.

For MARINE, the synthesis procedure was almost similar to SPHERE for the preparation of pellets,

but using UO_2 as precursor instead of $(U,Pu)O_2$. Two preparation routes were followed to synthetise the two types of fuel (pellet and spherepac) [29].

For pellets, the preparation flowsheet included the following steps: production of porous UO_2 beads (without americium) by the sol gel external gelation route providing beads without strict specifications on the size distribution; infiltration of the porous beads with americium solution (low acid Am nitrate solution to prevent UO_2 dissolution as much as possible) and subsequent calcination; pressing of the beads; sintering of the green pellets; control and selection. After preparation, the Am content was close to the specified 15 mol% with respect to total heavy metal. The microstructure was of good quality, with homogeneous distribution of porosity throughout the pellet (see Figure 1).

For the spherepac fuel preparation, the synthesis of the fuel was performed by group conversion from mixed nitrate solution, which was prepared by mixing U with Am nitrate solution in the required ratio. It required implementing the following steps: preparation of small size fraction by sol-gel external gelation route; preparation of large size fraction by the sol gel external gelation route to yield monodisperse sized particles; sintering of the beads; control and selection.

A detailed study using Nd prior to Am was performed to define optimal preparation conditions for large beads. Application of the process to Am showed nevertheless that the optimized conditions using acidified Nd solutions were not appropriate to provide the same good quality particles achieved with Nd surrogate solutions. Adjustments were made, leading to reasonably spherical particles (see Figure 2). The density of the large beads was estimated to be in the order of 67%, revealing that the porosity content was very high.

This sol-gel process was used for the 1st time to synthetise AmBB fuels under pellet and spherepac forms and the 2 MARINE pins were filled, one with 6 sintered pellets of $(U_{0.15}Am_{0.85})O_{2-x}$, obtained from a batch of small sized beads; the other one with a stack of beads of $(U_{0.15}Am_{0.85})O_{2-x}$ with 2 size fractions (50µm & 800µm), packed by vibrations up to a smear density of 55.4 % of the Theoretical Density (%TD), revealing an effective packing since the particles themselves have a density of ~67%. Figure 3 summarizes the results of the MARINE fuels preparation, along with those of SPHERE and MARIOS; it also includes the main irradiation conditions and associated PIE, which are detailed in section 4.3. The MARINE PIE will be performed in another framework than PELGRIMM and will

provide fuel performance results giving a feedback on this fuel preparation route.

3.2. Variant in the sol-gel processes: Microwave internal gelation

As seen above, external gelation is a well-developed process to produce homogeneous spherical particles of fuel for the so-called spherepac concept. The process is triggered by a temperature increase, which in usual systems is induced by a conductive heat exchange with a silicon oil hot bath, leading to secondary wastes. As it is irrelevant how and from which medium the heat is introduced into the beads, a variant of the external gelation route has been studied, the so-called microwave internal gelation, using for gelation of the drops, an electromagnetic heating within a microwave cavity [30], [31] instead of a silicon oil hot bath.

The production unit was developed and the process is illustrated in Figure 4. A non-radioactive unit composed of droplet production and microwave heating equipment was built in order to investigate the preparation of spherules with a metal surrogate (cerium). Models and simulations regarding the electromagnetic heating part were also developed [31]. Promising results were obtained for non-radioactive surrogates (see Figure 5). The equipment was then implemented in a glove-box to permit fully remote operation and now conforms to the laboratory safety requirements. The final device is now available to test the equipment on U-type compounds.

3.3. Adaptation of the Weak Acid Resin process

The ion exchange Weak Acid Resin (WAR) process was initially used for the production of carbide kernels for High Temperature Reactor particle fuels [32], [33]. The WAR flowchart has been revisited and adapted to oxide fuels [34] up to the synthesis of $(U,Am)O_2$ beads and pellets [35].

The synthesis of $(U_{0.9}Am_{0.1})O_{2-x}$ microspheres was prepared by thermal treatments of ion exchange resins loaded with Am^{3+} and UO_2^{2+} cations. The degradation of the polymeric skeleton under air followed by reducing heat treatment led to the synthesis of spherical precursors. The reduced actinide oxide beads were thoroughly characterized by SEM, TIMS, powder-XRD and coupled µGC-TGA. Analyses have shown that $(U,Am)O_2$ was produced with a reasonable amount of C residue (around

1500 ppm). The morphology of the spheres is fairly good and an inspection of high-magnification images of some broken spheres has shown that the microstructure of granule is homogeneous, as can be seen in Figure 6. The diameter of the spheres is around 400µm and the apparent density is 24 %TD. Am content versus total metal content has been assessed by the complete dissolution of the oxide and analysis of the bulk composition by TIMS: a ratio of 10.6% has been achieved, which is in fair agreement with ratio of the loading solution.

Because bulk density of microspheres was low (24%TD), densification of spherules has been investigated too. Thermal conversion tests were carried out on Ce(III) loaded resin beads, Ce being used as a surrogate of Am. Preliminary results have shown that it seems possible to reach highly dense microspheres (>90%TD) by adjusting the heating rate to a value as low as 0.1°C/min and by choosing an appropriate temperature for sintering. A modified WAR process with specific calcination conditions could then allow the synthesis of very dense actinide oxide microspheres which would meet spherepac specifications.

Moreover, oxide microspheres were suitable for pressing, and a dense pellet (density of 95%TD) has been achieved after dynamic sintering under a reducing atmosphere up to 1800°C. This pellet meets the required density specifications for Am transmutation in a UO_2 matrix in SFRs and proves the technical feasibility of this dust-free process.

4. OUTCOMES FROM IRRADIATION EXPERIMENTS

An irradiation campaign includes the design of the fuel, pin and device features, the preparation and assembly of the components, the implementation in a reactor and the execution of the PIE programme. As the time required for these activities is longer than the standard duration of a European project (~4 years), irradiation campaigns on Am-bearing fuels have regularly been split in steps that were distributed in projects that followed each other.

The PELGRIMM project hosted the PIE activities for SPHERE and MARIOS irradiation tests, as well as the design, manufacturing and implementation in HFR of the MARINE irradiation test. Figure 3 gives an overview of the SPHERE, MARIOS and MARINE irradiation tests and the main outcomes

gained from each irradiation are detailed in the following sections.

4.1. SPHERE

The objectives of the SPHERE semi-integral irradiation were to provide the very first results on MADF spherepac fuel behaviour under irradiation as well as a direct comparison between spherepac and pellet MADF fuel performances. To do that, the SPHERE experimental device consisted of two short pins containing $(U,Pu,Am_{0.03})O_{2-x}$ fuel. One mini-pin was filled with pellets and the other with a stack of beads of 2 size fractions (50 & 800µm). The irradiation was performed in HFR during 295 Equivalent Fuel Power Days (EFPD), leading to a maximum burnup of ~5at% and a maximum linear heat rate around 300W.cm^{-1}. The SPHERE irradiation was designed, prepared and irradiated within the FAIRFUELS project [5]. The details of the fuels and pins characteristics, experimental device and irradiation parameters are given in [26] and summarized in Figure 3.

PELGRIMM hosted the PIE activities for the SPHERE irradiation. Optical microscopy has been performed on 6 samples: one axial and two radial cuts, for both the pellet and the spherepac fuel pins. For each type of fuel, one of the two radial samples was cut in 4 quadrants and prepared for elemental analysis (SEM/WDS). For each sample, an estimation of the associated linear power has been deduced from post-irradiation calculations and gamma spectrometry measurements of non-volatile fission products. The main results deduced from Non Destructive Examinations (NDEs) and Destructive Examinations (DEs) are summarized in Table 3.

From a macroscopic point of view, the behaviour of the pellet and spherepac MADF fuel is globally the same. For the two types of fuels: the cladding has not been degraded nor deformed; the fuel stacks have not been elongated (nor creeped); the non-volatile FPs (^{95}Nb, ^{95}Zr) distributions are consistent with axial neutron flux (peaking at the ends) and have been used to recalculate the axial power profile, used for the analysis of DEs; the puncturing results are consistent with 100% He release and ~90% Xe (and Kr) release for both spherepac and pellet fuels, despite large uncertainties due to calibration issues.

The behaviour under irradiation of pellet and spherepac fuels is also quite similar in terms of fuel

microstructure. A central hole was formed, smaller (and even undetected by neutron radiography) for pelletized than for spherepacked stacks due to a lower temperature regime in pellets that can be explained by a higher thermal conductivity of the pelletized compared to spherepac fuel. Both forms of fuel exhibit a restructured region with columnar and equi-axed grains and with similar microstructure (increased/decreased porosity for pellet/spherepac respectively, with respect to the corresponding as-fabricated porosity).

The radial actinide distribution in the pellet fuel confirms the observation reported for previous comparable irradiation tests, such as SUPERFACT [13]-[16], Am1 [17]-[19] or AFC-2C&2D [20]: the same tendency and magnitude have been observed. For the spherepac fuel, the americium profile shows a redistribution which seems in line with literature [36]. The plutonium redistribution for (restructured) fuels with fuel center temperature ≥ 2000°C shows a deviation from nominally observed distributions (where Pu redistribution is more pronounced, and Pu and Am-profiles are often similar).

Finally, a significant difference between pellet and spherepac fuels lies in the presence of FCMI for the pelletized pin, which seems absent for the spherepac pin.

To complete the analysis, the pellet and spherepac fuel pins irradiated in the SPHERE experiment were simulated blindly (previously to PIE execution) with several fuel performance codes in the framework of PELGRIMM, as presented in section 5.

4.2. MARIOS

The MARIOS separate-effect test was the first irradiation of a comprehensive R&D program of MABB fuel qualification started in 2008 [21], [22]. It was designed to investigate helium behaviour and fuel swelling of $(U_{0.85}Am_{0.15})O_{2-x}$ fuel as a function of microstructure (i.e. as-fabricated porosity) and temperature. Small disks (diameter: 4.5mm and thickness: 1.5mm) of fuels with 2 different open-porosity ratios (7.7% and 12.5%) were prepared by CEA and irradiated in an experimental device specifically designed in order to maintain constant flat temperature profiles in the fuel disks. Thus, four mini-pins, each containing 6 fuel disks, were irradiated in HFR during 304 EFPD at constant temperatures. The MARIOS irradiation was designed, manufactured and irradiated within the

FAIRFUELS project [5]. The details of the fuels and pins characteristics, experimental device and irradiation parameters are given in [22], [27] and [37] and summarized in Figure 3.

PIE was performed within PELGRIMM. DEs focused on the effect of fuel microstructure: they were performed on the fuel disks of pin #1 and #4, with high density and low density microstructure, respectively, and which were submitted to a similar temperature of ~1000°C. DEs have included optical macro and microscopy, SEM, EPMA, SIMS and XRD. The main results deduced from NDEs and DEs are summarized in Table 4.

NDEs have revealed a clear effect of temperature regarding volatile FPs and fission gas release: Cs release has been evidenced for the pin submitted to the highest temperature (pin #2) and Xe and Kr releases are strongly temperature dependent in the investigated temperature range and rather consistent with Cs behaviour (qualitatively). On the contrary, considering that He release during cooling time is negligible, and despite large uncertainties, it has been concluded that all He produced during irradiation was released to the plenum, irrespective of differences in porosity and temperature. For this type of fuel, the threshold for high He release seems to be below 1000 °C.

The fuel disks were in a relatively good shape after irradiation (intact or in several fragments, but no powder), whatever the fuel porosity and the irradiation temperature. However, it is clear that low density fuel sample deteriorated at high temperature: the disks of pin#3 (1180°C) are in numerous small fragments whereas the disks of pin#4 (980°C) are all intact except one. For high density fuels, the effect of temperature is not so clear: the disks of pin #1 and #2 are globally in the same shape (i.e. in several small fragments).

The effect of porosity on fuel behaviour can directly be deduced from the comparison of metrology and microanalysis results obtained on pin #1 and pin #4, as the temperature was similar for the 2 pins (990-980°C). Globally, there is no significant difference between pin #1 and pin #4 fuel behaviour. The porosity after irradiation for both type of fuels has remained very similar to the as-fabricated porosity and no macroscopic swelling has been evidenced for pin #1 and #4 fuels, which is consistent with high He release (~100%) and low fission rate (~1.14%). Finally, the main difference between high and low density fuels lies in their mechanical behavior: most of the low density disks are intact after irradiation, which would promote the use of high porosity microstructure for such irradiation

conditions.

In addition, apparent transmutation and fission rates have also been assessed by EPMA, as well as isotopic ratios by SIMS: a very good agreement between measurements and calculations (based on neutron data and re-scaled thanks to dosimetry measurements [37]) is observed, with a transmutation rate close to 46% for a fission rate about 1.14%.

4.3. MARINE

As stated above, the MARINE irradiation [29] is part of the second step in the testing of $(U,Am)O_2$ fuels (separate-effect tests like MARIOS belonging to the first step). In the MARINE experiment, the case of an AmBB pin situated close to the SFR core has been considered, with values of power, irradiation temperature and helium production situated in the upper range of those related to the various pins in the AmBB subassembly [38]. This choice is consistent with the previously irradiated MARIOS experiment.

In addition, MARINE is equivalent to SPHERE as it includes 2 mini-pins of pelletized and spherepacked fuels, but differs in fuel composition: $(U_{0.15}Am_{0.85})O_{2-x}$. One of its main objectives is also to study the role of microstructure and temperature on fission gas and helium release as well as on fuel swelling. To do that, an improvement of the MARINE experiment is that both mini-pins have been instrumented with pressure transducers in order to measure online the pressure to better understand the gas release behaviour during the irradiation.

The fuel preparation conditions are detailed in section 3.1 and summarized in Figure 3. The results of the calculations performed in order to design the experimental device and predict the irradiation conditions are detailed in [29]. Neutronic analyses were performed for an effective irradiation duration of 15 cycles of the HFR. In addition, thermal analyses predicted a fuel maximum temperature ranging from 950°C to 1200°C and 920°C to 1120°C for the spherepac and pellet pins, respectively. These results were obtained assuming the absence of fuel restructuring (not expected at these temperatures). So, outcomes from MARIOS at 980°C-1180°C could directly be used for the interpretation of MARINE PIE results. Moreover, as gas release is part of the main objectives of the MARINE

experiment, the helium production (see Figure 7) was intended to be representative of Am recycling scenarios in SFR reactors [38] and an objective of 2.7 $mg.cm^{-3}$ (i.e. 336 days of irradiation in HFR) has come to be a good compromise with the timescale of the PELGRIMM project.

Finally, the irradiation of the MARINE experiment was performed in HFR during 12 reactor cycles, equivalent to 359 Full Power Days (FPD), from January 2016 up to May 2017. The on-line pressure measurements that were implemented for the first time on Am-bearing fuel pins have been available up to the end of the 4th cycle, for the pelletized fuel pin. From these measurements, it will be possible to deduce the kinetics of gas release as a function of irradiation time. The MARINE irradiation stage is now fully complete and PIE is expected to be performed in a near future (within another framework than PELGRIMM, that ended in June 2017) to take full benefit of this first semi-integral irradiation of pellet and spherepac MABB fuels.

5. MODELLING AND SIMULATION OF FUEL BEHAVIOUR UNDER IRRADIATION

Most of fuel performance codes have originally been developed, verified and validated to model the behaviour of standard fuels for Light Water Reactors and Fast Reactors systems. Some of the codes under consideration within PELGRIMM were already upgraded within previous European projects to integrate some of the specificities of Am-bearing fuels or of spherepacked fuels. These codes are MACROS [39], TRANSURANUS [40], [41], SPHERE-3 and SPACON codes [42], [43]. In addition, the calculation code GERMINAL [44], has also been considered within PELGRIMM to describe the MABB fuel behaviour under irradiation.

The objective of the work within PELGRIMM, was to capitalize on previous investigations to address the main challenges due to specific issues of MADF and MABB fuels under spherepac and pellet forms, such as:

- low MA content in $(U,Pu)O_2$ support matrix and high MA content in UO_2 support matrix;
- high temperatures in SFR MADF fuels and moderate or even low temperatures (<1500°C) expected for MABB fuels in dedicated blanket assemblies near the SFR core periphery;

- high helium release ratios in MADF fuels and potentially low helium release ratios in MABB fuels, the latter potentially leading to excessive MABB fuel swelling and needing its accommodation, possibly including microstructures changes making release easier;
- transition from pellet to spherepac forms of MA-bearing fuels, leading to modification of thermal and mechanic property descriptions as well as changes in FCMI due to an expected softer mechanical behaviour of spherepac fuels.

Extensive work has been done in PELGRIMM to extend the capabilities of the codes to model and simulate the fuel behaviour under irradiation for both MADF and MABB fuels shaped as spherepac and pellet. The approach has consisted in reviewing, at the beginning of the project, the capabilities of the codes, collecting, from well-qualified experiments, data that cover material properties, cladding and design parameters, then developing models and working out recommendations. The upgrades of the codes have consisted in the implementation of new models or in the modifications of existing models and correlations for standard fuels when appropriate. The efforts have covered aspects such as: helium production and release under a fast neutron spectrum, plutonium and oxygen redistribution, melting temperatures and evolution rate of fuel restructuring, columnar grain growth and central void formation [45]-[50].

In parallel, a comparison of spherepac and pellet fuel behaviour under irradiation based on existing experimental data and a review of the principles of equivalence of the two fuel concepts have been drawn up. The aim of the study was to evaluate several analytical tools and their functional abilities and to work out recommendations for practical and adequately simplified models needed for the simulation of pelletized and spherepacked MADF fuels. For SPHERE calculations, equivalent formulas were established, between spherepac and pellets, for the most important fuel properties (thermal conductivity, irradiation-induced solid and gas swelling) and simplified semi-theoretical correlations were made to model specific power profile in the fuel pins under thermal flux.

Finally, the evaluation of the upgraded fuel performance codes (MACROS, TRANSURANUS and SPHERE-3) to simulate the behaviour of fuel pins within the SPHERE irradiation test (described in details in section 4.1) was performed (blind as the irradiation was still underway at the time of the calculations). The results of the comparison are gathered in Table 5.

Whatever code was used, the results were consistent (when comparisons between codes could be made) and an initial comparison between calculated and experimental results can be made, on the basis of the PIE results of the SPHERE irradiation (see Table 3).

For the spherepacked fuel, the calculated center-line temperature is well above 1800°C during the majority of in-reactor time so that the fuel would show restructuring, sintering and density changes, with an original spherepac structure still existing within a short bound near the outer surface. This is rather consistent with the experimental observations of the neutron radiography performed after the 1st cycle of irradiation as well as the microscopic observation performed during PIEs.

For the pelletized fuel, the calculated center-line temperature is below 1800°C, which is a threshold for columnar grain growth and central void formation. Thus, neither central hole nor fuel restructuration has been predicted by the simulation whereas a small central hole and a partially restructured fuel have been observed experimentally. However, given the low diameter of the measured central hole and the dispersion of the calculated temperatures (1400-1800°C), the calculated and measured results are not inconsistent.

Whatever the fuel shape, the major discrepancy concerns the calculated and measured released fractions for fission gas and helium. Nevertheless, the uncertainties on puncturing results were large, so the interpretation regarding gas release should be done with lot of caution. In a general way, the conclusions drawn here remain very preliminary. A refined analysis of these results has to be done (out of the PELGRIMM scope) in order to provide new insights in the modelling of MADF fuel shaped as pellets and spherepac.

6. SIMPLIFIED DESIGN AND SAFETY PERFORMANCE PRE-ASSESMENT OF AN ADVANCED SPHEREPAC (U,Pu,MA)O_2 SFR CORE

As spherepacked fuels are foreseen to be good candidates for MA-bearing fuel concepts, PELGRIMM started linking the investigation of spherepacked fuel synthesis and behaviour under irradiation with an assessment of core physics, design and safety performance. Among the issues to be dealt with in a safety demonstration, are lower melting margins compared to pellet fuels and an effect

of loss of fissile granulates in the coolant in case of cladding failure.

The study was in continuity with the former CP-ESFR project [4] which aimed at designing and analyzing a 3600 MWth SFR loaded with a standard driver fuel (shaped as pellets) and assessing its safety behaviour and its transmutation capabilities. From CP-ESFR project recommendations, the so-called CONF-2 core, an optimized version of the 'ESFR working horse core', was chosen to start the PELGRIMM investigations [51].

The CONF-2 core was firstly revisited and its safety analysis completed, analyses that were missing in the CP-ESFR project. The introduction of spherepac fuels instead of pellets as well as of $(U,Pu)O_2$ and $(U,Pu,Am)O_2$ fuel compositions, was then considered. At Begin Of Life (BOL), the essential differences between pellet and spherepac pins remain on the distribution of the free areas in the fuel columns [52]: central hole and fuel/clad gap for pelletized fuel pins and free inter-particle spaces for spherepacked fuel pins. As a consequence, the fuel center temperature in the spherepac pins is much higher than in the pellet pins. At higher burn-up, the thermal regimes of both fuel concepts become close. Then, neutronic analyses were performed for variants of the CONF-2 core that contain up to 4% Am in the fuel. As expected, the results reveal a deterioration of the safety parameters in CONF-2 with burnup and Am content [52]. Provided that the Am content is limited, spherepac fuel can be inserted in a SFR core instead of pellets without significantly changing the design and without having a major impact on the core layout and safety coefficients.

Finally, accidental conditions were simulated with different codes: SAS4A [53], BELLA [54] and MAT5DYN [55] for the initiation phase of the accident, SIMMER-III [56] up to conditions of potential whole core melting and core disruption. The codes were adapted as much as possible to the specificities of a spherepac fuel, in particular to take into account the heat transfer in a bead stack and the absence of a fuel-clad gap as well as the dispersive feature of a non-restructured spherepac fuel in case of cladding failure. Two relevant accidental situations were analyzed: the unprotected loss of flow accident (ULOF) and unprotected transient over-power accident (UTOP).

For ULOF analyses, transient calculations for the CONF-2 core with the SIMMER-III code [52]-[57] were performed for both pellet and spherepac fuel; for spherepac fuel under BOL conditions, 2 cases must be considered: before and after fuel restructuring, because high temperatures could be

reached by the non-restructured fuel if no starting procedure has been implemented to moderate the power level at the first power rise. Figure 8 shows the power and reactivity evolution during the ULOF for the non- and restructured spherepac fuels. The simulations of a ULOF at BOL show very mild transients [57].

The same ULOF was then considered after 3 irradiation cycles. The nuclear power trace and reactivity development of the CONF-2 core is displayed in Figure 9 for both pellet and spherepac fuel. Compared to the BOL case, a slight increase of the nuclear power peak can be observed, but the negative reactivity effects can still balance the positive contributions from core voiding. As expected from the similar thermal conductivity and macrostructure of both fuel types at this stage of irradiation, the spherepac and pellet core show a very similar behaviour under these accidental conditions. With loading of Am for transmutation and burning (2-4%) a significant deterioration of the void worth and the other safety parameters, such as the Doppler feedback, take place. Consequently the safety advantages observed in the BOL core vanish and severe transients with total core disruption and melting result, irrespective of the fuel type.

In the case of a UTOP, the use of spherepac fuel degrades the CONF-2 core safety performance, because of its low thermal conductivity, besides reducing the margin against fuel melting at steady-state, leads to larger fuel temperature gradients ensuing from positive reactivity insertions, likely causing its melting; however, the resulting transient was rather mild, with an estimated peak power level of 2-3 times the nominal one. As a result of these findings, it can be concluded that the use of spherepac fuel in the optimized CONF2 core does not lead to significant changes in the accident scenario sequence when spherepac fuel is used instead of pellet fuel. The possibility of early spalling of the spherepac particles and their release from the core might lead to an even milder accident behavior.

7. CONCLUSION

PELGRIMM has constituted a new step in the long term process of the MA-bearing fuel safety testing, with the investigation of a wide range of items: from pellet to spherepac fuel forms, from homogeneous to heterogeneous MA-recycling modes, from fuel preparation and characterization to

behaviour and performance under irradiation, from experiments to modelling and simulation, from normal operating conditions to severe accidents.

Regarding the fuel preparation aspects, alternative routes of MA-bearing fuel synthesis have been investigated to seek improvements (simplification, robustness, lower secondary waste streams…). The Am-bearing fuel for MARINE, both pellet and spherepac types, have been prepared within PELGRIMM by infiltration of porous UO_2 precursor beads, prepared by sol-gel gelation, with americium nitrate solutions. In addition, a variant of the sol gel process, based on micro-wave internal gelation was developed and a new dedicated facility is now available. In parallel, the adaptation of the WAR process to the synthesis of $(U,Am)O_2$ beads and pellets has started and has provided promising results with the preparation of high density microspheres and pellet. Finally, by demonstrating the feasibility of these different fuel synthesis routes, PELGRIMM has opened the path to new possibilities for Am-bearing fuel concepts.

The realization of the PIE of innovative irradiation tests, such as SPHERE and MARIOS have largely contributed to improve the knowledge on Am-bearing fuel behaviour under irradiation for both MADF and MABB concepts, in spherepac and pellet forms. A first comparison between sphere-packed and pelletized $(U,Pu,Am)O_2$ fuel performances under irradiation was made, using PIE results of the SPHERE fuels, showing that for similar irradiation conditions, despite significantly different temperatures, the behaviour of different shaped fuels was rather similar. The main difference lies in the presence of FCMI for pelletized fuels, which seems absent for spherepacked fuels. The MABB concept has reached a key step of its testing program with the first separate-effect irradiation MARIOS, which PIE has shown that whatever the fuel porosity and the irradiation temperature (in the range of 1000°C-1300°C), no significant swelling has occurred which seems consistent with low fission rate and high He helium release during irradiation. Finally, the main difference between high and low density fuels lies in a better mechanical behavior of the low density fuels in such irradiation conditions. MARINE, the first semi-integral irradiation of MABB fuels is now complete and its PIE, to be planned in a framework other than PELGRIMM, should provide complementary results to SPHERE and MARIOS PIE.

For the modelling and simulation of fuel under irradiation, capabilities of the fuel performance

codes have been improved thanks to the implementation of more mechanistic models, new numerical methods, more reliable properties laws, etc. The outcome of benchmarks performed between PELGRIMM participants has been encouraging and has shown reasonably good agreements with experimental results: first attempts to simulate the fuel behaviour during SPHERE irradiation thanks to fuel performance codes have provided, for most of the cases, preliminary calculated results consistent with PIE results.

In parallel, to form a coherent whole, an optimized core loaded with $(U,Pu,Am)O_2$ spherepac fuels was successfully assessed for safety performance, in an initial scoping assessment. Two relevant accidental situations were analyzed: the unprotected loss of flow accident (ULOF) and unprotected transient over-power accident (UTOP). Based on the current analyses, the implementation of spherepac fuel does not cause any specific design problems and the first safety analyses also indicate that spherepac fuels do not seem to cause any specific safety problems, if introduced in an SFR.

Finally, the PELGRIMM project has capitalized on efforts made within previous European projects (ACSEPT, FAIRFUELS, F-BRIDGE, CP-ESFR) and has taken a new step in the development of both MA-bearing fuel options: $(U,Pu,MA)O_2$ and $(U,MA)O_2$, related to fuel preparation processes, irradiation behaviour and core safety performance, including a comparison on fuels shaped as pellets and beads.

ACKNOWLEDGMENT

We gratefully acknowledge the PELGRIMM consortium constituted of CEA, AREVA, EDF, ENEA, ENEN, JRC, KIT, KTH, LGI, NRG, PSI, SCK•CEN. This research was supported by the European Commission through the FP7 PELGRIMM project (Grant Agreement No. 295664).

DATA AVAILABILITY

The raw/processed data required to reproduce these findings cannot be shared at this time due to legal or ethical reasons.

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List of abbreviations

BOL: Begin Of Life
DE: Destructive Examination
EFPD: Equivalent Full Power Day
EOI: End Of Irradiation
EPMA: Electron Probe Micro-Analysis
FCCI: Fuel Cladding Chemical Interaction
FCMI: Fuel Cladding Mechanical Interaction
HFR: High Flux Reactor
MA: Minor Actinide
MABB: Minor Actinide Bearing Blanket
MADF: Minor Actinide Driver Fuel
µGC-TGA: Micro Gaz Chromatograph - ThermoGravimetric Analysis
NDE: Non Destructive Examination
SEM: Scanning Electron Microscopy
SFR: Sodium-cooled Fast Reactor
SIMS: Secondary-Ion Mass Spectrometry
TD: Theoretical Density
TIMS: Thermal ionization mass spectrometry
ULOF: Unprotected Loss Of Flow
UTOP: Unprotected Transient Over-Power
WAR: Weak Acid Resin
WDS: Wavelength Dispersive Spectrometry
XRD: X Ray Diffraction

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Test	SUPERFACT	Am1	AFC-2C&2D	SPHERE	GACID
date	80's	2008	2008-2010	ready for irradiation	suspended
participants	CEA / JRC-ITU	JAEA	US DOE-INL	FAIRFUELS	GACID-PMB
reactor	PHENIX	JOYO	ATR	HFR	JOYO /MONJU
fuel form	pellets	pellets	pellets	pellets & spherepac	pellets
Am content	2%	2-5%	2%	3%	3%
MA compounds synthesis process	Sol-gel	powder metallurgy	powder metallurgy	gelation & Am infiltration	co-precipitation
Burn-up	6.5at%	10 min & 24h	8 & 19at%	-	-
Linear Heat Rate ($kW.m^{-1}$)	~38	43	<30	-	-

Table 1 : MADF irradiations done, in progress or in preparation at the emerging stage of PELGRIMM

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Test	SUPERFACT	MARIOS	DIAMINO
date	80's	2011 In pile	under preparation
participants	CEA / JRC-ITU	FAIRFUELS	CEA
reactor	PHENIX	HFR	OSIRIS
fuel form	pellets	disks	disks
Am content	20%	15%	7.5%-15%
MA compounds synthesis process	Sol-gel	powder metallurgy	powder metallurgy
Burn-up	6.5at%	-	-
Linear Heat Rate ($kW.m^{-1}$)	~17-27	-	-

Table 2 : MABB irradiations done, in progress or in preparation at the emerging stage of PELGRIMM

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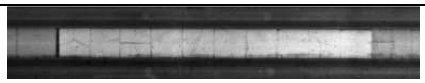
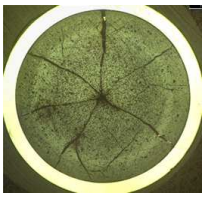
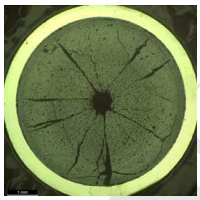
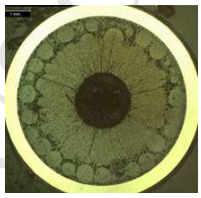
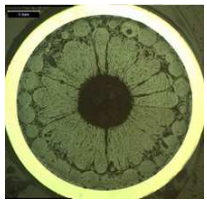
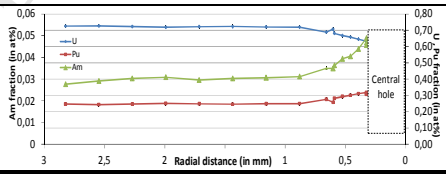
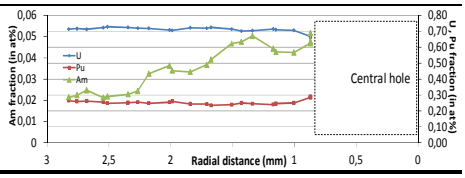
	SPHERE pellet fuel pin		SPHERE spherepac fuel pin	
Fuel composition	$(U,Pu,Am_{0.03})O_{2-x}$			
Neutron radiographies after 1rst cycle (~28 EFPD, at 300-320 W/cm linear power);				
	not significantly different at EOI			
Gamma spectrometry scans ^{134}Cs, ^{137}Cs distributions	no significant elongation of the fuel stacks			
	no pronounced diffusion direction		clear diffusion toward the ends	
Profilometry	No significant cladding deformation			
Puncturing results (large uncertainties due to callibration issues)	Consistent with 100% He release Consistent with ~90% Xe (and Kr) release			
Optical microscopy (+SEM)				
Estimated linear power	~ 290 W/cm	~ 298 W/cm	~ 307 W/cm	~ 322 W/cm
Estimated temperature	~1800°C		≥2000°C	
	Difference of temperature can be explained by higher thermal conductivity of pellet fuel compared to spherepac fuel			
Central hole diameter	~ 0.2 mm	~ 0.65 mm	~ 1.86 mm	~ 1.74 mm
Restructured region : Columnar grains + equi-axed grains	No columnar grains but elongated grains	Columnar grains Diameter ~ 2.5 mm	Columnar grains Diameter ~ 3.68 mm	Columnar grains Diameter ~ 3.5 mm
Microstructure inside restructured region	Increased porosity; pores along grain boundaries		Decreased porosity; pores along grain boundaries	
Fuel Cladding Mechanical Interaction (FCMI)	No gap closure, No FCMI	FCMI Radial width ~ 25-30 µm	No homogeneous interaction layer (no FCMI)	
Radial actinide distibution (WDS)				

Table 3 : Results of NDEs and DEs on pellet and spherepac fuel pins after the SPHERE irradiation

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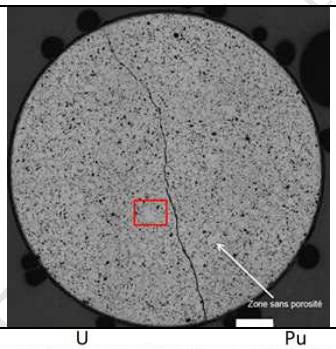
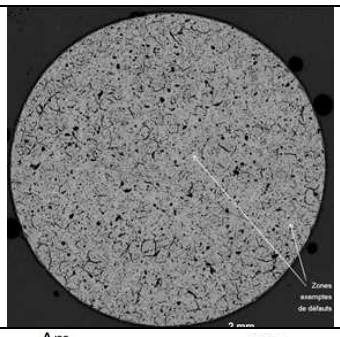
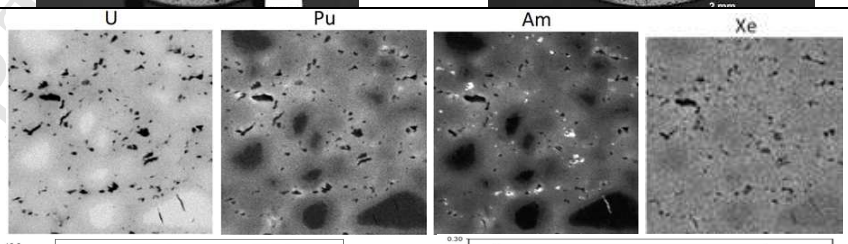
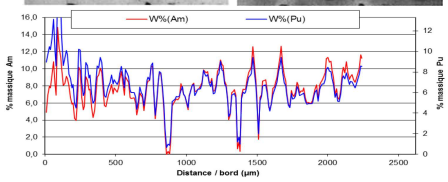
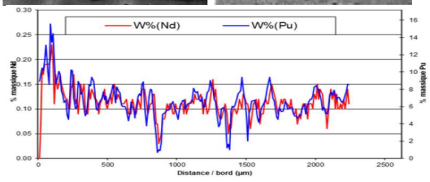
	Pin #1	Pin #2	Pin #3	Pin #4
Fuel composition	$(U_{0.85}Am_{0.15})O_{2-x}$			
As-fabricated microstructure: Density / open porosities	~92% TD 7.7% porosities	~92% TD 7.7% porosities	~87%TD 12% porosities	~87%TD 12% porosities
Power density at EOI (W/cc)	412	542	492	364
Burn-up at EOI (at%)	1.14	1.57	1.53	1.11
Temperature (°C)	990	1370	1180	980
Gamma spectrometry scans *** with the assumption of no Cs release for pin #1 and #4**	axial distributions of Nb, Ru (non-volatile) : good agreement with calculated production			
	~ no Cs release*	~65% Cs release*	Not evaluated	~ no Cs release*
Puncturing results (large uncertainties ~20%, unexpected presence of argon)	100% He release (assuming no release during cooling time)			
	17% Kr release 10% Xe release	80% Kr release 87% Xe release	48% Kr release 47% Xe release	15% Kr release 13% Xe release
Number of fragments, Visual inspection	Several large fragments	Several large fragments	Numerous small fragments	5 disks intacts 1 in 2 fragments
Geometrical density variation	No swelling		Not measurable	No swelling
Hydrostatic density variation	Not significant		Not significant	Not significant
Optical macro/ microscopy (+SEM)				
EPMA: Pin #1 (similar results for pin #4) **X maps of mid-width central area** **Radial profiles**				
Comparison measurement (M) and calculation (C)				
	Transmutation rate M :T_T=45.7% ; C :T_T=45.9%		**Fission rate** M :T_F=1.14%; C :T_F=1.14%	

Table 4 : Results of NDEs and DEs on fuel disks after the MARIOS irradiation

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	SPHERE pellet fuel modeling		SPHERE spherepac fuel modeling	
	MACROS	**TRANSURANUS**	**MACROS**	**SPHERE-3**
Linear Heat Rate ($W.cm^{-1}$)	270-300	270-300	270-300	250-300
Burn-Up (GWd/t_{IHM})	~ 47	~ 40	~ 47	~5 %fima
Center Line Temperature (°C)	1600-1700	1400-1800	~2000	2100-2500
Fuel Surface Temperature (°C)	600-800	600-700	~ 500	
Cladding Temperature (°C)	~ 500	~ 500	~ 400	~ 500
Fission Gas Release at EOI (%)	~ 35	~ 35-45		~ 35-45
Helium Release at EOI (%)	~ 20			
Fuel swelling at EOI (µm)	+250 µm		- 4.5% (densification)	
Smear Density at EOI (%TD)	~ 87		~ 83.5	
Restructuring formation			After ~ 5h	After ~ 5h
Central Void diameter (mm)			1.25	
Columnar Zone diameter (mm)			2.4	

Table 5 : Results of pellet and spherepac fuel simulation for the SPHERE irradiation

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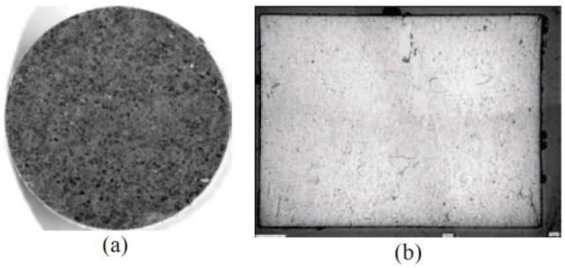

Figure 1 : Visual aspect (a) and ceramography (b) of a MARINE pellet

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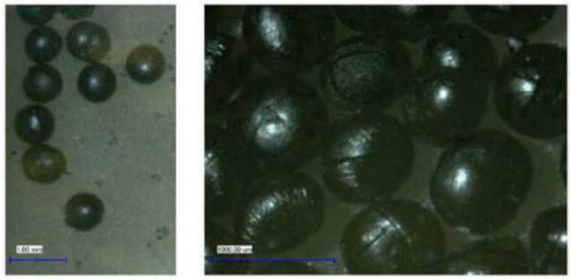

Figure 2 : Large size MARINE beads visual aspect

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		SPHERE		MARIOS				MARINE	
		mini-pin #1 top	**mini-pin #2** bottom	**mini-pin #1** top	**mini-pin #2**	**mini-pin #3**	**mini-pin #4** bottom	**mini-pin #1** top	**mini-pin #2** bottom
fuel	**project**	FAIRFUELS		FAIRFUELS				PELGRIMM	
	recycling mode-fuel concept	homogeneous-MADF		heterogeneous-MABB				heterogeneous-MABB	
	composition	$(U_{0.76}Pu_{0.2}Am_{0.03})O_{2-x}$	$(U_{0.75}Pu_{0.22}Am_{0.034})O_{2-x}$	(U. 15%Am)O2				(U. 13%Am)O2	
	fabrication	gelation & Am infiltration		powder metallurgy				gelation & Am infiltration	
	type of fuel	spherepac	pellet	pellet				spherepac	pellet
	geometry	beads	sintered beads	disks				beads	sintered beads
	number of pellets / disks		6	6	6	6	6		6
	fuel stack heigth	48 mm	59 mm					61 mm	55.6 mm
	disks **D: diameter; w: width**	D = 50 µm & D = 800 µm	D = 4.5 mm w = 10 mm	D = 4.5 mm w = 1.5 mm				D = 50 µm & D = 800 µm	D = 5.37 mm w = 10 mm
	density	75.5 %TD	94 %TD	92.5 %TD	92.5 %TD	88 %TD	88 %TD	~ 67 % TD	94-95 % TD
irradiation	**project**	FAIRFUELS		FAIRFUELS				PELGRIMM	
	reactor	HFR		HFR				HFR	
	begining - end	august 2013-april 2015		march 2011-may 2012				january 2016-may 2017	
	duration	295 EFPD		304 EFPD				359 EFPD	
	power density (EOI)	~ 300 W/cm		412 W/cc	542 W/cc	492 W/cc	364 W/cc	~ 55-70 W/cm *	
	burn-up (EOI)	~ 5 %at		1.14 %at	1.57 %at	1.53 %at	1.11 %at		
	temperature	~ 2300°C	<1800°C	990 °C	1370 °C	1180 °C	980 °C	<1000°C*	<1000°C*
PIE	**project**	PELGRIMM		PELGRIMM				**FUTURE**	
NDE	**neutronoraphies**	fuel restructuring	small cracks		cracks	cracks			
	gamma spectrometry (scan)								
	puncturing : gaz released fraction	~ 90% Xe-Kr ~ 100% He	~ 90% Xe-Kr ~ 100% He	~ 10-20 % Xe-Kr ~ 100% He	~ 80-90 % Xe-Kr ~ 100% He	~ 45-50 % Xe-Kr ~ 100% He	~ 10-20 % Xe-Kr ~ 100% He		
ED	**number of fragments**			1 to 5	1 to 2	6 to 14	1 to 2		
	geometric density variation			not significant			not significant		
	hydrostatic density variation			not significant			~7% densification		
	optical macro/microscopy								
	SEM, XRD								
	WDS, EPMA, SIMS								

* to be confirmed after irradiation

Figure 3 : SPHERE, MARIOS and MARINE fuel features, irradiation conditions and PIE results

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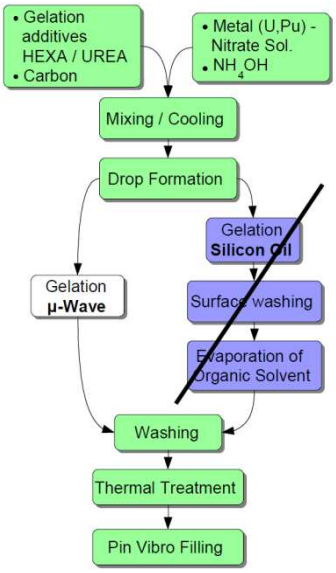

Figure 4 : Flowchart of the internal gelation route through a microwave cavity (left) compared to a silicon oil bath gelation step (right)

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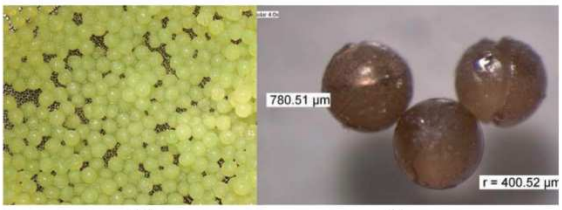

(a) (b)

Figure 5 : Spheres collected after microwaved gelation before (a) and after (b) drying

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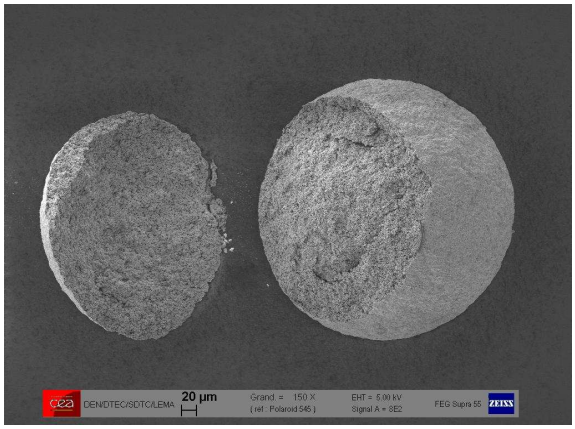

Figure 6 : SEM micrographs of $U_{0.9}Am_{0.1}O_{2-x}$ beads prepared by WAR technology

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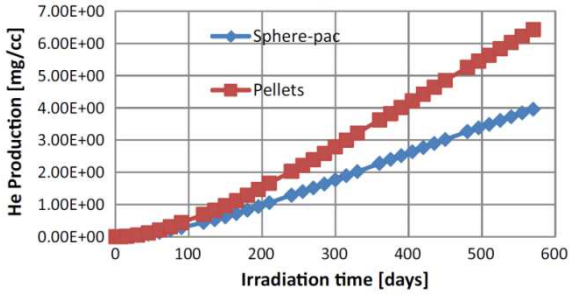

Figure 7 : Predicted helium production of the MABB fuel during MARINE irradiation based on neutronic pre-calculation

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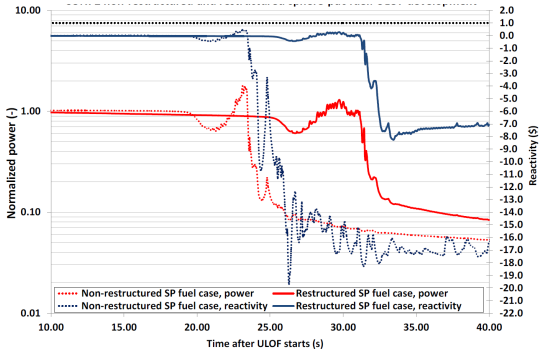

Figure 8 : Behaviour of the CONF-2 core during ULOF at BOL for restructured/non-restructured spherepac fuel

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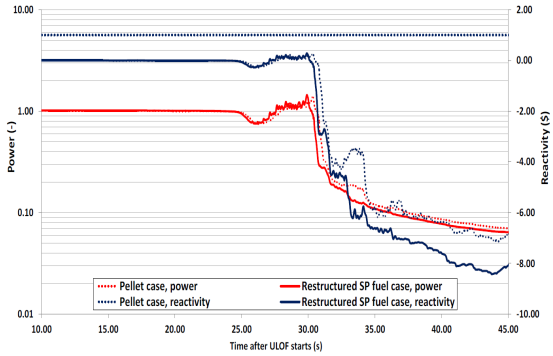

Figure 9 : Behaviour of the CONF-2 core during ULOF at equilibrium core conditions for spherpac/pellet fuel

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Highlights:

- PELGRIMM : a European Project carried out from 2012-2017 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

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