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on behalf of the PELGRIMM Consortium

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Summary

This report is the final report of the PELGRIMM project. It presents the activities and contributions of the 12 partners during the period 01 January 2012 to 31 June 2017.

Approval

Rev.	Date	First author	SP leader	Project Coordinator
0	30/08/2017	Annelise Gallais-During (CEA)	-	F. Delage (CEA)

Distribution list

Name	Organisation	Comments
M. Dzubinsky	EC	
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Declaration by the scientific representative of the project coordinator

I, as scientific representative of the coordinator of this project and in line with the obligations as stated in Article II.2.3 of the Grant Agreement declare that:

- The attached periodic report represents an accurate description of the work carried out in this project for this reporting period;
- The project (tick as appropriate) [1]:
  - ☐ has fully achieved its objectives and technical goals for the period;
  - ■ has achieved most of its objectives and technical goals for the period with relatively minor deviations.
  - ☐ has failed to achieve critical objectives and/or is not at all on schedule.
- The public website, if applicable
  - ■ is up to date
  - ☐ is not up to date
- To my best knowledge, the financial statements which are being submitted as part of this report are in line with the actual work carried out and are consistent with the report on the resources used for the project (section 3.4) and if applicable with the certificate on financial statement.
- All beneficiaries, in particular non-profit public bodies, secondary and higher education establishments, research organisations and SMEs, have declared to have verified their legal status. Any changes have been reported under section 3.2.3 (Project Management) in accordance with Article II.3.f of the Grant Agreement.

Name of scientific representative of the Coordinator: Fabienne Delage

Date: 30/ 08/ 2017

[1] If either of these boxes below is ticked, the report should reflect these and any remedial actions taken.

1. Final publishable summary report

1.1 Executive summary

PELGRIMM that stands for “PELlets versus GRanulates: Irradiation, Manufacturing, Modelling”, has been a FP-7 European project started in 2012, that has investigated Minor Actinides - bearing fuels, shaped as pellets and beads, for Generation IV – Sodium Fast Reactor Systems. Both Minor-Actinide transmutation options: the MA homogeneous recycle in driver fuels and the MA heterogeneous recycle on UO_2 fuels located in radial core blankets, have been under consideration. The objectives of the project have been to capitalize on efforts made within the previous European projects: ACSEPT, FAIRFUELS, F-BRIDGE as well as CP-ESFR, and to take a new step in the long term process of the MA-bearing fuel qualification rationale. Investigations have covered a wide range of items: from fuel fabrication and characterization to behaviour under irradiation; from experiments to modelling and simulation; as well as a spherepacked loaded core design and safety performance pre-assessment from normal operating conditions to transients and severe accidents to keep the link between fuel investigations and key issues of core physics.

Innovative irradiation tests and Post-Irradiation Examinations performed within the project have largely contributed to improve the knowledge on Am-bearing fuel behavior under irradiation for both MADF and MABB concepts, in spherepac and pellet forms. Regarding MADF concept, PIEs of the semi-integral SPHERE irradiation have provided a direct comparison of the behaviour of pelletized and spherepacked fuels. For comparable irradiation conditions, despite significantly different temperatures, the behaviour of different shaped fuels has been rather. The main difference lies in the presence of FCMI for pelletized fuels, which seems absent for spherepacked fuels. The MABB concept has got over a key step of its qualification program with the first separate-effect irradiation MARIOS which PIEs have been performed, and the first semi-integral irradiation MARINE which lasted 300 EFPD ending in May 2017. MARIOS PIEs have shown that the AmBB discs were in a relatively good shape after irradiation in the temperature range of 1000°C-1300°C. Whatever the fuel porosity and the irradiation temperature, no significant swelling has been measured and tailored porosity disks have been slightly densified. Regarding gas behaviour, all the helium produced during irradiation was released, regardless porosity and temperature, whereas the released fractions of Kr and Xe were strongly temperature dependent.

Regarding fuel synthesis, alternative routes of MA-bearing fuel fabrication processes have been investigated to seek for improvements (simplification, robustness, lower secondary waste streams…). The Am-bearing fuel for MARINE, both pellet and spherepac types, were synthesized by infiltration of americium nitrate solutions in porous UO_2 precursor beads prepared by sol-gel gelation. 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 provided promising results and high densified pellets have been prepared. Finally, by demonstrating the feasibility of these different fuel synthesis routes, PELGRIMM has opened the path to new possibilities for Am-bearing fuel developments.

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 outcomes of benchmarks performed are encouraging: first attempts to simulate the fuel behaviour during SPHERE, SUPERFACT and MARIOS irradiations thanks to fuel performance codes have been performed, providing, for most of the cases, preliminary calculated results consistent with PIE results.

In parallel, an optimized core loaded with $(U,Pu,Am)O_2$ spherepac driver fuels and corresponding safety performance assessment have been successfully performed. Two relevant accidental situations have been analyzed: the unprotected loss of flow accident (ULOF) and unprotected transient over-power accident (UTOP). Based on first scoping (i.e. preliminary) studies, 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, PELGRIMM has promoted the implication of European students and young researchers, including both internal actions for developing skills of European students (arrangement of internships for students at MASTER level in organizations involved in PELGRIMM, and external actions (allocation of

grants to attend scientific events and summer schools, arrangement of a workshop) for fostering the dissemination of the project actions and results. Regarding dissemination of foreground, PELGRIMM has been represented at key international meetings (GLOBAL, ICAPP, …) and selected results have been made available in highest quality journals. International relations have ensured PELGRIMM integration and alignment with programs inside and outside Europe by liaising and/or organizing information flow with other collaborative initiatives.

1.2 Summary description of project context and objectives

1.2.1 Introduction

The PELGRIMM project [1] stands for PELlets versus GRanulates: Irradiation, Manufacturing and Modelling. It has been carried out from 2012 to 2017 and has been devoted to the investigation of spherepacked and pelletized fuel forms for Minor Actinide (MA) transmutation, since one of the challenges for the next generation of reactors (Gen IV systems) is to reduce the inventory of high level wastes by transmuting the most radiotoxic and long-lived elements into non radio-active or short-lived ones. Two recycle options have been considered within PELGRIMM: homogeneous recycling mode in driver fuels, or Minor Actinide Driver Fuel (MADF) concept, and heterogeneous recycling mode on UO_2 fuels located in radial core blankets, or Minor Actinide Bearing Blanket (MABB) concept.
PELGRIMM has aimed at constituting a new step in the long term process of the MA-bearing fuel qualification rationale, initiated within the European projects ACSEPT (2008-2012), F-BRIDGE (2008-2012), CP-ESFR (2008-2013) and FAIRFUELS (2009-2015) [2-5]. Besides, the PELGRIMM and ASGARD [6] projects implemented in parallel within FP-7 have been 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, have collaborated to share and leverage their skills, progress and achievements, covering a comprehensive set of investigations. The PELGRIMM project has addressed all the key R&D items relative to fuel developments for qualification, for both homogeneous and heterogeneous recycling modes and for both spherepac and pellet fuels:

- Fabrication process developments,
- Semi-integral and analytical irradiation testing of MA-bearing fuels and Post Irradiation Examinations (PIEs),
- Irradiation behaviour modelling and predictive code developments,
- Preliminary safety performance assessment.

The present report intends to make a synthesis of the main technical outcomes gained within PELGRIMM. The fuel development approach being the main orientation axis of the PELGRIMM project, it has deliberately been chosen, in this synthesis report, to follow this rationale approach and not to describe the scientific and technical Work Packages one by one.

In the following sections, the project context, the motivation and the technical items under consideration within the project are firstly reminded. A brief status of the knowledge available at the beginning of the PELGRIMM project about the two MA-recycle options led to consider the pending issues related to the homogeneous recycling mode with the MADF concept and the heterogeneous recycling mode with the MABB concept. The main developments on spherepac fuel are also summarized as they highlight this type of fuel as an attractive concept for MA-bearing fuels. In addition, an overview of the content, dependencies and two-way links of the PELGRIMM project is reminded.

The part 1.3.1 is dedicated to the outcomes gained from the irradiation tests under consideration within PELGRIMM. It gives the major results of the PIEs performed on SPHERE and MARIOS pins and fuels. They provide the very first results respectively on the comparison between spherepacked and pelletized (U,Pu,Am)O2 fuel performances and on helium behaviour in $(U,Am)O_2$ fuels. In addition, a new irradiation test, MARINE, has been designed, manufactured and implemented in HFR within PELGRIMM. This semi-integral irradiation constitutes on one hand the step following MARIOS – a separated effect experiment - in the (U, Am)O_2 fuel qualification rationale and on the other hand, a first of a kind as the promising spherepac concept is tested for the first time on MABB compositions.

The section 1.3.2 focusses on alternative routes developed within PELGRIMM for MA-bearing fuel (MADF and MABB) fabrication processes in order to limit secondary waste streams. In this prospect, several options regarding the spherepac technology, used for bead or pelletized fuel fabrication, have been investigated. The internal gelation route, based on sol-gel processes that lead to dense or porous spherical particles of homogeneous compounds have been used for Am-bearing fuel synthesis of the MARINE irradiation. A variant of the internal gelation route has also been investigated, using an electromagnetic heating within a microwave cavity instead of a silicon oil hot bath for the gelation of the drops. Finally, the adaptation to oxide fuels of the Weak Acid Resin technology initially implemented in the 1970's for the production of uranium carbide kernels has shown promising results.

The part 1.3.3 addresses modelling and simulation activities related to fuel performance codes. Significant progress has been made in developments of codes capabilities to model and simulate the Am-bearing fuel behaviour under irradiation which has contributed to improve their reliability. Benchmarks have been performed between existing fuel performance codes in order to upgrade them to take into account the specific issues related to MADF and MABB fuels under spherepac and pellet forms. The importance of coupling experiments and modelling has also been highlighted and data from PIEs have been identified as key elements to contribute to a better understanding of phenomena occurring under irradiation and to produce experimental database for the modelling validation.

Finally, in synergy with F-BRIDGE and CP-ESFR projects, PELGRIMM has drawn up a preliminary safety performance assessment of spherepacked MADF fuels. This investigation, summarized in section 1.3.4, has started linking spherepac fuel fabrication and irradiation behaviour developments to the problematics of core physics, design and safety performance. The PELGRIMM investigations have started with the design of an optimized core loaded with spherepac (U,Pu,Am)O_2 driver fuel and the determination of the core safety parameters and burn-up behavior. Two different accidental situations have been considered: first, an unprotected loss of flow accident (ULOF), then an unprotected transient over-power accident (UTOP). The first safety assessments and sensitivity analyses have benne performed. Even though they are simplified and preliminary assessments, they give trends of a core behaviour filled with spherepacked fuels and provide rather unexpected promising results.

1.2.2 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 Actinide (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 level wastes [8-9].
Based on historical experience and knowledge, oxide fuels have emerged in Europe as the shorter term solution to meet the Gen-IV assigned performance and reliability goals and two main MA-recycle options have led to consider within PELGRIMM:

- the homogeneous recycling mode, or Minor Actinide Driver Fuel (MADF) concept, where MAs are diluted in the standard driver fuel (U,Pu)O_2 at a low enough content (<3%) to limit the MA impact on the performance of the fuel and the core safety and on the fuel cycle facilities;

- the heterogeneous recycling mode on 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).

Regarding the first option, national and international R&D programs have been conducted for 25 years [10] and many issues have been addressed by irradiations such as SUPERFACT [11-14], Am1 [15-17] or AFC-2C&2D [18]. Besides, the GACID project that started in 2007 [19] within the GEN-IV International Forum, has aimed to supply the next key data required for the homogeneous recycling demonstration implementing irradiations up to bundle level in a Japanese SFR reactor.
Table 1 gives an overview of the irradiations already done, in progress or in preparation, related to homogeneous recycling mode, at the emerging stage of the PELGRIMM project.

Test	SUPERFACT	Am1	AFC-2C&2D	SPHERE	GACID
date	80's	2008	2008-2010	ready for irradiation	under preparation
participants	CEA / JRC-ITU	JAEA	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%	4%	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 : List of MADF irradiation tests done, in progress or in preparation at the emerging stage of PELGRIMM

Besides the MA strong impact on SFR core neutronic parameters that limits MA content in MADF [20] to less than 3%, MA addition to $(U,Pu)O_{2-x}$ can significantly affect major fuel properties such as melting temperature, thermal conductivity and oxygen potential, that are related to fuel behaviour and performance under irradiation. One of the main issues still under consideration is the high helium production during irradiation: this is a specificity of fuel containing MAs and the amount of helium produced is all the more significant as the ^{241}Am content is high. This helium production results from α disintegration of ^{242}Cm, itself formed by capture and successive β^- disintegrations of ^{241}Am. It continues out of pile by natural decrease of ^{242}Cm. This high helium production could drag additional fission product release or enhance fuel gaseous swelling favorable to Fuel-Cladding Mechanical Interaction (FCMI).
In addition, the impact of introducing MAs in the fuel remains a major concern for fuel manufacturing plants. The high neutron emission and the high thermal power of americium and especially curium generate significant technological constraints in order to limit exposure of staff, criticality risks, etc. Manufacturing must be carried out in shielded cells with remote handling, which means that the processes need to be revised.

In the MABB concept, MAs are concentrated in the radial blankets of the core to limit the neutron impact on the core physics. Moreover, 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.
However, its operation in the reactor under very specific conditions has raised many questions and experimental data on MABB remained scarce with the unique experiment of SUPERFACT. In this

experiment, the irradiation of $U_{0.6}Am_{0.2}Np_{0.2}O_{1.926}$ pellets led to a complete release of helium during irradiation and a highly porous fuel microstructure [12-13], consistent with high temperature operating conditions that were calculated (between 1500 and 1900°C according the assumptions performed). Nevertheless, the occurrence of FCMI and the absence of a central hole have remained unexplained.
For MABB fuel, the helium production is huge compared to MADF, due to the higher content of Am. In addition, the thermal conditions in MABB fuels correspond to moderate irradiation temperatures likely to result in significant swelling. A comprehensive R&D program of MABB fuel qualification has started in 2008 within the framework of the French national nuclear program [21]. It includes, as a first stage, two separate-effect irradiation tests: MARIOS irradiated within the FP7-FAIRFUELS project and DIAMINO implemented within the French national nuclear program [22], that aim at investigating helium behaviour and fuel swelling as a function of temperature, MABB microstructure as well as He production rate. Table 2 gives an overview of the irradiations already done, in progress or in preparation, related to heterogeneous recycling mode, at the emergence stage of the PELGRIMM project.

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 : List of MABB irradiation tests done, in progress or in preparation at the emergence stage of PELGRIMM

Regarding manufacturing process, if blankets loaded with MAs have to be manufactured in dedicated plants, the possibility to reprocess them by dilution with the standard flux of fuel assemblies in the current plants is under investigation, which would be a major asset of the MABB concept [8]. Nevertheless, sharp challenges have to be overcome such as the high specific heat for assembly manufacturing, the high decay heat level for in-core and out-of-core assembly handling, the high neutron source level at the fuel treatment step, etc [23]. As for the homogeneous recycling mode, the MA-bearing fuel fabrication process needs shielding, remote handling, simplification as well as implementation of relatively dust-free steps, but on a lower material mass flows than for the homogeneous mode.

Finally, in both kinds of MA-bearing oxide fuel investigations, 2 points emerged as of major concerns that could be taken into consideration within PELGRIMM:

- the high to huge helium production during irradiation, which could:
    - combined with low temperatures of MABB fuel, enhance the fuel gaseous swelling and FCMI
    - for MADF, drag additional Fission Product release as helium is expected to be totally released at high temperatures, and lead for improved Fuel Cladding Chemical Interactions;

- the need for simplification of the manufacturing process as well as implementation of relatively dust-free steps in the prospect of an industrial production.

1.2.3 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, would be attractive regarding MA-bearing fuels:

- the fabrication process could be significantly simplified thanks to the elimination of some process steps as milling, pressing and grinding, that involve fuel powders and dust.

- the potentially better accommodation of solid swelling (compared to pellets) through the re-arrangement of the free inter-particular areas under irradiation, could ultimately lead to better management of the helium generated during irradiation; this point, still to be demonstrated, would be a significant advantage of spherepac fuels;

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), which have been operated by Russia for about forty years [24]. Their advantages mainly are their behaviour at high temperature, which is similar to that of pellet fuels (formation of a central hole, columnar grains…), 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 and a risk of loss of fissile granulates in the coolant in case of cladding failure.

In Europe, the development of granulate (carbide) fuels started in the mid-80's [25], initially within the framework of the NIMPHE series collaboration (CEA/JRC-Karlsruhe/PSI) [26] on advanced fuels for SFR. Substantial expertise was acquired by PSI and JRC-Karlsruhe about beads synthesis. Moreover an experimental device was designed by PSI in order apprehend beads behavior in case of cladding failure. Regarding granulated oxide fuels, the first irradiation experiment: BORA-BORA was implemented within a collaborative frame from 1997 and 2007 between CEA and IPPE (Russia) [27]. Part of the experiment consisted of the fabrication, irradiation in the BOR 60 reactor and examination of $U_{0.55}Pu_{0.45}O_{2-x}$ fuel columns made of pellets or granulates that lead to satisfactory PIE results. In addition, a few other international experiments on granulated fuels are described in the literature. For instance, the FUJI irradiation [28-30], carried on in the HFR reactor (2004-2005) between JNC, NRG and PSI consisted in the study of $U_{0.8}Pu_{0.2}O_{2-x}$ and $U_{0.75}Pu_{0.2}Np_{0.05}O_{2-x}$ fuels under pelletized and granulated forms (beads and angular shards), for SFR-type irradiation conditions. In parallel, fuel performance codes [31] such as SPACON (PSI), SPHERE (PSI) and CEDAR-VIPAC (JAEA) were developed for $(U,Pu)O_2$ granulated fuels.

Within European projects frameworks, developments on granulated fuels were firstly performed 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. The studies covered the thermal properties of spherepac stacks, the fabrication process developments and the appropriation of the vibro-compaction techniques, the simulation of granulate fuel pins under irradiation thanks to SPACON and SPHERE codes and a technical-economic study for Generation IV systems [32]. Within FAIRFUELS, the objective included the design, the manufacturing and the irradiation stages of the SPHERE experiment in HFR [33], in order to compare the behaviour under irradiation of $(U,Pu,3\%Am)O_{2-x}$ fuels under pelletized and spherepacked shapes, fabricated by ITU. (PIEs of the SPHERE irradiation were to be performed in a FAIRFUELS follow-up).

As a conclusion, regarding the developments on spherepac fuels, the following points emerged for building the PELGRIMM project:

- the need to perform the PIEs of the SPHERE test in order to make use of the irradiation,

- the interest to go on efforts initiated within previous initiatives regarding spherepacked fuel fabrication process, irradiation behaviour and performance, as well as to extend the investigation to an exploratory analysis of a SFR core physics loaded with spherepacked Am-bearing fuels.

1.2.4 Overview of the PELGRIMM technical items

The key points mentioned in the previous sections were used as basements for the PELGRIMM project that is described into details in [1].

Figure 1 gives an overview of the contents, dependencies and links between the technical items the Scientific and Technical Work-packages (WP1 to WP4) and other FP7 projects, that explains the choice performed in the present report to outcomes according to rational different from results gained by Work-Package.

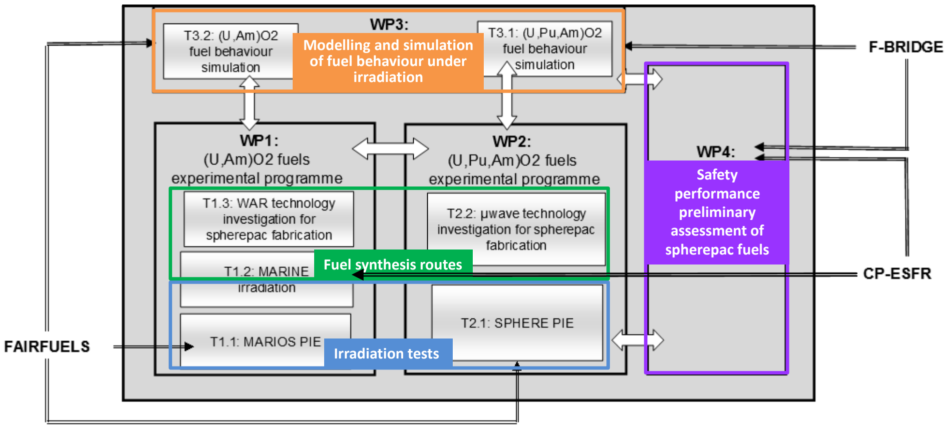


Figure 1 : PELGRIMM project overview

As shown in Figure 1, two-way close connections exist within and between technical Work-Packages:

- experimental activities (WP1, WP2) and modelling-simulation (WP3, WP4),
- experiments on MABB (WP1) and MADF (WP2),
- MADF pin behaviour under normal operation conditions (WP1, WP3) to problematics of core physics under normal and off-normal conditions (WP4),
- pelletized versus spherepacked fuel behaviour (T1.1, T2.1, T3.1),
- spherepac fabrication through several technologies (T1.2, T1.3, T2.2).

Moreover, dependencies to other FP7 projects are as follows:

- PIEs within PELGRIMM framework address MARIOS and SPHERE irradiations, performed within FAIRFUELS and valorize their output,
- developments of the fuel performance code MACROS were performed in FAIRFUELS regarding MA-Inert Matrix fuels and have been extended within PELGRIMM to MA-bearing fuels on UO_2 support,
- the fuel performance code TRANSURANUS has been upgraded within F-BRIDGE project to integrate spherepac fuel geometry as well as some of mesoscopic information already gained from fundamental research activities, which govern macroscopic Gen-IV fuel behaviour at a macroscopic scale,

- the fuel performance codes SPHERE and SPACON, dedicated to spherepacked fuel behaviour under irradiation, have been upgraded within F-BRIDGE project to be able to simulate the behaviour of advanced spherepacked fuel in Gen-IV systems,

- thermal properties of $(U,Am)O_2$ samples have been measured within CP-ESFR and have provided reliable and accurate data for the MARINE irradiation design,

- the preliminary safety performance assessment of spherepac MADF fuel (WP4) has been in continuity with F-Bridge evaluations made on the impact and suitability of spherepacked fuels for Gen-IV systems as well as with CP-ESFR neutron and safety assessment made on pelletized MADF core designs.

To reflect the fuel development approach followed throughout the project, it has been chosen to develop the main technical outcomes gained within PELGRIMM as follows:

- irradiation tests (section 1.3.1)

- fuel synthesis routes (section 1.3.2)

- modelling and simulation of fuel behaviour under irradiation (section 1.3.3)

- safety performance preliminary assessment of spherepac fuels (section 1.3.4).

1.3 Description of the main S&T results / Foregrounds

1.3.1 Outcomes from irradiation experiments

An irradiation campaign includes the design of the fuel, pin and device features, the manufacturing and assembly of the components, the implementation in a reactor and the execution of the PIE program. As the time required for an irradiation campaign 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 follow each other.

The PELGRIMM project has 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:

- **the PIEs of the SPHERE semi-integral irradiation have provided the first results on MADF spherepac fuel behaviour under irradiation as well as the direct comparison between spherepac and pellet MADF fuel performances;**

- **the PIEs of the MARIOS analytical irradiation have provided the very first results on helium behaviour and fuel swelling concerning two MABB fuel microstructures irradiated at two temperatures of interest regarding heterogeneous recycling mode implementation;**

- **the MARINE semi-integral irradiation in HFR has constituted a second step in the long term qualification approach of MABB fuels, by testing in a semi-integral and comparable way the behaviour of pellet and spherepac MABB fuels.**

Table 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 paragraphs.

		SPHERE mini-pin #1 top	SPHERE mini-pin #2 bottom	MARIOS mini-pin #1 top	MARIOS mini-pin #2	MARIOS mini-pin #3	MARIOS mini-pin #4 bottom	MARINE mini-pin #1 top	MARINE mini-pin #2 bottom
fuel	**project**	FAIRFUELS		FAIRFUELS				PELGRIMM	
	recycling mode-fuel concept	homogeneous-MADF		heterogeneous-MABB				heterogeneous-MABB	
	composition	(U, Pu, 3%Am)O2		(U, 15%Am)O2				(U, 13%Am)O2	
	fabrication	sol-gel process		powder metallurgy				sol-gel process	
	type of fuel	spherepac	pellet	pellet				spherepac	pellet
	geometry	beads	sintered beads	disks				beads	sintered beads
	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				**NOT PLANNED**	
NDE	**neutronographies**	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								
	EPMA, SIMS								

* to be confirmed after irradiation

Table 3 : Summary of SPHERE, MARIOS and MARINE fuel features, irradiation conditions and PIE results

1.3.1.1 SPHERE

The SPHERE semi-integral irradiation [33] has emerged as a first of a kind since its PIEs have provided unique results on MADF spherepac fuel behaviour under irradiation as well as the sole direct comparison between spherepac and pellet MADF fuel performances. The PELGRIMM project has hosted the PIE activities for SPHERE irradiation, which was designed, manufactured and irradiated within the FAIRFUELS project (2009-2015).

SPHERE is an experiment dealing with homogeneous recycling of MAs in SFRs. The main objective of the SPHERE experiment has been to study the in-pile behaviour of fuel containing 3% of americium and in particular the role of microstructure (spherepac versus pellet) and temperature on fission gas and helium release as well as on fuel swelling.

The SPHERE $(U,Pu,Am_{0.03})O_{2-x}$ beads were prepared (within the FAIRFUELS project) at JRC-Karlsruhe by infiltration of porous $(U,Pu)O_2$ precursor beads (prepared by sol-gel gelation), with americium nitrate solutions. Two sizes of Am-bearing beads (50 and 800µm) were synthesized and heat treated. Two fabrication routes were implemented to prepare the two types of fuel (pellet and spherepac) [33]. Representative pictures of fuel pellets and spheres are presented in Figure 2 and Figure 3.

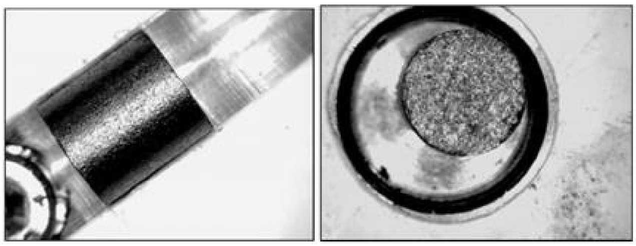


Figure 2 : Am-bearing MOX pellets fabricated for the SPHERE irradiation

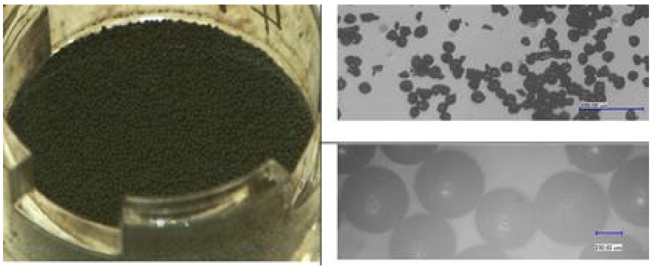


Figure 3 : Am-bearing MOX spheres for the SPHERE irradiation in two size fractions: small (≈60 µm, left) and large one (≈800 µm, right)

The SPHERE experimental device include two pins, made with 15–15 Ti austenitic steel cladding and arranged as follows:

- one mini-pin was loaded with 6 sintered pellets of $(U,Pu,Am_{0.03})O_{2-x}$, obtained from a batch of small sized beads;
- one mini-pin contained a stack of beads of $(U,Pu,Am_{0.03})O_{2-x}$ with 2 size fractions (50µm & 800µm), packed by vibrations.

The pins were placed one on top of the other with fuel stacks positioned in the highest flux area (i.e. close to the medium plane of the core) in HFR. The detailed characteristics of the fuel irradiated in SPHERE are given in [33].

The irradiation of the SPHERE experiment was performed (within the FAIRFUELS project) in HFR during 11 reactor cycles, from September 2013 up to April 2015, with the following conditions:

- irradiation duration: ~295 EFPD
- maximum burnup: ~5at%
- maximum Linear Heat Rates of ~300W.cm^{-1} with the linear power history* shown on Figure 4

(*: In order to get an accurate estimate of the deposited power in each of the fuel samples, both photons and neutrons are included in the power calculation [34].)

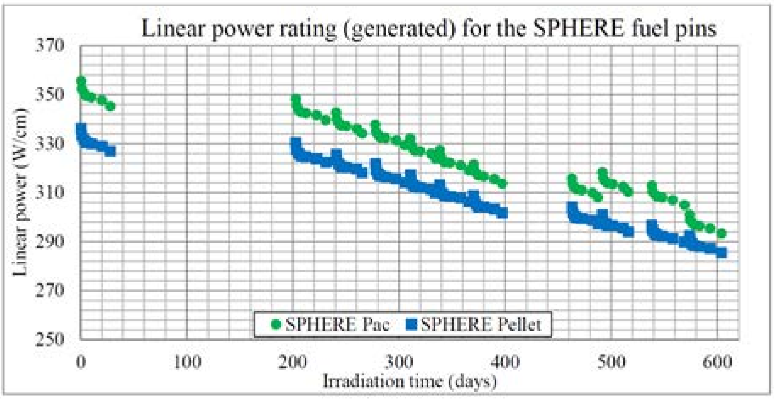


Figure 4: Linear power in the SPHERE fuel pins as a function of the irradiation time

All Post-Irradiation Examinations have been performed by NRG [34-35]. (Destructive Examinations, initially scheduled at JRC-Karlsruhe, have finally been done by NRG as the transport of the pins has not been possible within the timescale of the project).

The main results deduced from NDEs are summarized in Table 4.

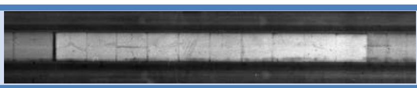
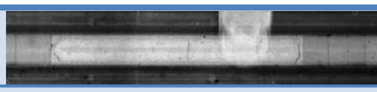
	SPHERE pellet fuel pin	SPHERE spherepac fuel pin
Neutron radiographies after 1rst cycle (~28 EFPD, at 300-320 W/cm linear power); **Note: not significantly different at EOI**		
	no central hole detected	central hole
	no fuel restructuring detected	fuel restructuring
	cracks	no cracks
	no significant elongation	
Gamma spectrometry scans	no significant elongation	
	non-volatile FP (^{95}Nb, ^{95}Zr) distribution : consistent with axial neutron flux (peaking at the ends) ⇨ axial power profile recalculation	
	^{134}Cs, ^{137}Cs distributions : no pronounced diffusion direction	^{134}Cs, ^{137}Cs distributions : clear diffusion toward the ends
Visual inspection	No significant cladding degradation: no scratches, no dents, no tears	
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	

Table 4: Results of NDEs on pellet and spherepac fuel pins after the SPHERE irradiation

From a macroscopic point of view, the behavior of the pellet and spherepac MADF fuel is globally the same. For the two types of fuels:

- **the clad has not been degraded nor deformed;**
- **the fuel stacks have not been elongated (nor creeped);**
- **the non-volatile FP (^{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 destructive examinations;**
- **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.**

Regarding Destructive Examinations, optical microscopy has been performed on 6 samples: one axial and two radial, 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 SEM/WDS for elemental analysis. 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 DEs are summarized in Table 5.

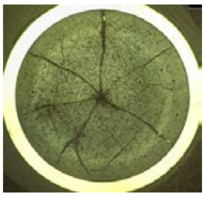
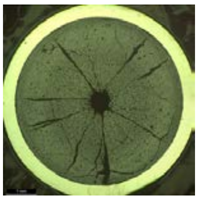
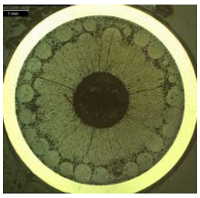
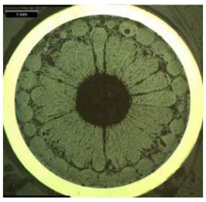
The behaviour under irradiation of pellet and spherepac fuels is quite similar in terms of fuel microstructure:

- formation of a central hole, smaller (and for undetected by neutron radiographies) pelletized than spherepacked stacks due to a lower temperature regime in pellets that can be explained by a higher thermal conductivity of the pelletized compared to spherepacked fuel,
- restructured region with columnar and equi-axed grains,
- similar microstructure, in this restructured area, with increased/decreased porosity for pellet/spherepac respectively, with respect to the corresponding as-fabricated porosity,
- presence of pores mainly along the grain boundaries, in this restructured area.

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

The radial actinide distribution in the pellet fuel confirms the observation reported for previous comparable irradiation tests, such as SUPERFACT [11-14], Am1 [15-17] or AFC-2C&2D [18]: 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 redistribution is located in the columnar grain region. 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).

To confirm these very first results, an obvious recommendation would be to perform DE on other samples of these columns.

	SPHERE pellet fuel		SPHERE spherepac fuel	
Optical microscopy (+SEM)				
Estimated linear power	~ 290 W/cm	~ 298 W/cm	~ 307 W/cm	~ 322 W/cm
Cracks	6 “big” cracks	8 “big” cracks		
Central hole	Very small Diameter ~ 0.2 mm	Small Diameter ~ 0.65 mm	Diameter ~ 1.86 mm	Diameter ~ 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
For spherepac fuel : sintered/recrystalized ~ solid porous matrix	Equi-axed grains Diameter ~ 4.35 mm	Equi-axed grains Diameter ~ 3.9 mm	Equi-axed grains (gradual) Diameter ~ 4.41 mm	Equi-axed grains (gradual) Diameter ~ 4.2 mm
Microstructure inside restructured region	Increased porosity; pores along grain boundaries		Decreased porosity; pores along grain boundaries	

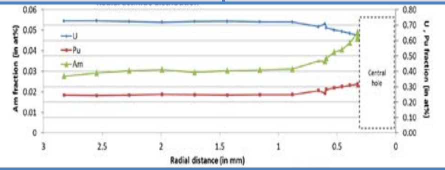
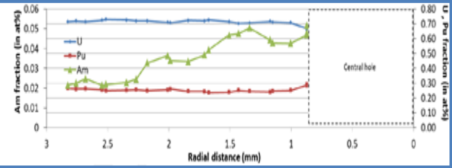
Microstructure beyond restructured region	~ as fabricated + several large pores		High density of small pores
Fuel Cladding Mechanical Interaction (FCMI)	No gap closure, No FCMI	FCMI Radial width ~ 25-30 µm	No homogeneous interaction layer but metallic precipitates (iron) + grey colored phase (Al_2O_3)
Radial actinide distibution (WDS)			

Table 5 : Results of DEs on pellet and spherepac fuels after the SPHERE irradiation

To complete the analysis, let's mention that within WP 3, the pellet and spherepac fuel pins irradiated in the SPHERE experiment have been simulated blindly (previously to PIE execution) with MACROS, TRANSURANUS and SPHERE_3 codes. The similarities and differences between the codes and the discussion concerning the comparison of the calculated results obtained with fuel performance codes with those deduced from PIEs and neutron calculations are presented in section 1.3.3. In short, a reasonably good agreement has been obtained between measured and calculated fuel temperature, central hole formation and fuel restructuring for both spherepac and pellet fuels, even if they seem to have been under-estimated. The major discrepancy concerns the calculated and measured released fractions for fission gas and helium, for which the measurement uncertainties were large, so definite conclusions, could not be drawn from these calculations.

1.3.1.2 MARIOS

The MARIOS separate-effect test [37] which is the first irradiation of a comprehensive R&D program of MABB fuel qualification, started in 2008 [21-22], has been designed in order to investigate helium behaviour and fuel swelling for 2 $(U,Am)O_2$ microstructures under irradiation in the HFR reactor, kept at constant temperatures.

Both dense and tailored porosity $U_{0.85}Am_{0.15}O_{2-x}$ pellets were fabricated by a powder metallurgy process in ATALANTE hot cells according to the flow sheet given in [38]. Two different densities (and open porosity ratio) were obtained: ~92% of the theoretical density for the dense disks and ~87% of the theoretical density for the tailored porosity disks [38]. As shown on Figure 5, there was a significant difference between the two microstructures:

- the tailored porosity microstructure exhibited the presence of both interconnected open porosity and elongated pores which were inside dense zones at grain interfaces;
- Regarding the dense compounds, they had almost a uniform microstructure with large grains sizes. The porosity was mainly closed at grain interfaces.

The detailed characteristics of the fuel irradiated in MARIOS are given in [37-38].

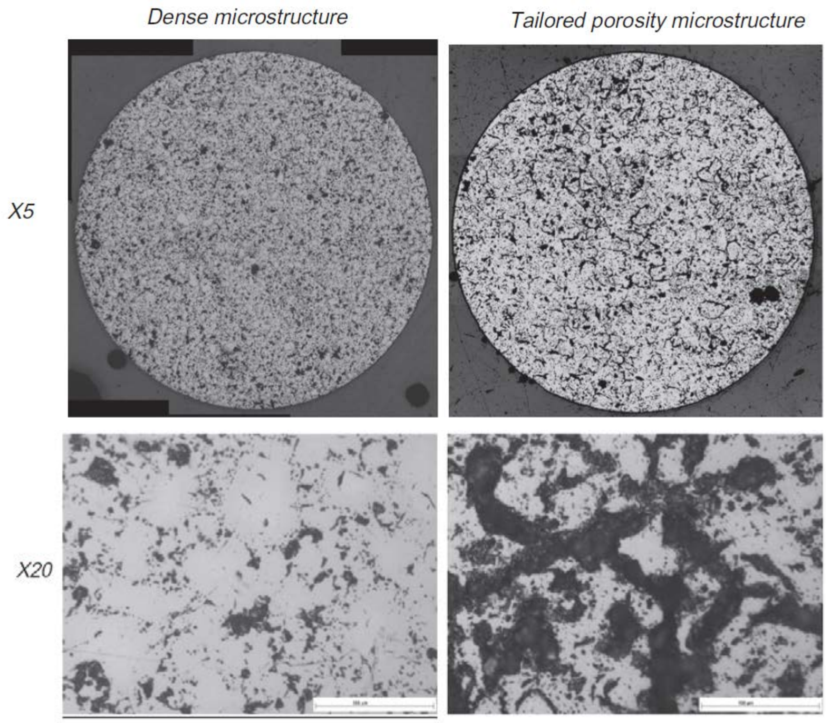


Figure 5 : Optical micrographs of dense and tailored porosity disks

For this irradiation, fuel shapes, pins, sample holders and irradiation devices were specifically designed to get an accurate control of the temperature, to provide a flat intra-pellet temperature distribution and to allow a free swelling of the fuel [22].

The MARIOS experimental device consisted of four sealed mini pins, made of Inconel 718. Each pin contained a stack of tungsten alloy (TZM) trays containing six fuel disks and the top tray contained a thermocouple in the radial center as shown in Figure 6.

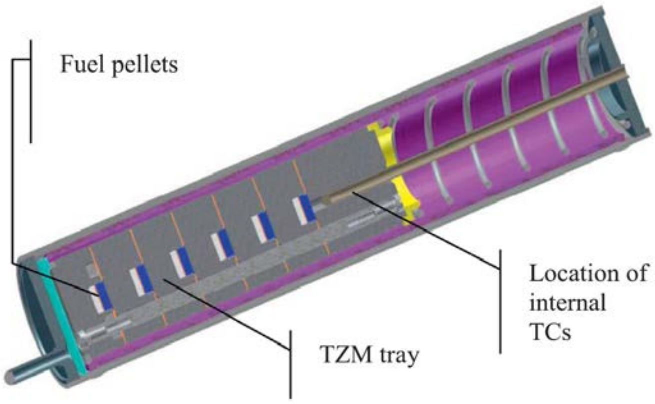


Figure 6 : Schematic view of the MARIOS sample holder

The four fuel pins were stacked vertically inside a sample holder and placed in the highest flux position (i.e. close to the core mid-plane), with:

- two mini-pins (pin #1 -#2) containing 6 "dense" disks of $U_{0.85}Am_{0.15}O_{1.94}$, with a density of 92% of the theoretical density and 7.7% open porosities,
- two mini-pins (pin #3 -#4) containing 6 "tailored porosity" disks of $U_{0.85}Am_{0.15}O_{1.94}$, with a density of 87% of the theoretical density and 12% open porosities.

The irradiation of the MARIOS experiment was performed (within FAIRFUELS) in HFR during 11 reactor cycles, i.e. 304 Equivalent Full Power Days (EFPD), from March 2011 up to May 2012. Selected results of the irradiation conditions are presented in Table 6 for each mini-pin [37] [39]. Figure 7 shows that the fuel disk powers rise continuously over the course of the irradiation, and that fuel disk powers are highest in the two central pins (pins #2 and #3).

	Pin #1	Pin #2	Pin #3	Pin #4
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

Table 6: Average power density, burn-up and temperature at end of irradiation (EOI) for each mini-pin.

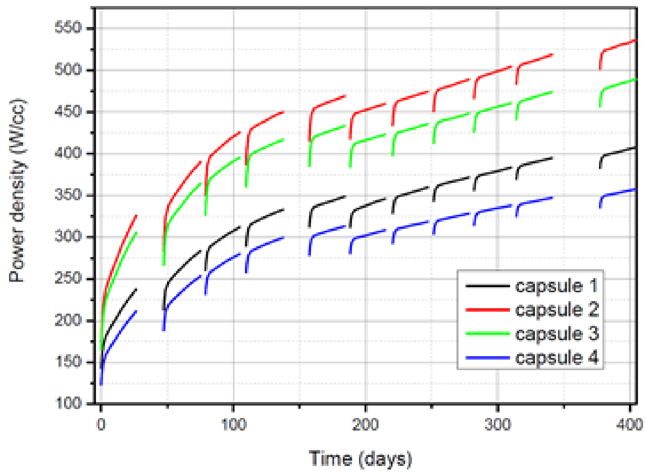


Figure 7 : Calculated fuel power densities for the 4 pins as a function of irradiation time.

Figure 8 represents the temperature histories of the TZM trays (thermocouple measurements) and illustrates the essence of the MARIOS test with the quasi-isothermal irradiation of the MABB pins. After the irradiation, the fuel disk temperatures were calculated from the temperatures of the TZM trays as monitored during irradiation (~100°C higher than thermocouple measurements, cf. Table 6). The condition of well-defined, constant fuel temperature was mostly satisfied during the whole irradiation period [37] [39]: the temperature spread during irradiation (2σ) was about 70°C. However, in pin #2, the temperature was much higher than expected (1370°C vs 1200°C). It seems that during the assembly and the final welding of pin #2, some argon from the filling glove box may have entered inside the pin, leading to an irradiation temperature higher than expected due to the high thermal conductivity of argon.

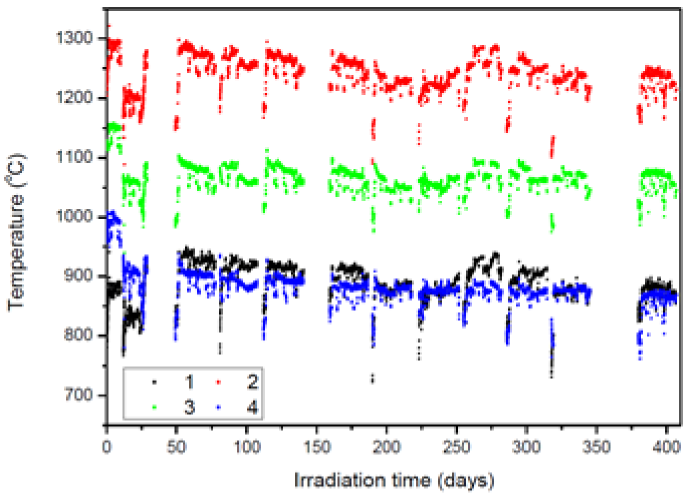


Figure 8 : Temperature histories of the TZM trays containing the fuel disks

Regarding PIEs, Non Destructive Examinations have been performed in NRG hot cells [37] and Destructive Examinations in CEA LECA-STAR hot cells [40].

The main results deduced from NDEs are summarized in Table 7 and Figure 9.

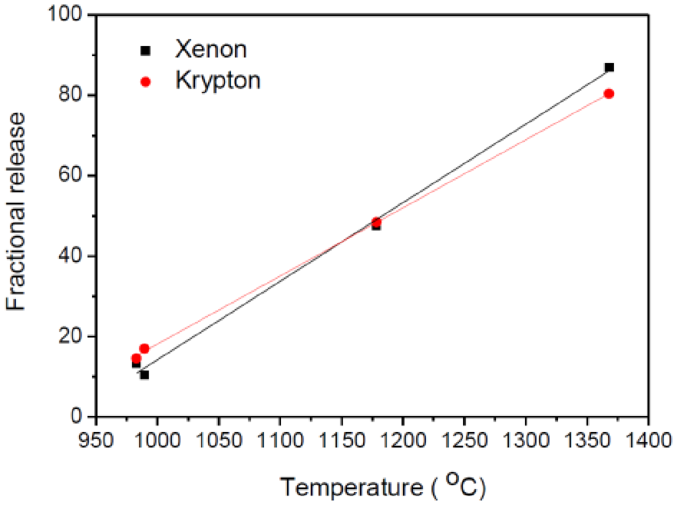


Figure 9 : Released fractions of Krypton and Xenon.
The lines are linear fits through the 4 points (no physical significance).

	Pin #1	**Pin #2**	**Pin #3**	**Pin #4**
Microstructure	High density / low porosity	High density / low porosity	Low density / tailored porosity	Low density / tailored porosity
Power density at EOI (W/cc)	412	542	492	364
Temperature (°C)	990	1370	1180	980
Neutron radiographies at EOI	No crack detected	Cracks detected	Cracks detected	No crack detected
Gamma spectrometry scans	axial distributions of Nb, Ru (non-volatile) : good agreement with calculated production			
***estimation of pin #2 Cs release with the assumption of no Cs release for pin #1 and #4**	~ no Cs release*	~ 60-70% Cs release*	Not evaluated (misalignment)	~ no Cs release*
Puncturing results (uncertainties ~20%, unexpected presence of argon)	100% He release during irradiation (assuming no release during cooling time)			
	17% Kr release	80% Kr release	48% Kr release	15% Kr release
	10% Xe release	87% Xe release	47% Xe release	13% Xe release

Table 7 : Results of NDE on fuel pins after the MARIOS irradiation

At this stage, a clear effect of temperature has been evidenced:

- **cracks have been detected by neutron radiographies for the 2 pins submitted to the highest temperature (pin #2 and # 3),**
- **Cs release has been evidenced for the pin submitted to the highest temperature (pin #2),**
- **Xe and Kr release are strongly temperature dependent in the investigated temperature range and rather consistent with Cs behavior (qualitatively), as shown Figure 9.**

On the contrary, considering that the He release during cooling time is negligible, it has been concluded that all helium produced during irradiation was released in the plenum, irrespective of differences in porosity and temperature. Apparently the threshold for high helium release lies below 1000 °C.

Destructive Examinations [40] have focused on the effect of fuel microstructure: they have been performed on the fuel disks of pin #1 and #4, which microstructure is respectively of high and low density, and which have been 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 DEs are summarized in Table 8.

	Pin #1	Pin #2	Pin #3	Pin #4
Microstructure	High density / low porosity	High density / low porosity	Low density / tailored porosity	Low density / tailored porosity
Power density at EOI (W/cc)	412	542	492	364
Temperature (°C)	990	1370	1180	980
Number of fragments, Visual inspection	4 disks in 3 frag[t] 1 disk intact 1 disk in 5 frag[t]	5 disks in 2 frag[t] 1 disk intact	4 disks in 6 to 8 frag[t] 1 disk in 12 frag[t] 1 disk in 14 frag[t]	5 disks intacts 1 disk in 2 frag[t]
Geometrical density variation	Not significant: no macroscopic swelling		Not measurable	Not significant: no macroscopic swelling
Hydrostatic density variation	Not significant		-5.6% : densification	-7.2% : densification

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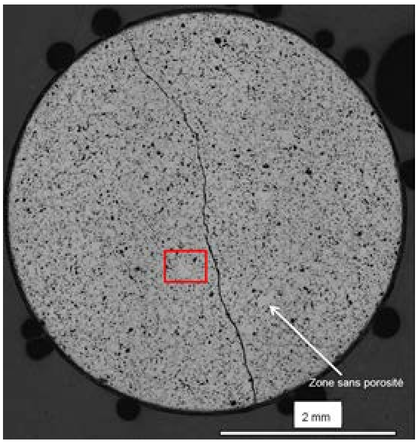
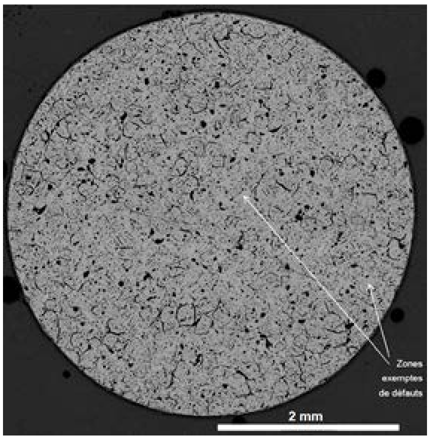
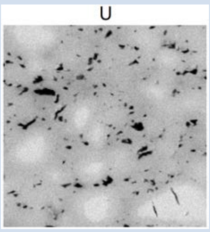
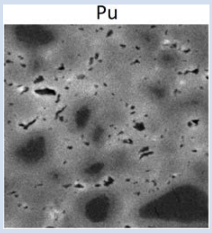
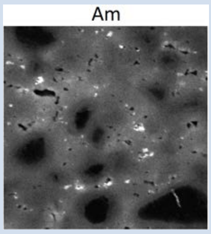
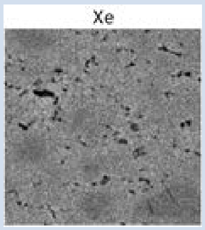
<tr><td>Optical macro/ microscopy (+SEM)</td><td colspan="2">
</td><td colspan="2">
</td></tr>
<tr><td></td><td colspan="4">Pin #1 (similar results for pin #4)</td></tr>
<tr><td rowspan="3">EPMA

Qualitative X maps of mid-width central area

Quantitative radial profiles</td><td>
</td><td>
</td><td>
</td><td>
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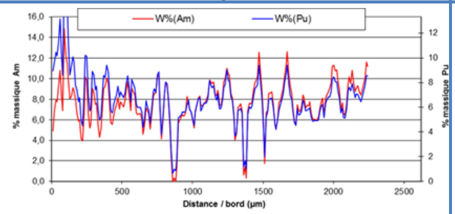
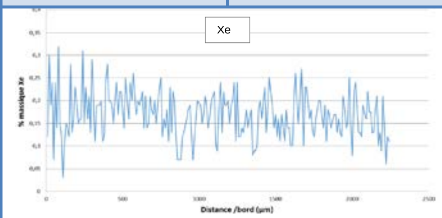
<tr><td colspan="2">
</td><td colspan="2">
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M measurement
C calculation</td><td>Transmutation rate
M :T_T=45.7%
C :T_T=45.9%</td><td>Fission rate
M :T_F=1.14%
C :T_F=1.14%</td><td>Fission gas: Xe
M(wt%): 0.17%
C(wt%): 0.15%</td></tr>
<tr><td>SIMS</td><td colspan="4">Detection of He,
Other elements: isotopic ratios in good agreement between measurement and calculation</td></tr>
<tr><td>XRD</td><td colspan="4">No significant phase modification</td></tr>
</table>

Table 8 : Results of DE on fuel disks after the MARIOS irradiation

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 fuels have been 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.

The effect of microstructure on fuel behavior 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, except for densities: tailored porosity disks (pin #4) have been densified, on the contrary to dense disks (pin #1) which have remained stable.

No macroscopic swelling has been evidenced for pin #1 and #4 fuels, and the microstructure after irradiation for both type of fuels has remained very similar to the as-fabricated microstructure (see Figure 5).

Xe concentration measured by EPMA is consistent with low release estimated by puncturing (~10% for pin #1), especially since Xe concentration has been measured on a single (intact) piece of disk with EPMA while Xe release, estimated by puncturing, is an average of the release of the 6 disks, some of them cracked, potentially leading to higher release. A significant amount of He has been detected by SIMS, but not quantified. It is assumed to be He formed during cooling time, essentially by α decay.

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]) can be underlined.

Preliminary results of fuel performance simulation for MARIOS pins have been obtained with the MACROS fuel performance code (see section 1.3.3): the burn-up of the fuel determined by calibration of post-irradiation burnup calculations and by MACROS code calculations are in good agreement with reported values. Neutron considerations in model analysis of the MARIOS pins are consistent with NRG results. Reasonably good agreement in terms of He and Xe release was obtained for the four pins, compared to puncturing measurements. However, quantitative amounts of generated He were noticeably different. MACROS code gave higher production of He. Even if a refine analysis is necessary, taking into account the PIE results and uncertainties, which were not available at the time of the simulation, these preliminary results show that quantitatively reported design, operational and PIE results cover most of data that fuel performance codes need as inputs.

1.3.1.3 MARINE

The MARINE irradiation [41-42] is part of the second step in the long term qualification approach of $(U,Am)O_2$ fuels (separated-effect tests like MARIOS belonging to the first step). MARINE is the first semi-integral test of the AmBB development programme. In this 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 [43]. This choice is consistent with the previously irradiated MARIOS experiment.

In addition, MARINE is the SPHERE matching piece as it included 2 mini-pins of pellet and spherepac fuel stacks of $Am_{0.85}U_{0.15}O_{2-x}$. 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 behavior during the irradiation.

The Am-bearing fuel for MARINE, both pellet and spherepac shapes, were prepared at JRC-Karlsruhe. The $U_{0.85}Am_{0.15}O_{2-x}$ beads were synthesized by infiltration by americium nitrate solutions, of porous UO_2 precursor beads (prepared by sol-gel gelation). Two sizes of Am-bearing beads were prepared and heat treated. The two fabrication routes implemented to prepare the two types of fuel (pellet and spherepac) and the characteristics of the fuels are detailed in section 1.3.3.

The MARINE experimental device consists of two pins made with 15–15 Ti austenitic steel supplied by CEA. The 2 pins have been packed as follows:

- one mini-pin was loaded with 6 sintered pellets of $U_{0.85}Am_{0.15}O_{2-x}$, obtained from a batch of small sized beads;

- one mini-pin contained a stack of beads of $U_{0.85}Am_{0.15}O_{2-x}$ with 2 size fractions (50µm & 800µm), packed by vibrations.

The pins have been placed one on top of the other with the two separate fuel stacks placed in the highest flux position (i.e. close to the mid-plane of the core).

The results of the calculations performed in order to design the experimental device and predict the irradiation conditions that are detailed in [41-42], are summarized hereafter.

The nuclear analyses have been performed for a total effective irradiation duration of 15 cycles (450 full power days), but to reflect the real operating conditions of HFR, outages of 30 days every 90 days of operation were included, leading to a cumulated irradiation duration of 19 cycles (570 days). The calculation of the power history has shown, for both pellet and spherepac fuels, a linear power increasing with burn-up, mainly due to the production of Pu from the chain reaction of Am (see Figure 10).

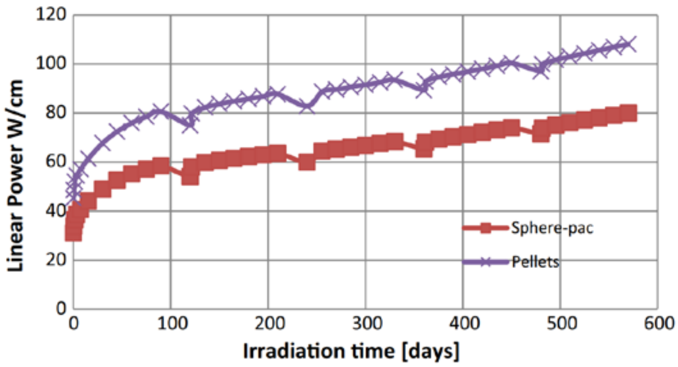


Figure 10 : Linear power as a function of irradiation time in EFPD

In addition, thermal analyses for the beginning (BOI) and the end of irradiation (EOI) have been performed. As, during the irradiation the temperature of the pins could be adjusted by changing the gas mixture (He-Ne) in the sample holder, the temperature distribution in the pins has been calculated considering four extreme design cases (BOI, 100% Helium; EOI, 100% Helium; BOI, 100% Neon; EOI, 100% Neon). From Figure 11, it is clearly visible that the model predicts a fuel central maximum temperature about 950°C to 1200°C and 920°C to 1120°C for the spherepac and pellet pins respectively, depending on the composition of the He-Ne gas mixture. These results have been 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.

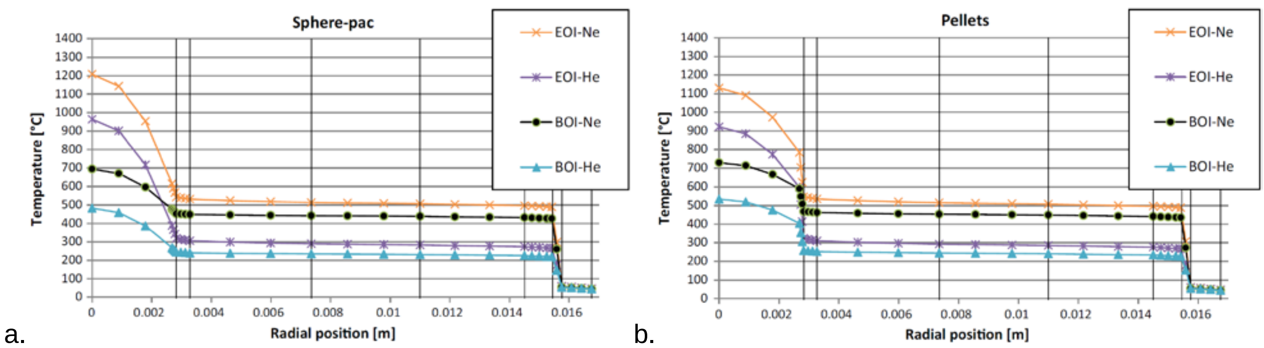


Figure 11 : Comparison of radial temperature distribution for the different load cases,
a. spherepac fuel, b. pellets fuel

Moreover, as gas release is part of the main objectives of the MARINE experiment, the helium production (Figure 12) has aimed being representative of Am recycling scenarios in SFR reactors [43] 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 project.

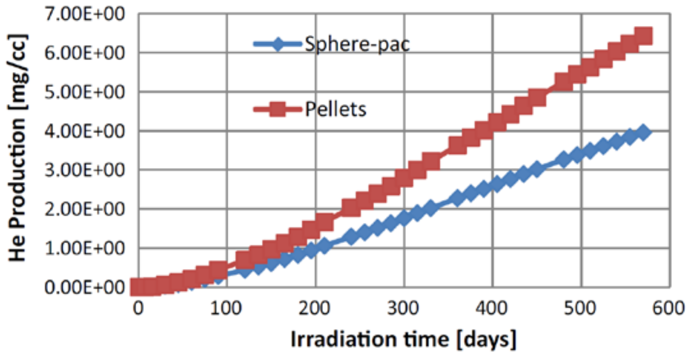


Figure 12 : Predicted helium production of the Am-BB fuel based on MCNP/FISPACT burn-up calculations

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 [44]. Regarding on-line pressure measurements that were implemented for the first time on Am-bearing fuel pins, the pressure recordings of the pelletized fuel pin have been available up to the end of the 4th cycle whereas the pressure transducer of the spherepacked fuel pin has failed at the beginning of the irradiation. Figure 13 shows the pressure readings and average LVDT temperatures of the Linear Voltage Differential Transducer (LVDT) during the first four cycles of irradiation for the pelletized fuel pin.

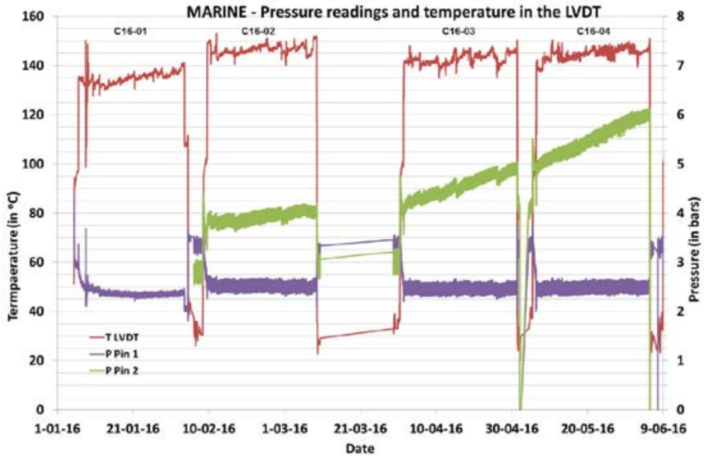


Figure 13 : Pressure readings during the MARINE irradiation (pin 1: spherepac, pin 2: pellet)

Figure 14 shows the measured pressure during progressive irradiation, converted to released gas atoms in the free volume, together with the produced gas calculated in the nuclear analysis. From these plots, it can be deduced that ~46% of the gas that is calculated to be produced, has been released into the pin plenum. Absolute number of released gas atoms won't nevertheless be available before recalculations of real irradiation conditions and puncturing measurements.

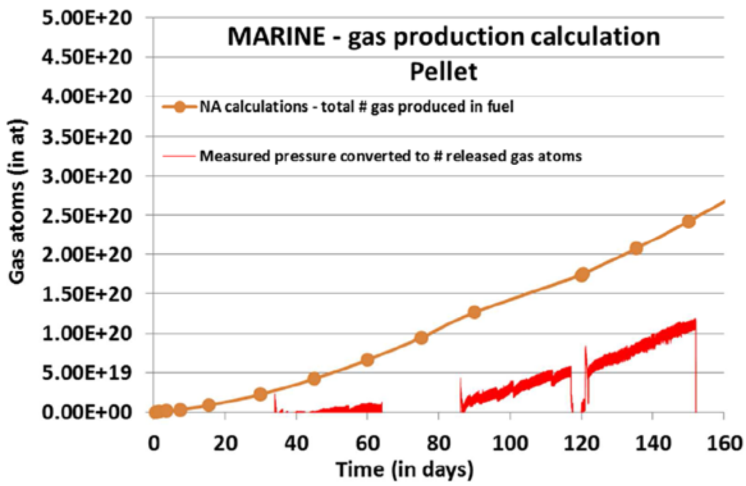


Figure 14 : Measured pressure during irradiation, converted to released gas atoms in the free volume (red line) ; produced gas atoms, calculated in the nuclear analysis (orange line)

The MARINE irradiation stage is currently fully completed and PIE are expected to be performed in a near future (within another framework) to take full benefit of this first semi-integral irradiation of pellet and spherepac MABB fuels.

1.3.1.4 Conclusion on the irradiation tests

Innovative irradiation tests and their PIEs performed within PELGRIMM have largely contributed to improve the knowledge on Am-bearing fuel behavior under irradiation for both MADF and MABB concepts, in spherepac and pellet forms.

Regarding MADF concept, PIEs of the semi-integral SPHERE irradiation has provided a direct comparison of the behaviour of pelletized and spherepacked fuels. For similar irradiation conditions, despite significantly different temperatures, the behaviour of different shaped fuels has been rather similar. For both fuel shapes: fuel restructuring and central void formation have occurred; a high level of fission gas release was measured (~90% for Xe and Kr and ~100% for He); the claddings were intact with neither measurable elongation nor creep effects. The main difference lies in the presence of FCMI for pelletized fuels, which seems absent for spherepacked fuels.

The MABB concept has got over a key step of its qualification program with the first separate-effect irradiation MARIOS which PIEs have already been performed, and the first semi-integral irradiation MARINE which has ended in May 2017.

MARIOS PIEs have shown that the AmBB discs were in a relatively good shape after irradiation in the temperature range of 1000°C-1300°C. Whatever the fuel porosity and the irradiation temperature, no significant swelling has been measured and tailored porosity disks have been slightly densified. Regarding gas release, all the helium produced during irradiation was released, irrespective of differences in porosity and temperature, on the contrary to the released fractions of Kr and Xe which are strongly temperature dependent.

The MARINE semi-integral irradiation in HFR has been successfully completed and its PIEs, to be planned in another framework than PELGRIMM, will provide the very first results on Am-BB fuels shaped as pellets and spherepac.

In parallel, first attempts to simulate the fuel behaviour under irradiation for SPHERE and MARIOS experiments thanks to fuel performance code developments have been performed. Despite some discrepancies, most of the preliminary results are consistent with PIE results. A refine analysis of these results that remains to be done (in another framework than PELGRIMM) will provide new insights in the modelling of MADF and MABB fuels shaped as pellets and spherepac. In addition,

these encouraging results enhance the need to take benefit from new experimental results by performing and exploiting PIE on the latest irradiation tests.

1.3.2 Outcomes from fuel synthesis routes investigations

Powder metallurgy flowsheets used to supply $(U,Pu)O_2$ standard fuels at industrial scale, can be used at lab-scale to prepare Am-bearing fuel samples, as the MARIOS disks for example [38]. However, their major drawback 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 fabrication processes. In this prospect, the spherepac technology is attractive as it would lead to a significant simplification of the fabrication process thanks to the elimination of some process steps as milling, pressing and grinding that involve fuel powders and dust. Moreover, the compactness of the fabrication process would be increased.

PELGRIMM has aimed investigating several options for spherepac fuel synthesis:

- **The internal gelation route, based on sol-gel processes that lead to dense or porous spherical particles of homogeneous compounds, has been used for Am-bearing fuel synthesis of the MARINE irradiation.**
- **A variant of the internal gelation route has also been investigated, using an electromagnetic heating within a microwave cavity instead of a silicon oil hot bath for the gelation of the drops.**
- **Finally, the adaptation to oxide fuels of the Weak Acid Resin technology initially implemented in the 1970's for the production of uranium carbide kernels, that restarted at CEA in the 2000's has been carried on within PELGRIMM.**

1.3.2.1 Sol-gel process and MARINE AmBB fuel fabrication

The main advantage of sol–gel processes involve the easy shaping during the gelification stage, thanks to the fluidity of the initial solution. In particular, they allow a controlled fabrication of dense or porous microspheres depending on their subsequent use such as for instance Spherepac fuel beads or pelletized fuel obtained 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 [45].

Already, within FAIRFUELS, the SPHERE $(U,Pu)AmO_{2-x}$ beads were prepared by infiltration of porous $(U,Pu)O_2$ precursor beads prepared by sol-gel gelation, with americium nitrate solutions (see § 1.3.1.1). Two sizes of Am-bearing beads (50 and 800µm) were synthesized and heat treated. One batch fraction of small sized beads was then transformed to sintered pellets, which were then loaded in one mini-pin. The other batch fraction of small sized beads and the batch of bigger beads were packed by vibrations in the other mini-pin.

For MARINE, the synthesis procedure has almost been similar to SPHERE for the preparation of pellets, but using UO_2 as precursor instead of $(U,Pu)O_2$. Two fabrication routes have been followed by JRC-Karlsruhe to supply the two types of fuel (pellet and spherepac) [46].

For pellets, the fabrication flowsheet included the following steps:

- production of porous UO_2 beads (without americium) by the sol gel external gelation route to give 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.

The Am content was close to the specified 15 mol% with respect to total heavy metal. The microstructure was of good quality, with a good distribution of porosity throughout the pellet (see Figure 15). Finally, the dense (95%TD) and defect free $U_{0.87}Am_{0.13}O_{1.93}$ pellets were stacked in the MARINE #1 mini-pin.

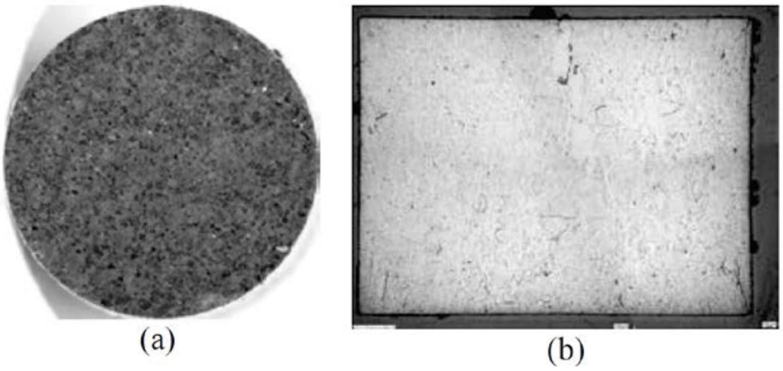


Figure 15 : Visual aspect (a) and ceramography (b) of a MARINE pellet

The spherepac fuel fabrication has been much more challenging. The synthesis of the fuel fractions for the particle fuel was performed by group conversion from mixed nitrate solution, which was prepared by mixing Uranium with Americium 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 fabrication conditions for large beads. This development succeeded in producing relatively good quality spherical particles. The optimization involves reducing the U(VI) in the solution to U(IV), and further adjustment of the free acid (present when Am solutions are prepared) and the metal to polymer ratio. Application of the process to Am showed nevertheless that the optimized conditions using acidified Nd solutions were appropriate to provide the same good quality particles achieved with Nd surrogate solutions. Adjustments were made and in the end moderately spherical particles were obtained (see Figure 16). An attempt to determine the density of the beads has revealed that the porosity content was very high: the density of the large beads was in the order of 67%.

Figure 16 : Large size MARINE beads visual aspect

The 2 MARINE pins were filled as follows:

- one with 6 sintered pellets of $Am_{0.85}U_{0.15}O_{2-x}$, obtained from a batch of small sized beads;
- the other, with a stack of beads of $Am_{0.85}U_{0.15}O_{2-x}$ with 2 size fractions (50µm & 800µm), packed by vibrations up to a smear density of 55.4 %TD (as the particles themselves have a density of ~67°%).

The resulting pins have been examined using X-ray radiography. The pellet fuel pin has shown no flaws, but the data for the sphere-pac fuel pin showed two regions of different density (see Figure 17). The bottom two thirds of the column was of high density, while the upper third was slightly lower. The reason for this discrepancy is not clear, but probably be linked to an undesired effect of vibrations, which would have crush particles at the top of the column, disabling their ability to pass through the bed below.

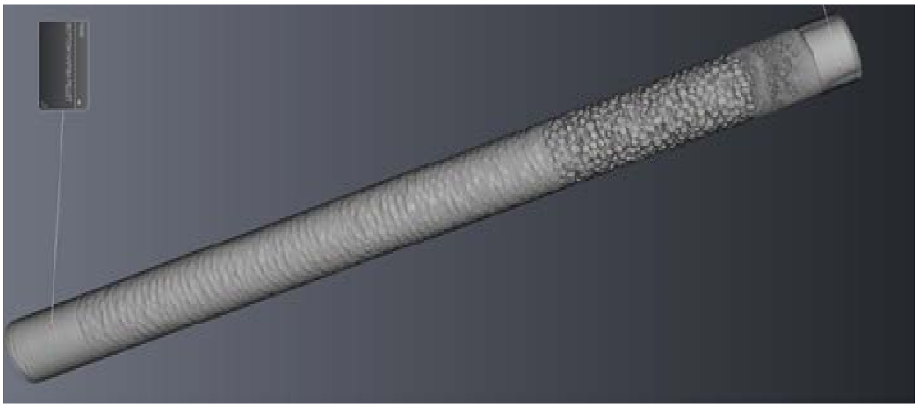


Figure 17 : X-ray radiography picture of MARINE 2 beads stack

Despite a lot of difficulties encountered during the fabrication process and the pin loading, this sol-gel process was used for the 1st time to synthetize AmBB fuels under pellet and spherepac forms for the MARINE irradiation. Now that this irradiation is complete, the PIEs (to be performed in another framework than PELGRIMM) will provide fuel performance results that may give a feedback to the fuel fabrication route.

1.3.2.2 Variant in the sol-gel processes: Microwave internal gelation

As seen above, internal gelation is a well-developed process to produce homogeneous spherical particles of nuclear fuel for the so-called Spherepac nuclear fuel 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, which leads to secondary wastes.

As it is irrelevant how and from which medium the heat is introduced into the spheres, a variant of the internal gelation route has been studied, using for gelation of the drops, an electromagnetic heating within a microwave cavity [47-48] instead of a silicon oil hot bath [49].

The production unit has been developed in the PSI hot laboratory and the process is described in Figure 18.

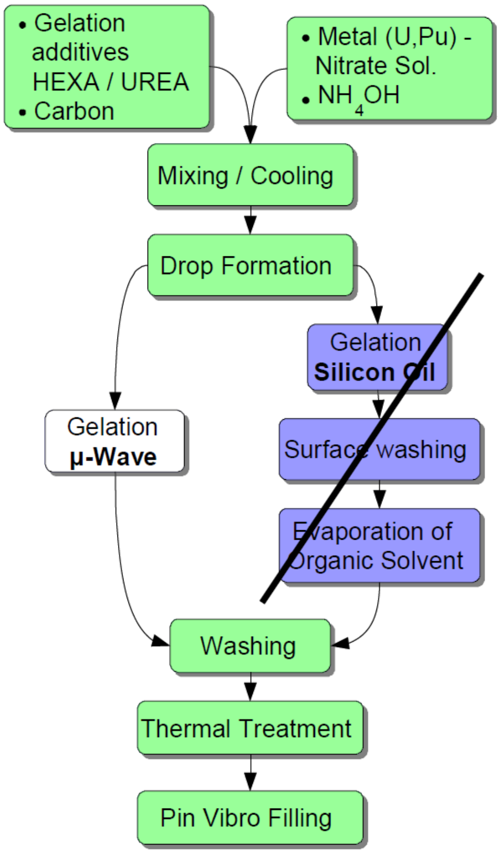


Figure 18 : Flowchart of the internal gelation route through a microwave cavity (left) compared to a silicon oil bath gelation step (right).

Firstly, a non-radioactive unit composed of droplet production and microwave heating equipment has been built in order to investigate the fabrication of spherules with a metal surrogate (cerium). This has enabled the testing of numerous combinations of educts concentrations (cerium nitrate, urea, hexamethylenetetramine (HMTA)): depending on the broth composition and the microwave power sent to the cavity, the broth drops do or do not undergo gelation.

Models and simulations regarding the electromagnetic heating part have been developed too [48].

Promising results have been obtained (Figure 19) for non-radioactive surrogates.

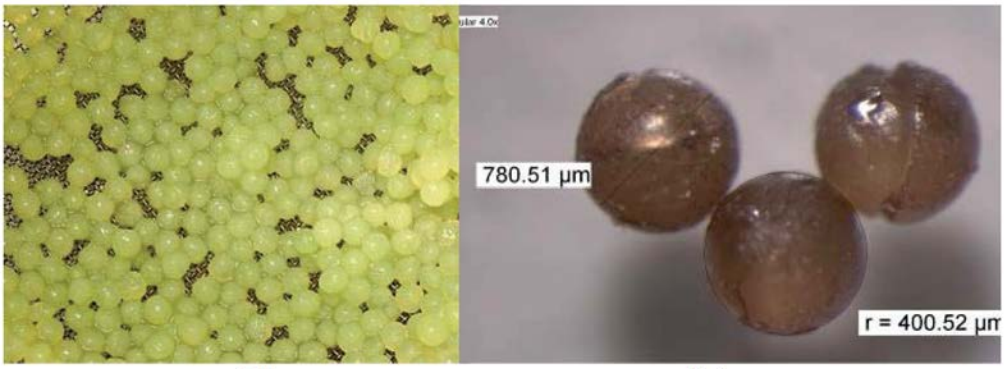


Figure 19 : Spheres collected after microwaved gelation before (a) and after (b) drying.

Then, the implementation of the devices in glove-boxes started for validation on U-type (before (U,Pu)-type) compounds :

- a new mixing device has been purchased and commissioned: this unit provides rapid mixing of the feed solutions (Actinide nitrate, urea and HMTA);
- as the actinides are self-heating, which is detrimental for the gelation process that can then occur prematurely, the solutions need additional cooling and piping paths have to be short: the glove box design to implant this equipment in a reliable manner has also been completed;
- concerning the microwave components, only the cavity and one waveguide will be placed in the glove-box, with the interface provided by a microwave window, for which a special development has been realized;
- due recognition to cleaning issues with concomitant solutions to maintain the equipment have been made.

A variant of the internal gelation route, using for gelation of the drops a microwave cavity instead of a silicon oil hot bath (that lead to secondary wastes), has been successfully investigated a PSI on non-radioactive surrogates as a first stage. The equipments were then implemented in a glove-box to permit fully remote operation. Thanks to huge efforts the device is now conform to the laboratory safety requirements vis-a-vis nuclear operation and risk due to earthquake.

1.3.2.3 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 HTR (High Temperature Reactor) particle fuels [50]. The WAR flowchart has been revisited and adapted to oxide fuels [51-53] up to the synthesis of $(U,Am)O_2$ beads and pellets [54].
The process is divided in 4 steps as illustrated in Figure 20:

- cation exchange (or metal loading),
- washing and drying,
- calcination (or mineralization),
- reductive gas heat treatment.

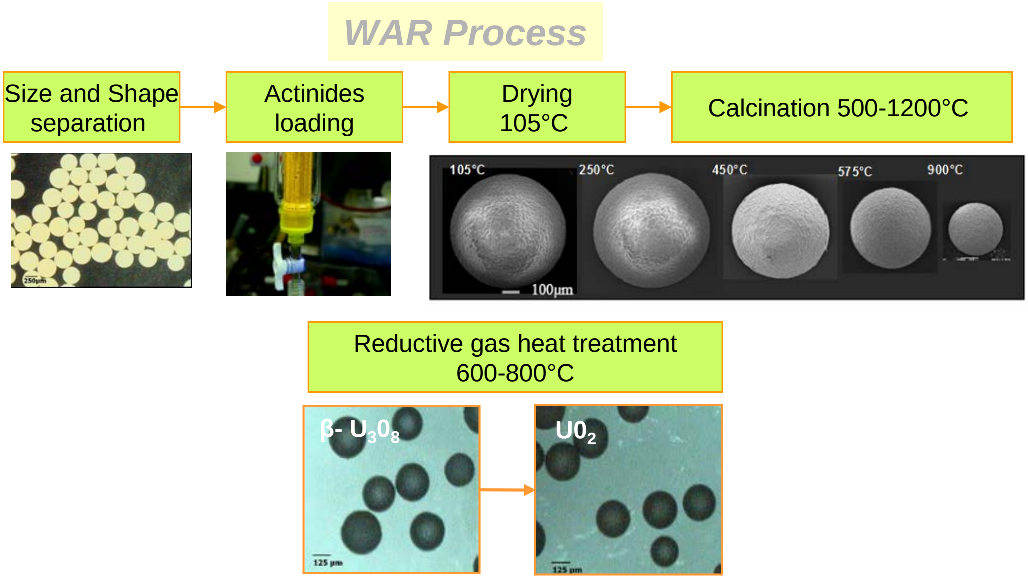


Figure 20 : Principle of the WAR process applied to Uranium dioxide based materials synthesis

The synthesis of 700 mg of $U_{0.9}Am_{0.1}O_2$ microspheres was prepared in the CEA-Atalante facility 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 spherules were thoroughly characterized by SEM, TIMS, powder-XRD and coupled µGC-TGA. Analyses have shown that an uranium-americium mixed oxide was produced with a reasonable amount of C residue (around 1500 ppm). The morphology of the spheres is fairly good and zoom on some broken spheres has shown that the microstructure of granulate was homogeneous as can be seen in Figure 21. The diameter of the spheres is around 400µm and the apparent density of 24 %TD.

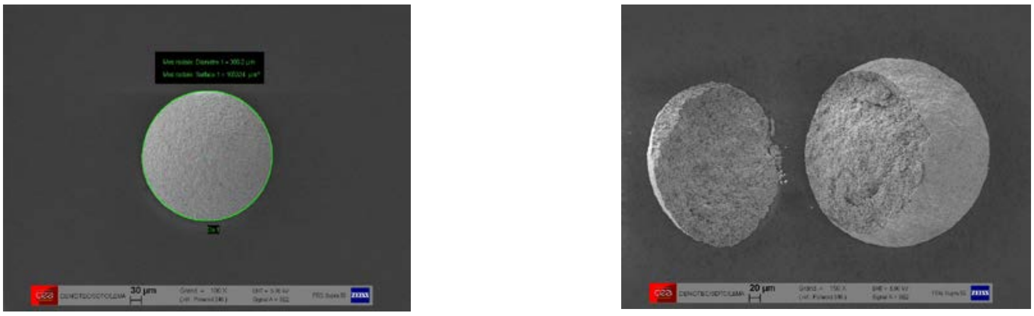


Figure 21: FEG-SEM micrographs of $U_{0.9}Am_{0.1}O_2$ beads prepared by WAR technology [13]

Am content versus total metal content has been assessed by the oxide complete dissolution and analysis of the bulk by TIMS: a ratio of 10.6% has been achieved which is in fair agreement with ratio of the loading solution.

As bulk density of microspheres was low (24% TD), densification of spherules has been investigated too. Thermal conversion tests have been carried out on Ce(III) loaded resin beads, Ce being used as a subrogate of Am. Preliminary results have shown that it seemed possible to reach highly dense microspheres (>90% TD) by adjusting the temperature rate to value as low as 0.1°C/min and by choosing 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 are 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 specifications for dense pellet envisaged for Am transmutation on an UO_2 support in SFRs and proves the technical feasibility of this dust-free process.

Finally, even if sol-gel and infiltration routes have been considered as more mature techniques, the adaptation of the WAR route could lead to a promising process as it is unique, simple and can produce either small or large particles with simple eluate composed of U(VI), nitrate and water that can be recycled easily. For the WAR process applied to spherepac fuel synthesis, the challenge remains to reach high densification ratios (>80%) for microspheres during calcination and sintering operations.

1.3.2.4 Conclusion on the investigation of fuel synthesis routes

The spherepac technology has been identified as leading to a significant simplification of the fabrication process and dust-free routes thanks to the elimination of some process steps as milling, pressing and grinding that involve fuel powders and dust.

The different fuel synthesis routes investigated within PELGRIMM for the fabrication of pellet and spherepac fuels have reached various stages of maturity:

- **the sol-gel process of the MARINE fuels, despite a lot of fabrication difficulties which have been overcome, has nevertheless shown some potentiality (to be confirmed by feedback from the PIE program in a future project) ;**
- **the variant of the sol-gel process with the micro-wave internal gelation, after validation tests on a non-radioactive unit for the synthesis of spherules made of an Am-surrogate compound, has given promising results. The implementation of the final device in a glove-box is now complete and available to test the equipment on U-type compounds;**
- **the adaptation of the WAR process to the synthesis of (U, Am)O_2 beads and pellets was successfully performed. Moreover, the densification of the microspheres tested using Ce as a surrogate of Am, has provided promising results with the fabrication of high density (>90% TD) microspheres. Moreover, oxide microspheres whatever their density was, have been proved to be suitable for pressing and a dense pellet (95% TD) has been prepared.**

Therefore, by demonstrating the feasibility of these different fuel synthesis routes, PELGRIMM has opened the path to new possibilities for Am-bearing fuel developments.

1.3.3 Modelling and simulation of fuel behaviour under irradiation

Most of fuel performance codes have originally been developed, verified and validated to model standard fuels for Light Water Reactor and Fast Reactor systems. Some of the codes under consideration within PELGRIMM were already upgraded within the frame of previous European projects to take into account some of the specificities of Am-bearing fuels or of spherepacked fuels. These codes are:

- MACROS (SCK-CEN) [55] implemented in FUTURE (FP5), EUROTRANS (FP6) and FAIRFUELS (FP7) projects to predict ADS type fuel behaviour under irradiation,
- TRANSURANUS [56, 57], developed by JRC and made available to other partners, implemented within the F-BRIDGE (FP7) project to integrate spherepac fuel geometry as well as some of mesoscopic information already gained from fundamental research activities, which govern macroscopic Gen-IV fuel behaviour at a macroscopic scale,

- SPHERE and SPACON codes (PSI) [58,59], dedicated to spherepac fuel behaviour under irradiation, implemented within F-BRIDGE to be able to simulate the behaviour of advanced spherepac fuel in Gen-IV systems.

In addition the calculation code GERMINAL (CEA) [60], dedicated to SFR standard fuels, upgraded during the last 10 years to strengthen the modelling of mixed oxide fuel pin using finite elements models for thermal analysis and mechanics, 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 investments in order to address the main challenges due to specific issues of MADF and MABB fuels under spherepac and pellet forms, such as:

- high MA content in UO_2 support matrix and low MA content in $(U,Pu)O_2$ 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 go further in the capabilities of the codes to model and simulate the fuel behaviour under irradiation regarding 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 [61-62]**
- **collecting from well-qualified experiments, data that cover material properties, cladding and design parameters;**
- **developing models and working out recommendations [63-65]**
- **for SPHERE calculations, establishing**
  - **equivalent formulas between spherepac and pellets, for the most important fuel properties (thermal conductivity, irradiation-induced solid and gas swelling);**
  - **simplified semi-theoretical correlations to model specific power profile in the fuel pins under thermal flux;**
- **and testing the upgraded codes on SPHERE and SUPERFACT irradiation conditions (see table 9) for MADF [66] and MABB [67] fuels respectively.**

<table>
<tr><th colspan="2">Minor Actinide Driver Fuels
$(U,Pu,MA)O_2$
SPHERE conditions</th><th>Minor Actinide Bearing Blanket fuels
$(U,MA)O_2$
SUPERFACT conditions</th></tr>
<tr><td>Pellets</td><td>Spherepac</td><td>Pellets</td></tr>
<tr><td>MACROS (SCK-CEN)
TRANSURANUS (ENEA and NRG)</td><td>MACROS (SCK-CEN)
TRANSURANUS (NRG)
SPHERE/SPACON (PSI)</td><td>MACROS (SCK-CEN)
TRANSURANUS (JRC-Karlsruhe)
GERMINAL (CEA)</td></tr>
</table>

Table 9: List of fuel performance codes and conditions involved in benchmarking.

1.3.3.1 Case of MADF fuels

The up-grades of the codes have consisted in the implementation of new models or in the modifications of models made by correction 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 [68,69],
- melting temperatures [70],
- evolution rate of fuel restructuring, columnar grain growth and central void formation [69],[71-72].

In parallel, a comparison of spherepac and pellet fuel behavior under irradiation based on existing experimental data and a review of the principles of equivalence of the two fuel concepts have been drawn up [61]. 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 spherepac MADF fuels.

The evaluation of the fuel performance codes (MACROS, TRANSURANUS and SPHERE-3) to simulate the behaviour of fuel pins within the SPHERE irradiation test (described into details in §1.3.1.1) was the performed (in blind as the irradiation was still underway at the time of the calculations). The results of the comparison [65] are gathered on Table 10.

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

Whatever code was used, the results are consistent (when comparisons can be done):

- **the center-line temperature for the pelletized fuel is below 1800°C, which is a threshold for columnar grain growth and central void formation.**
- **the center-line temperature for the spherepacked fuel 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.**
- **In all cases, Fission Gas release rates are high (≥35%).**

As the PIE program of the SPHERE irradiation is currently completed (see §1.3.1.1), a first comparison between calculated and experimental results is given hereafter:

- For the spherepac fuels, the (early) restructuring, central hole, columnar zone diameters and centerline temperatures calculated are almost consistent with the results of the neutron radiography performed after the 1rst cycle of irradiation as well as the microscopic observation performed at the end of irradiation.
- For the pellet fuels, neither central hole nor fuel restructuration have not 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 fuel shapes, 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 refine analysis of these results has to be done (out of the PELGRIMM frame) in order to provide new insights in the modelling of MADF fuel shaped as pellets and spherepac.

1.3.3.2 Case of MABB fuels [62],[65-66]

MABB fuels are still at an early stage of their design and preliminary testing. These fuels are expected to be efficient but de-facto they have inherited more complexities than conventional driver fuels, in terms of He production, operating temperatures and longer stay in a reactor core. Very few data exist for the concept of MABB fuel.

The SUPERFACT experiment [11-14], that was performed within a collaborative frame between JRC and CEA and that included MABB type fuels (operated like driver fuels i.e. at high temperatures), remained the first and almost unique source of in-reactor data on such a type of fuel at the beginning of PELGRIMM. The data from this experiment were analyzed and reported in datasheets to support calculations.

Besides, in parallel to the acquisition of the experimental data from the literature, new experimental data have been generated for helium solubility and mobility on well characterized samples produced and analyzed at JRC-ITU [73-74].

TRANSURANUS, MACROS & GERMINAL codes have then been upgraded taking into account these results and calculations of the behaviour of MABB type fuels within the SUPERFACT conditions have been made.

The outcomes of the calculations are encouraging, especially when taking into account experimental uncertainties and uncertainties on some of the input variables. For instance, calculated data on fission xenon seemed in reasonably good agreement with measured data, showing that the fission gas release models would not need further improvements.

Some discrepancies have nevertheless been pointed out:

- **considerable disagreement between calculated and measured helium production, that could be explained by insufficient knowledge on the detailed time-power irradiation history;**
- **fuel restructuring and central void formation have been calculated whereas they are not observed experimentally;**
- **FCMI has not been calculated, which is inconsistent with the experimental results which reveal significant cladding deformation and the presence of circumferential cracks in the fuels.**

Remark: In addition to the calculation of the SUPERFACT irradiation, first attempts to calculate the MARIOS irradiation have been performed with the MACROS code to test models and code's functionality and the results from non-destructive PIEs of the MARIOS irradiation have been analyzed [65]. Some of the results are summarized in Table 11. Calculated temperatures are about 900°C, 1250°C, 1100°C, and 900°C for pins 1 to 4, comparable to as-measured temperature (thermocouples in TZM trays, see Figure 8). For the four pins, the released gas fractions obtained with MACROS are in good agreement for fission xenon and reasonably consistent for helium taking into account the measurement uncertainties due to unexpected presence of argon in the pins (see § 1.3.1.2).

	MARIOS calculation (MACROS)			
	Pin #1	Pin #2	Pin #3	Pin #4
Power density at EOI (W/cc)	~ 360			~ 325
Burn-up at EOI (at%)	~ 1.15	~ 1.5	~ 1.5	~ 1.05
Temperature (°C)	~ 900	~ 1250	~ 1100	~ 900
Xe Release at EOI (%)	~ 20	~ 80	~ 35	~ 18
Helium Release at EOI (%)	~ 80	~ 95	~ 95	~ 75

Table 11 : Results fuel modelling for the MARIOS irradiation with the MACROS code

1.3.3.3 Conclusion

Fruitful interactions have led to gather and review data from relevant irradiation tests and new out-of-pile experiments. Recommendations and a path forward have been proposed and followed, leading to the implementation of new models in order to improve the capabilities of the codes to model and simulate the fuel behaviour under irradiation regarding both MADF and MABB fuels in both spherepac and pellet forms.

Efforts have been made in PELGRIMM to amend existing fuel performance codes by introducing up-graded models describing fuel behaviour under irradiation for both MADF and MABB fuels under spherepac and pellet forms. The outcome of benchmarks performed between PELGRIMM participants is encouraging and shows reasonably good agreements with experimental results. Even if definite conclusions cannot be drawn yet and key issues are still pending, the work performed here has identified directions of progression.

1.3.4 Simplified design and safety performance pre-assessment of an advanced spherepac (U,Pu,MA)O2 SFR core

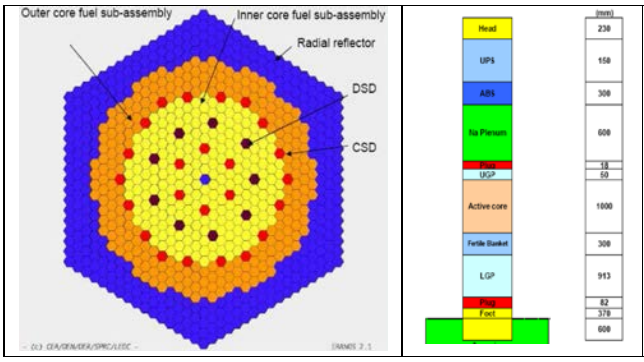
As spherepac shaped fuels are foreseen to be promising candidates for MA-bearing fuel concepts due to simplifications of the fabrication process associated with the production of beads, and to potentially good swelling behaviour under irradiation, the PELGRIMM project started linking the investigation of spherepac fuel behaviour under irradiation and synthesis to problematics of core physics, design and safety performance.

The study is in continuity with the former FP-7 CP-ESFR project [4] which aimed at designing and analyzing a 3600 MWth Sodium-cooled Fast Reactor 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 CONF2 core was chosen to start the PELGRIMM investigations [75]. The CONF-2 core has firstly to be revisited and its safety analysis completed [76]. The introduction of spherepac instead of pellets as well as of (U,Pu)O_2 and (U,Pu,AM)O_2 fuel compositions, has then to be considered [76]. Finally, accidental conditions have to be simulated [77-78] and different codes to be used: SAS4A [79], BELLA [80] and MAT5DYN [81] for the initiation phase of the accident, SIMMER-III [82] up to conditions of potential whole core melting and core disruption. The codes have to be adapted as much as possible to the specificities of a spherepac fuel, in particular to take into account the heat transfer in a bead stacks 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.

1.3.4.1 Consideration of the CONF2 core loaded with Am-bearing spherepacked fuels

The CONF2 core has emerged as an optimized version of the Working Horse (WH) cores [83], as the safety analyses for the WH core revealed that the sodium reactivity worth was too high and that a large scale core disruption could not be prevented in case of an Unprotected Loss of Flow (ULOF) accident [84-86]. The two cores differ mainly axially with the replacement of the lower axial steel blanket by a fertile blanket, the suppression of the upper axial blanket and the enlargement of the sodium plenum. The changes also include the introduction of an absorber layer to the upper part of the Sub-Assemblies (SA), above the sodium plenum. Apart from axial material rearrangements summarized on Figure 22, the pin design is equal to the WH core one.
This CONF2 design features a relatively low extended sodium void worth compared to the Working Horse (WH) core: 400-500 pcm at BOL against 1200-1400 pcm. Moreover, assessment of accident situations calculated within PELGRIMM have shown that the CONF2 core at Beginning Of Life (BOL) does not reach a whole core melt situation when subjected to a ULOF [87] and the accident undergoes a very mild transient, leaving the core in a subcritical state. The further accident evolution then strongly depends on the ability of cooling down the reactor i.e. removing decay heat. The unprotected transients end without any significant power excursion and gross core melting. The decay heat has to be evacuated to prevent further core disruption.



Active S/A design		
Sub-assemblies pitch	mm	210.8
Sodium gap width inter assembly	mm	4.5
Wrapper tube outer flat to flat width	mm	206.3
Wrapper tube thickness	mm	4.5
Wrapper tube material		EM10 steel
Wire wrap spacer diameter	mm	1
Wire wrap helical pitch	mm	225
Wire wrap spacer material		ODS steel
Number of pins per sub-assembly		271
Outer clad diameter	mm	10.73
Inner clad diameter	mm	9.73
Cladding material		ODS steel
Fuel pellet outer diameter	mm	9.43
Fuel pellet inner diameter	mm	2.5
Fuel density	%	95.5
Fuel averaged density 1	%TD	83.4
Fuel averaged density 2	%TD	88.8
O/M		1.98
Inner Pu content	at%	14.76
Outer P content	at%	17.15

Figure 22: Diametrical and axial core layout as well as SA features of CONF-2 [75]

Investigations have covered the introduction of sphere-packed fuels with the assumption that the smear density in the fuel pins remain unchanged (~84%). Besides neutron analysis, thermal-hydraulic calculations have been performed with RELAP-3D code in order to assess fuel temperature profiles [76]. Indeed, the thermal regimes in fuels can be very different.

At BOL, the essential differences between pellet and spherepac pins remain on the distribution of the free areas in the fuel columns [87]: 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 (Figure 23) than in the pellet pins (even if the heat transfer between the fuel surface and the cladding is enhanced in sphere-pac pins due to the absence of the gap between the fuel and the cladding).

At higher Burnup, the thermal regimes of both fuel concepts become close (see Figure 24).

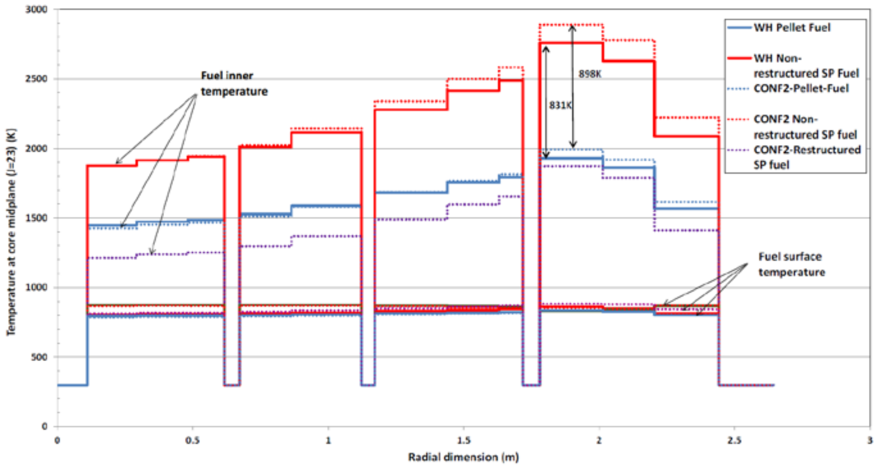


Figure 23: Map of fuel centerline and surface temperatures for different fuel loadings in the core at the very Beginning Of Life [87]

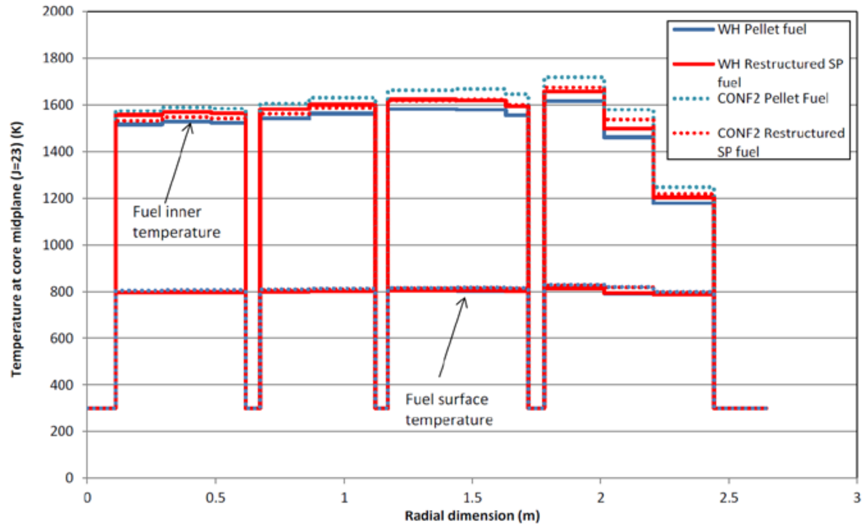


Figure 24: Fuel centerline temperatures for different fuel loadings at the End of Cycle 3 (~300EFPD) [87]

Then, neutron analyses have been performed with the MCNPX code for variants of the CONF2 core that contain up to 4% Am in the fuel. The results revealed an extended void worth (voiding of core and upper sodium plenum) that worsens (as expected) with Am content (Table 12). The Doppler constant decreases (in absolute value) as Na void coefficient increases.

	CONF2		CONF2 with 2%Am		CONF2 with 4%Am	
	BOL	EOC3	BOL	EOC3	BOL	EOC3
Sodium void reactivity effect (pcm)	+1423	+1951	+1636	+2029	+1821	+2104
Extended Sodium void reactivity effect (pcm)	+496	+1170	+781	+1290	+1031	+1407
Doppler constant, K_D (pcm)	-1158	-843	-904	-785	−712	−600

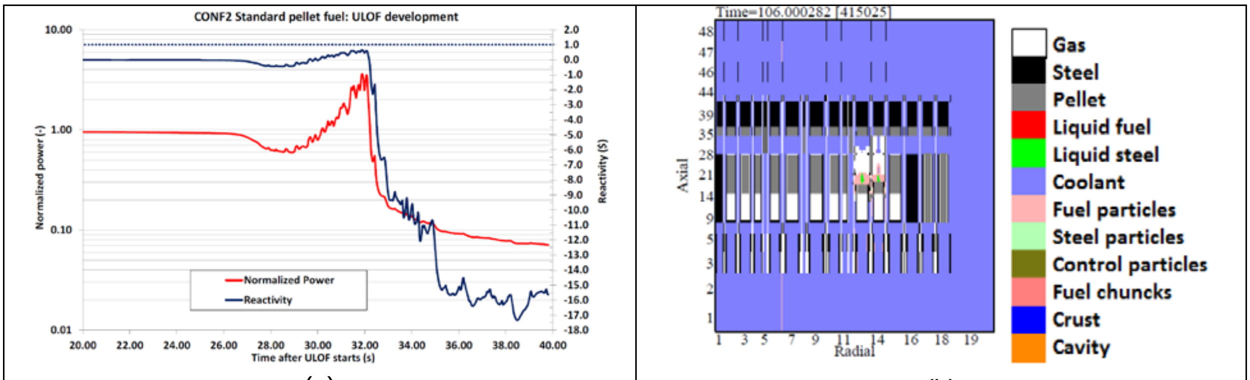
Table 12: Deterioration of the safety parameters in CONF-2 with burnup and Am content [87]

1.3.4.2 Simulations of ULOF accidents

The ULOF accident is traditionally analyzed within safety assessments of SFRs as it presents a transient with a global impact on the core and covers most of the phenomena which might occur during a core melt-down. In addition, as the scenario of the ULOF starts with coolant boiling, it is the perfect transient for investigating the impact of the design changes of the WH core to the CONF2 core (with the large upper sodium plenum) on the development of the transient.

The initiating event sequence for a ULOF starts with the loss of primary pump flow due to electric break-down accompanied by not functioning of the available shut-down systems. Coolant flow reduction after some seconds leads to the sodium temperature increase, up to the saturation level (boiling onset). Dependent on the positive "sodium void effect", a primary core power excursion is initiated and generalized core degradation and melting occurs. This scenario was clearly observed in the CP-ESFR project for the WH core [4].Transient calculations for the CONF2 core have been performed: both pellet and spherepac fuel variants have been investigated [77, 78].

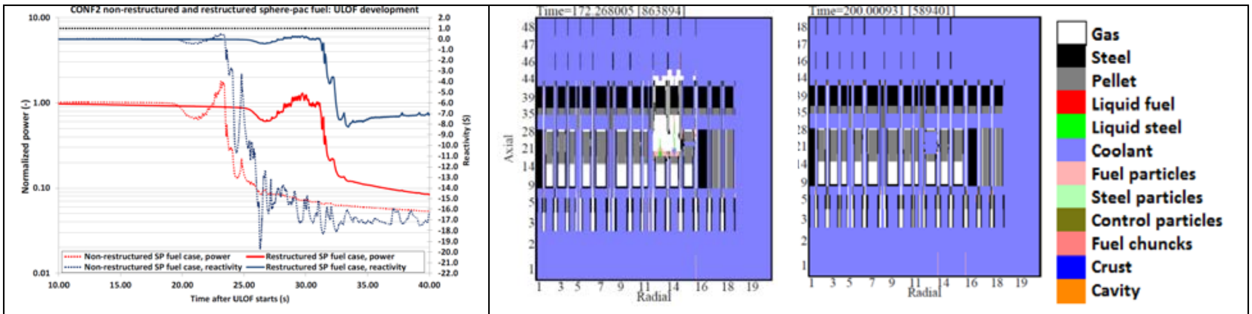
Firstly, the CONF2 core with pellet fuel has been analyzed, especially to confirm the improvement by introducing a large upper sodium plenum 'compared to the WH core). Results [87] have shown that the sodium plenum seems to effectively prevent positive reactivity surges and subsequent power excursions (Figure 25a): the plenum voiding introduces enough negative reactivity to balance positive reactivity effects, and contrary to the WH core after a first mild power excursion, no re-criticality appears. The low transient power has allowed the rewetting of structures and the disruption process has remained limited (Figure 25b); the possible accident outcome would be a slow melting under decay heat conditions.



(a) (b)

Figure 25: Behaviour of the CONF-2 core – pelletized fuel – during ULOF conditions at BOL.
(a): Normalized power and reactivity versus time.
(b): Material distribution at the end of the accident

For spherepac fuel under Begin Of Life (BOL) conditions [87], 2 cases have been considered: before and after fuel restructuring, due to the high temperatures that could be reached by the non-restructured fuel if any starting procedure hasn't been implemented to moderate the power level at the first power rise (cf Figure 23). Figure 26(a) shows the power and reactivity evolution during the ULOF for the non- and restructured spherepacked fuels; the material redistributions at the end of the ULOF are illustrated on Figure 26(b). For both conditions the plenum effect has been active and has prevented a scenario with multiple re-criticalities. No fuel melting conditions are reached during the transient. This finally allows the achievement of a very mild transient letting the core in a subcritical state. The further accident evolution depends on the ability of cooling down the reactor i.e. of the capacity of sufficiently evacuating the residual heat.



(a) (b) (c)

Figure 26: Behaviour of the CONF-2 core – spherepacked fuel – during ULOF conditions at BOL [87]. (a): Normalized power and reactivity versus time; Material distribution at the end of the accident for (b) non- and (c) restructured spherepac fuel

All simulations in the BOL CONF2 core show very mild transients, mainly attributed to the action of the large upper plenum, which introduces upon its voiding sufficient negative reactivity to balance the positive voiding contributions within the core and reactivity additions from fuel compaction or steel loss. The first results clearly demonstrate that a core could be equipped with spherepac fuel without unduly compromising safety conditions.

The same ULOF has then been considered after 3 irradiation cycles [87]. The nuclear power trace and reactivity development of the CONF2 core is displayed on Figure 27 both for pellet and sphere-pac 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 sphere-pac and pellet core show a very similar behavior under these accidental conditions. The unprotected transients end without any significant power excursion and gross core melting has to be prevented by a reactor scram to achieve permanent nuclear shut-down. The decay heat has to be evacuated to prevent further core degradation.

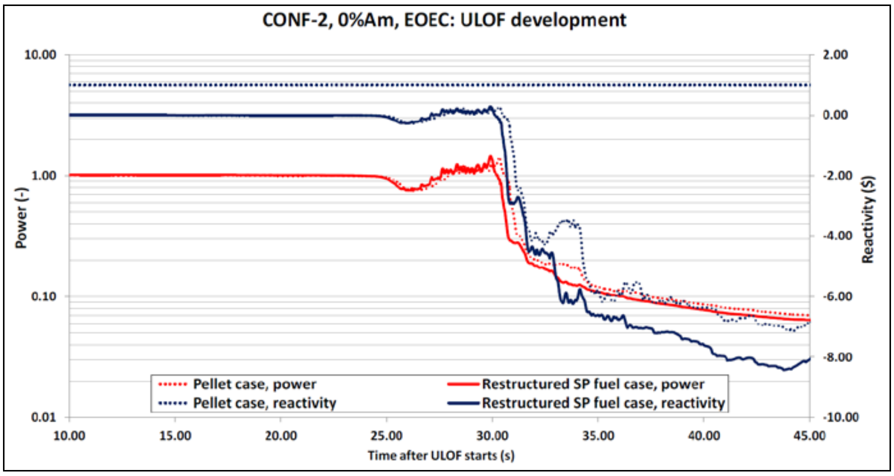


Figure 27: Normalized power and reactivity for pelletized and spherepacked fuel CONF2 cores during ULOF conditions at equilibrium core conditions [87].

The key findings of the first safety assessment can be summarized as follows:

- **spherepac fuel can be inserted in a SFR core without significantly changing the design and without having a major impact on the core layout and safety coefficients;**
- **safety analyses represent first scoping studies as no sound experimental data base exists on transient behavior of spherepac fuels;**
- **the CONF2 BOL pellet fuel core with a large sodium plenum shows expected improved safety behavior due to the reduced reactivity void worth: no significant power excursion under ULOF conditions have been observed;**
- **the transient ULOF analyses for the CONF2 core with SIMMER do not show a significant change in the accident scenario when using spherepac fuel instead of pellet fuel. The possibility of early spalling of the spherepac particles and their release of the core might lead to an even milder accident behavior;**
- **the start-up of a spherepac fuelled core requires a special procedure as e.g. starting at lower power until fuel restructuring has been achieved;**
- **for BOL conditions and in a core without Am the introduction of the large sodium plenum gives a strong safety advantage. No fuel melting conditions are reached during the transient;**
- **under EOC3 conditions and/or with MAs in the core the safety coefficients deteriorate for the CONF2 core and severe accident scenarios can again be identified.**

In addition, a sensitivity analysis of ULOF accident at BOL has been performed, using MAT5DYN code, a simplified code for transient analysis developed [88]. It has been completed by a study performed by KTH using both SAS and BELLA codes [89], which was in good agreement with the predictions of EDF. Four configurations have been studied:

- reduced fuel-clad exchange coefficient; among the issues of spherepac fuel is the unknown fuel-clad gap status. If the fuel is not restructured in that part, it is possible that the spheres will leave some space between them and that the fuel-clad gap will be partially open. In that case, a much lower thermal exchange coefficient can be expected. As an example, it has been chosen to divide by a factor 4 the fuel-clad coefficient observed in nominal conditions;

- free conditions for fuel expansion; if the gap is open or partially open, it is likely that the fuel will not be linked to the clad: the fuel will axially expand according to its own temperature, as opposed to the reference case, where it is supposed to be linked to the clad;

- lower fuel conductivity; the fuel conductivity for spherepac is likely to be lower than that of pellet, at least in less restructured zone in the outer rim of the fuel region: a sensitivity case was run with a conductivity decreased by about 5%;

- reduced fuel density ; it is always possible that a high smeared density could not be easily reached with spherepac: for that reason, a case with fuel density reduced by 5% has been studied.

Finally, the most severe scenario has been obtained when reducing the fuel-clad exchange coefficient by 4. However, the span between results for boiling time was very limited: about 7s, from ~28s to ~35s. The change has not been so drastic during this phase of the ULOF transient, because the positive sodium feedback of the chosen design has made the transient very fast. After boiling, it is possible that the positive sodium void worth would trigger a primary power peak, and that fuel would largely melt. The difference between spherepac and pellet fuel would hence not be so dramatic either.

1.3.4.3 Simulations of Unprotected Transient Over-Power (UTOP) accidents

Even if ULOF accidents constitute undoubtedly the most harmful scenarios for SFR safety, the investigation of unprotected transient over-power (UTOP) accidents is also relevant with respect to the specific case of spherepac fuel core loading, since prompt power excursions brought by positive reactivity insertions bring rapid fuel temperature increases, which would most likely cause the fuel to melt, owing to significantly lower thermal conductivity compared with pellet fuel, while not leading the coolant to boiling.

A preliminary safety assessment [78] of the CONF-2 core at BOL, loaded with both pellet and spherepac fuels was performed by KTH using the BELLA code and the SAS4A/SASSYS-1 code, with core neutronic characteristics and safety parameters being calculated with the Serpent code. The UTOP accident was simulated, along with a set of sensitivity studies in order to assess the influence of uncertainties affecting both safety coefficients and fuel thermal conductivity.

The major safety analysis outcomes are here summarized:

- **contrarily to the case of a ULOF accident, the use of spherepac fuel degrades the CONF-2 core safety performance in case of UTOP accidents, since its low thermal conductivity, besides reducing the margin against fuel melting at steady-state, leads to larger magnitudes of the fuel temperature gradients ensuing from positive reactivity insertions, likely causing its melting; however, the transient resulted to be rather mild, with an estimated peak power level of 2-3 times the nominal one;**
- **consistently with the previous conclusions, uncertainties in the determination of the fuel thermal conductivity are expected to influence the UTOP simulations, but to have no significant impact on the ULOF transient predictions;**
- **appreciable effects on the core safety performance have been found to be brought by the magnitude of the Doppler constant, making its accurate determination critical for the system safety assessment in case of a UTOP accident;**
- **as a corollary conclusion, it could be preliminarily inferred that the detrimental effect of burn-up and MA loading on the core reactivity coefficients might be critical when incorporating spherepac fuel, due to its reduced thermal conductivity, and therefore it needs to be carefully and further investigated.**

As a consequence of these findings, it has preliminarily been concluded that the use of spherepac fuel may bring some disadvantages from the safety point of view in the event of a UTOP accident, whereas no concerns have been raised for a ULOF scenario. Therefore, two main recommendations have been suggested:

- It is necessary to define acceptable limits (e.g., percentage, means, etc.) of melted fuel in the core, or, as an alternative option, to limit the core linear heat rate, so as to decrease fuel steady-state temperature values and consequently increase the margins against melting;
- Accordingly, the core designer is recommended to take additional provisions, along with larger safety margins against fuel melting, aiming at limiting the consequences of a UTOP accident within the provided boundaries.

1.3.4.4 Conclusion

Within PELGRIMM, the simplified design of an optimized core loaded with MADF spherepac fuels and corresponding safety performance assessment has been successfully performed. Two relevant accidental situations have been analyzed: the unprotected loss of flow accident (ULOF) and unprotected transient over-power accident (UTOP). The safety simulations, completed by

sensitivity analyses, have given a first view and impression of the behavior of the spherepac fuel in order to identify possible show-stoppers.

No experimental data base on transient behavior of spherepac fuels exists up to now. The safety analyses therefore represent first scoping studies. Based on the current analyses, the implementation of spherepac fuel does not cause any specific design problems. For BOL conditions the ULOF simulation shows a very mild transient for the spherepac CONF2 core both with non- and restructured fuel. The first safety analyses also indicate that spherepac fuels do not seem to cause any specific safety problems, if introduced in an SFR.

In addition, other transients should be studied. For instance, during a control rod withdrawal, local power increase can induce fuel melting, gas release and mechanical stress on the cladding. Fuel properties such as gas retention, fuel clad gap, conductivity and porosity might have much more impact on such a transient. Slow transient of power could be interesting as well. Anyway, for this kind of transient, as for the ULOF, a better knowledge of fuel properties is needed to assess the real safety impact of the spherepac design.

Further investigations should also take into account the detailed modelling of fission gas and He release during operation and during accident situations. For this, however, more experimental information is needed. Another issue is to model in more detail the rim behavior of the restructured fuel and its behavior in case of clad breaching or clad melting.

1.3.5 General conclusion

PELGRIMM has constituted a new step in the long term process of the MA-bearing fuel qualification rationale, with the investigation of a wide range of items: from pellet to spherepac fuel forms, from homogeneous to heterogeneous MA-recycling modes, from fuel fabrication and characterization to behaviour and performance under irradiation, from experiments to modelling and simulation, from normal operating conditions to severe accidents.

The realization of the PIEs of innovative irradiation tests, such as SPHERE and MARIOS have largely contributed to improve the knowledge on Am-bearing fuel behavior 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 has been done thanks to PIEs implemented on the SPHERE fuels; the first results on helium behaviour and fuel swelling concerning two $(U, Am)O_2$ microstructures irradiated at two constant temperatures are available thanks to PIEs performed on MARIOS mini-pins. The MARINE semi-integral irradiation in HFR is now complete and its PIEs, to be planned in another framework than PELGRIMM, should provide complementary results to SPHERE and MARIOS PIEs.

Regarding the fabrication aspects, alternative routes of MA-bearing fuel fabrication processes have been investigated to seek for 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 fabrication 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 developments.

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 showed reasonably good agreements with experimental results: first attempts to simulate the fuel behaviour during SPHERE, SUPERFACT and

MARIOS irradiation thanks to fuel performance codes have been performed, providing, 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 and corresponding safety performance assessment has been successfully performed. Two relevant accidental situations have been analyzed: the unprotected loss of flow accident (ULOF) and unprotected transient over-power accident (UTOP). The safety analyses represent first scoping studies. 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 fabrication processes, irradiation behaviour and core safety performance, including a comparison on fuels shaped as pellets and beads.

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1.4 Potential impact

PELGRIMM has got a primary impact regarding the crosscutting nature of strategic and innovative fuel development with minor actinides for fast reactor systems as defined in the Strategic Research and Innovation Agenda – SRA - of the Sustainable Nuclear Energy Technology Platform – SNETP- (http://www.snetp.eu/). Moreover, activities within PELGRIMM have been able to support the Joint Programme on Nuclear Material –JPNM- (http://www.eera-jpnm.eu/) initiated within the European Energy Research Alliance – EERA -, and the European Sustainable Nuclear industrial initiative –ESNII- (http://www.snetp.eu/esnii/), both of which have been launched under the auspices of the European Union's SET Plan to formulate energy requirements of the future.

Under the presidency of Jose Manuel Barroso, the European Commission has defined ambitious goals within the terms of European 2020 Agenda: http://ec.europa.eu/europe2020/index_en.htm, and has identified a number of important flagships:

- Sustainable growth
Resource efficient Europe is a flagship focusing on low carbon technology to minimize impact on energy production on the environment. Nuclear energy can play an important role, as has been identified in the SET PLAN of the European Commission. PELGRIMM has had an important impact due to its focus on a new generation of fuels for fast reactor systems, optimizing use of natural uranium resources. Furthermore, feasibility of fuel demonstration with remote operation is also demonstrated.

- Smart Growth
PELGRIMM has gathered 12 leading organizations in the realm of nuclear fuel research, clearly demonstrating that the European Research Area (ERA) is a reality. It is of particular note that many have worked together in earlier programs, while keeping the door open to new partners with capabilities to contribute to program goals. PELGRIMM has offered the opportunity to develop a shared research – application vision.
Under the Flagship Innovation Union, inventions produced by PELGRIMM partners could be translated into innovation (i.e. applications on the market place).
Youth on the Move has been an important Europe 2020 Flagship. The very nature of fuel programs requires heavy infrastructures, and large teams operating computer codes, all of which are mostly located at research institutes or industry. The research institutes form a major part of PELGRIMM,

and they have offered training courses, PhD and post-doctoral research opportunities, which have been leveraged with effect within PELGRIMM as 5% of its budget has been dedicated to Education and Training programs.

The Digital Agenda has not been addressed specifically in PELGRIMM. Nevertheless, PELGRIMM launches a platform for modelling complex processes occurring during fission of Am bearing fuels and targets. The valorization of these models and simulation packages will lead to reduce complex experiment, wastes and energy required for validation and licensing processes, by providing engineering based models for the present codes.

- Citizen Agenda

Nuclear waste disposal is a fundamental concern of European citizens. PELGRIMM's prime most goals (minor actinide recycling) make vital advances in reducing

i. the long term toxicity of nuclear waste,
ii. the repository footprint needed to store the waste.

Moreover, PELGRIMM, before Fukushima events with four stricken reactors hit by a natural disaster, has recognized nuclear safety as an essential component, and included a dedicated work package on nuclear fuel operational safety, comparing conventional pellet and spherepac fuel, under design basis accidents and design extended conditions.

- Europe and the World

PELGRIMM has made important links outside European Commission:

i. The results generated form part of EURATOM's contribution to fuel projects, thereby reinforcing Europe's role, in the Generation IV fast reactor systems, with the SFR advanced fuel project identified as the first to benefit. Moreover, European Research will benefit through the exchange of results.
ii. OECD NEA hosts an Expert Group on Innovative Fuels, within which PELGRIMM partners are represented. PELGRIMM will have a significant impact in the update of the state of the art report on Minor-Actinides bearing fuels published in 2014.

1.5 List of Beneficiaries

Participants	Organisation name	Contact person
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2. Use and dissemination of foreground

Proper dissemination of knowledge inside and outside of the project has been performed through a dedicated internal/external website, open to public (external website) with project presentation and yearly progress updates, with a digital library of all publishable documents produced in the project as well as information relative to PELGRIMM major events (training courses, internships, workshop,…). PELGRIMM website has been part of internal/external communication too. Moreover, partners have regularly take part in actions and events that improves visibility of the project.
Many individuals of the participating organisations have been involved in working groups at the IAEA and OECD-NEA, useful for knowledge dissemination routes. Generation IV project participations have also provided a valuable means to disseminate knowledge as EURATOM and CEA are represented on GFR and SFR fuel projects. A set of deliverables to be freed to these projects has indeed be identified at the project beginning.
Synergies with other European projects are an excellent means to disseminate knowledge and PELGRIMM has been active to arrange a joined workshop (Zurich, Sept. 17 2015) with the FP-7 ASGARD.
A mark of high quality output lies in the publication and discussion of achievements though peer review driven processes. For this purpose, PELGRIMM has been represented at key international meetings (GLOBAL, ICAPP, etc.) and selected results obtained have been made available in highest quality journals.

International relations have ensured PELGRIMM integration and alignment with programmes inside and outside of Europe by : liaising and organising information flow with other European programmes, such as FAIRFUELS, F-BRIDGE, CP-ESFR, ASGARD, ESNII+, …; distributing information to partners within PELGRIMM, SNETP and EERA-JPNM, providing members of the latter not involved directly in PELGRIMM project updates of progress and achievements.

Furthermore, interaction with GIF has been organised to leverage PELGRIMM results (as part of EURATOM's contribution to GIF) to gain data from the other partners in GIF: the main focus has been the SFR-Advanced Fuel Project or even the SFR-Safety and Operation Project.

Finally, education and training activities, where ENEN has played a major role, has been an integral component of PELGRIMM and has inherently contributed to knowledge dissemination. Indeed, PELGRIMM has promoted the implication of European students and young researchers, including both internal actions for developing skills of European students (arrangement of 8 internships of 6 months in organization involved in PELGRIMM for MASTER students) and external actions (allocation of grants to attend scientific events and summer schools, arrangement of a workshop) for fostering the dissemination of the project actions and results at a wider scale.

Remark: The detail and the references of the project dissemination activities are uploaded on ECAS website.

3. Report on societal implications :

This section was directly completed on the ECAS website.