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SPHERE: Irradiation of sphere-pac fuel of $UPuO_{2-x}$ containing 3% Americium

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HIGHLIGHTS

- SPHERE is designed to check the behaviour of MADF sphere-pac concept.
- MADF sphere-pac are compared with MADF pellet.
- Swelling, helium release and restructuring behaviour will be the main output of the experiment.
- An experiment to check sphere-pac MABB fuel behaviour is now under design.

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ABSTRACT

Americium is a strong contributor to the long term radiotoxicity of high activity nuclear waste. Transmutation by irradiation in nuclear reactors of long-lived nuclides like ^{241}Am is therefore an option for the reduction of radiotoxicity of waste packages to be stored in a repository. The SPHERE irradiation experiment is the latest of a series of European experiments on americium transmutation (e.g. EFTTRA-T4, EFTTRA-T4bis, HELIOS, MARIOS) performed in the HFR (High Flux Reactor). The SPHERE experiment is carried out in the framework of the 4-year project FAIRFUELS of the EURATOM 7th Framework Programme (FP7). During the past years of experimental works in the field of transmutation and tests of innovative nuclear fuels, the release or trapping of helium as well as helium induced fuel swelling have been shown to be the key issues for the design of Am-bearing targets. The main objective of the SPHERE experiment is to study the in-pile behaviour of fuel containing 3% of americium and to compare the behaviour of sphere-pac fuel to pellet fuel, in particular the role of microstructure and temperature on fission gas release (mainly He) and on fuel swelling.

The SPHERE experiment is being irradiated since September 2013 in the HFR in Petten (The Netherlands) and is expected to be terminated in spring 2015. The experiment has been designed to last up to 18 reactor cycles (corresponding to 18 months) but may reach its target earlier.

This paper discusses the rationale and objective of the SPHERE experiment and provides a general description of its design.

1. Introduction

In the frame of the EURATOM 7th Framework Programme (FP7), the SPHERE irradiation test is part of the 4 year project FAIRFUELS (FAbrication, Irradiation and Reprocessing of FUELS and targets for transmutation), the aim of which is to provide a way towards a more efficient use of fissile material in nuclear reactors, to reduce the volume and hazard of high level long-lived radioactive waste, and to close the nuclear fuel cycle (FAIRFUELS).

Americium is one of few radioactive elements that contribute strongly to the long-term radiotoxicity of spent nuclear fuels. Transmutation by irradiation in nuclear reactors of long-lived nuclides as ^{241}Am is therefore an option for the reduction of the mass and radiotoxicity of nuclear waste.

The analysis of previous irradiation experiments (dealing with Americium Bearing Inert Matrix Fuel (IMF): EFTTRA-T4 (Konings

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et al., 2000) and EFTTRA-T4bis (Klaassen et al., 2003)) which were carried out in the High Flux Reactor (HFR), showed that the release/trapping of He is the key issue for fuel targets containing americium. In fact, in those experiments significant fuel swelling was observed and attributed to the production of helium which is characteristic for ^{241}Am transmutation. The following experiment, HELIOS (D'Agata et al., 2011), was conducted in the HFR to study the in-pile behaviour of IMF using two diverging approaches to deal with the production of He and its release: either trapping of He in open porosities of the matrix, or increase of target temperature to promote the release of He from the matrix. The Post Irradiation Examination of HELIOS is yet to be completed to check which of the two approaches works better.

Based on extensive fuel cycle and Sodium Fast Reactor (SFR) core design studies aiming at nuclear waste minimisation, two MA-recycle modes are currently under consideration:

- the homogeneous recycle mode, where small quantities (<5%) of MA are carried by the MOX driver fuel of a fast neutron reactor; this fuel is referred to as Minor Actinide bearing Driver Fuel (MADF).
- the heterogeneous mode, where higher MA contents (10–20%) are added to a UO_2 support containing natural or depleted uranium; as these MA-bearing sub-assemblies are located at the periphery of the core of a fast neutron reactor, this fuel is referred to as Minor Actinide Bearing Blanket fuels (MABB).

Recently (March 2011–May 2012) an experiment called MARIOS (D'Agata et al., 2013) on MABB fuel has been realised here at the HFR. MARIOS was testing the (MABB) concept having four pins containing $Am_{0.15}U_{0.85}O_{1.94}$, with two different densities and open porosity ratio (Prieur et al., 2011).

The primary objective of the experiment was to obtain information on the temperature dependence of fuel swelling and helium release in the temperature range of 1000–1200 °C. Another complementary experiment, DIAMINO (Bejaoui, 2011), is planned to be conducted in OSIRIS to investigate the temperature range 600–800 °C hence to have a complete range of possible working temperature (600–1200 °C).

Concerning MADF concept, two previous experiments have investigated the behaviour of MA-bearing driver fuels for sodium fast reactors; the Japanese AM-1 test irradiation (Kato et al., 2011; Maeda et al., 2009) and the American AFC-2 test (McClellan, 2013). AM-1 was a short irradiation which was carried out to investigate restructuring and actinide redistribution in MOX driver fuel containing <5% Am and Np at high power (425 $W\,cm^{-1}$, while AFC-2 targeted high burn-up (>10%) for similar fuel (as well as a range of fuel types), to address helium release behaviour and high burn-up effects at linear power below 400 $W\,cm^{-1}$.

SPHERE is the latest of a series of irradiations dealing with homogeneous recycling of minor actinides (MAs) in sodium-cooled fast reactors (i.e. the MA-bearing driver fuel concept). The results of SPHERE may be compared to the results for the oxide fuel in the AFC-2 test (INL) but differs from AFC-2 in two ways: the fuel does not contain Np and the test has been designed to directly compare conventional pellet-type fuels with so-called Sphere-Pac fuels. The latter have the advantage of an easier, dust-free fabrication process. Indeed, sphere-pac technology (leading to production of beads) would bring a significant simplification of the fabrication process thanks to the elimination of some process steps such as milling, pressing and grinding, which involve fuel powders (and consequently dust). Especially when dealing with highly radioactive minor actinides, dust-free fabrication processes are essential to reduce the risk of contamination and material loss.

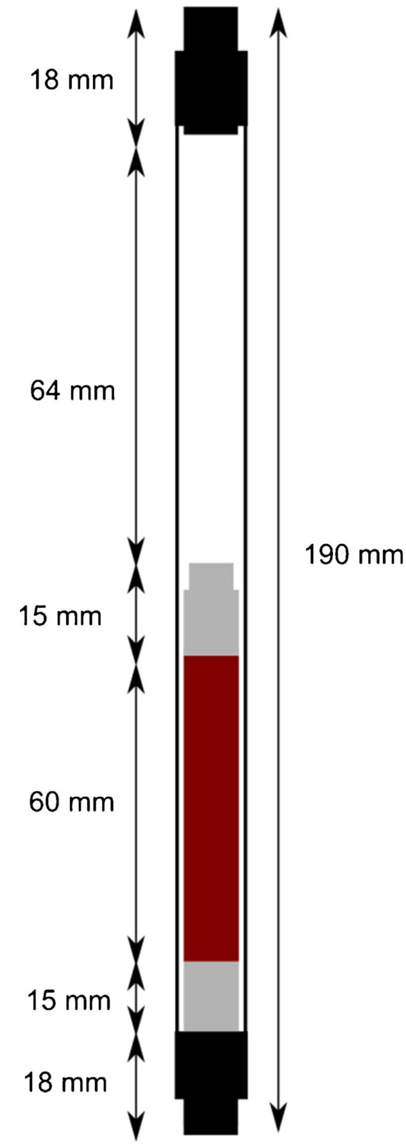

Fig. 1. Schematic layout of the fuel pins for the SPHERE irradiation.

SPHERE consists of two pins containing 3% of ^{241}Am diluted in a mixed oxide fuel (Am, U, Pu)O_{2-x}, in two different fuel forms, pellets and sphere-pac fuel.

The two kinds of fuel have a different overall density, lower for the sphere-pac with respect to the pellet form. Indeed, due to the geometry of the fuel, the sphere pac fuel will have a compactness which leads in a lower smeared density. Pins 1 and 2 containing pellets and sphere-pac fuel, are expected to operate at the same linear power (300 $W\,cm^{-1}$ at the start of the irradiation) which will initially produce a higher central temperature in the sphere-pac solution than in the pellet form. It will be checked via post-irradiation neutron radiograms and microscopy whether this has an impact on the fuel restructuring (i.e. the dimensions of the central hole, if present, and the columnar grain region).

Since past post-irradiation examination on fast reactor fuel has indicated strong fuel restructuring, central temperatures should be brought above the restructuring temperature in order to make SPHERE a relevant fuel test. As-fabricated sphere-pac fuel has a rather low effective thermal conductivity, which however strongly improves over the first day of irradiation due to restructuring of the

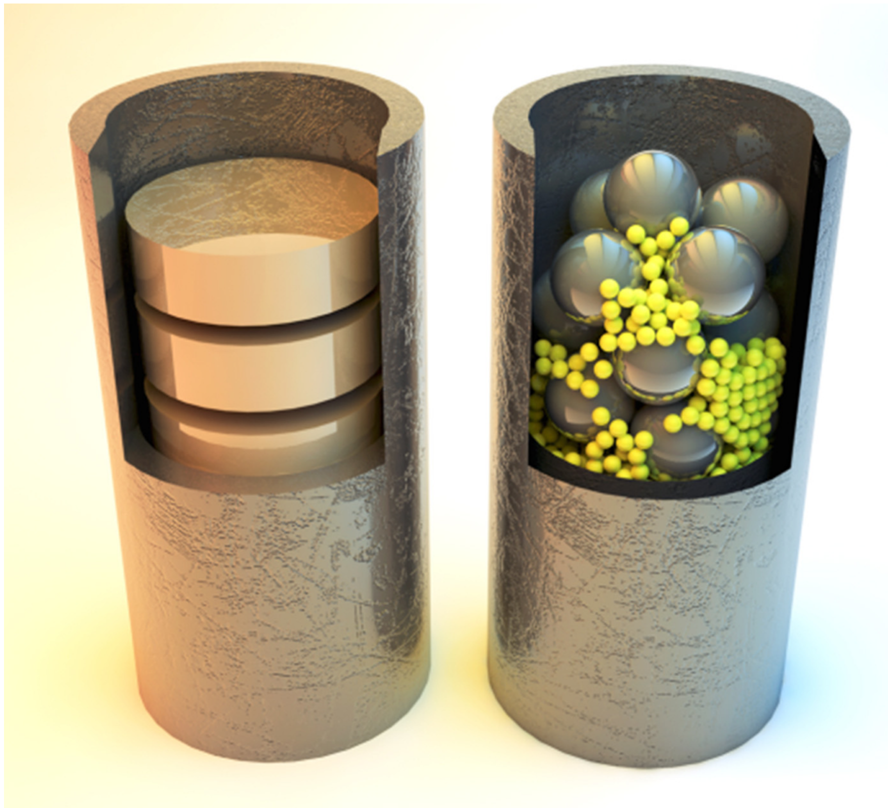

Fig. 2. Pellet versus sphere-pac concept.

fuel. The effect of this restructuring is a drop of the central temperature by 250–300 °C but depends on linear power (Hellwig et al., 2006).

Since sphere-pac restructuring occurs over a timescale of hours, the SPHERE irradiation has required a non-standard start-up procedure. The linear power of these targets needs to be increased slowly over a period of a few hours.

The SPHERE irradiation experiment is being carried out in position G7 of the HFR core, which has a thermal flux (<0.625 eV) of about $1.0 \times 10^{18}\,m^{-2}\,s^{-1}$, an epithermal flux (0.625 eV < E < 0.82 MeV) of about $2.48 \times 10^{18}\,m^{-2}\,s^{-1}$ and a fast flux (>0.82 MeV) of about $1 \times 10^{18}\,m^{-2}\,s^{-1}$ with a total neutron flux of about $4.5 \times 10^{18}\,m^{-2}\,s^{-1}$. The neutron spectrum of the HFR does not match a typical spectrum of a Sodium Fast Reactor even after spectral hardening using hafnium shields as applied to SPHERE. For example, for the ASTRID Sodium Fast Reactor (SFR) the average distribution of the flux is expected to be ≈0 for thermal flux, $2.55 \times 10^{19}\,m^{-2}\,s^{-1}$ for an epithermal flux, and $4.5 \times 10^{18}\,m^{-2}\,s^{-1}$ for a fast flux (Buiron, 2012). For this reason, the experiment is sometimes called "semi-integral" because some parameters are not representative. Nevertheless, the experiment will give important information on fuel behaviour, such as helium production/release and swelling. This paper will present the design and the objective of the experiment which was optimised to achieve an initially high temperature (>2000 °C) to trigger restructuring of the sphere-pac fuel.

The experiment has been designed to last 18 cycles (corresponding to 18 months) but may reach its target earlier. The post irradiation examination of the fuel irradiated in SPHERE will be performed at NRG and JRC-ITU within the European Project: PELGRIMM (Delage, 2012) (PELlets versus GRanulates: Irradiation Manufacturing & Modelling) that started in January 2012.

2. Fuel and pin characteristics

The americium-containing fuel for SPHERE, both pellet-type and Sphere-Pac-type, were fabricated at JRC-ITU in Germany.

The SPHERE experiment consists of two pins of 15–15 Ti steel (see Fig. 1), an austenitic steel clad which was used in the French sodium fast reactors Phénix and Super Phénix. One pin contains 6 fuel pellets, the other a 48 mm stack of sphere-pac fuel. The fuel pellets had a total length of 58 mm and were held in place with a spring. Hafnium oxide pellets have been placed at both ends of the fuel stack in order to decrease power peaking at the fuel stack edges. The sphere-pac fuel is a binary bed of beads of two sizes, around 0.8 and 0.06 mm, to enhance the packing fraction, and it is also flanked by hafnium oxide pellets. Fig. 2 shows a schematic view of the two fuel concepts tested in SPHERE.

The fuel needs to be irradiated at around 2200–2500 °C in order to be representative for its future application.

Each pin is filled with a mixture of 99% He and 1% Ne. The presence of the 1% neon is helpful to demonstrate the He/Ne

Table 1
Composition of the fuel irradiated in the SPHERE experiment.

Pin nr.	Composition	Fuel density ($g\,cm^{-3}$)	^{241}Am content (g)	^{238}U content (g)	^{239}Pu content (g)
1 (spheres)	$U_{0.75}Pu_{0.22}{}^{241}Am_{0.034}\,O_{2-x}$	8.33[a]	0.320	7.167	1.869
2 (pellets)	$U_{0.76}Pu_{0.2}{}^{241}Am_{0.03}\,O_{2-x}$	10.393 ≈ 93.8% TD	0.388	10.192	2.442

[a] This overall density takes into account both the density of the spheres and the overall packing density of the two size fractions in the sphere-pac column.

Table 2
Isotopic vector of plutonium and uranium (analysis 09.06.2011).

Isotope	Abundance (%)	Isotope	Abundance (%)
Pu-238	0.01721	U-234	0.03092
Pu-239	90.629	U-235	0.2878
Pu-240	9.1562	U-236	0.018
Pu-241	0.12364	U-238	99.66303
Pu-242	0.07363		

fraction after irradiation (higher precision than measuring the total He quantity) thus enabling a more accurate determination of He release from the fuel.

An overview of the fuel/targets irradiated in SPHERE is given in Tables 1 and 2.

Two fabrication routes were implemented by JRC-ITU to prepare the two types of fuel (pellet and sphere-pac):

- *Pellets*. The synthesis of the fuel pellets required a number of steps including:
  - Production of porous (U,Pu)O_{2-x} beads (without americium) by the sol gel external gelation route;
  - Infiltration of the porous beads with americium solution and subsequent calcination;
  - Pressing of the beads;
  - Sintering of the compacted material;
  - Control and selection.
- *Sphere-pac*. The synthesis of the fuel fractions for the particle fuel required a number of steps including:
  - Preparation of small size fraction porous (U,Pu)O_{2-x} beads (without americium) by the sol gel external gelation route;
  - Preparation of large size fraction porous (U,Pu)O_{2-x} beads (without americium) by the sol gel internal gelation route;
  - Infiltration of the porous beads (large and small size fractions) with americium solution and subsequent calcination;
  - Sintering of the infiltrated beads;
  - Control and selection.

The infiltration procedure can indeed yield different concentrations of Am in each individual bead that is infiltrated, simply due to porosity of each bead being different. Pressing these beads into pellets brings a multitude of these beads into intimate contact and during the sintering the material homogenises in Am content throughout the pellet. Thus we observe very sharp XRD patterns, signifying a single phase.

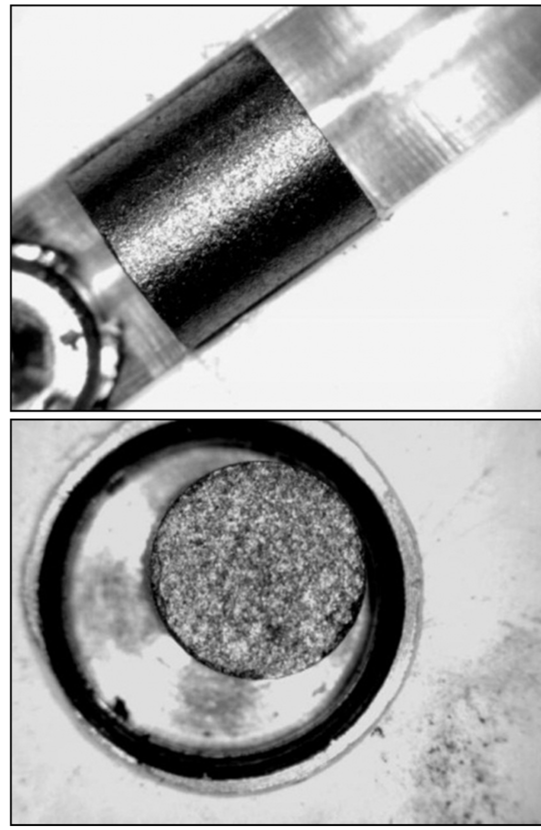

Fig. 3. Am-bearing MOX pellets fabricated for the SPHERE irradiation.

Representative pictures of fuel pellets and spheres are presented in Figs. 3 and 4. The Fig. 4 shows the MOX SPHERE fuel in the two sizes selected: 60 μm (top, right) 800 μm (bottom right).

The pins are placed one on top of each other with the two separate fuel stacks placed in the highest flux position (i.e. close to the centre of the core).

3. Experimental

The SPHERE irradiation is carried out in the wet channel of a TRIO 131 Dry Wet Dry (DWD) rig with a standard rig head (see Fig. 5). This is one of the non-standard re-usable irradiation rigs employed in the HFR.

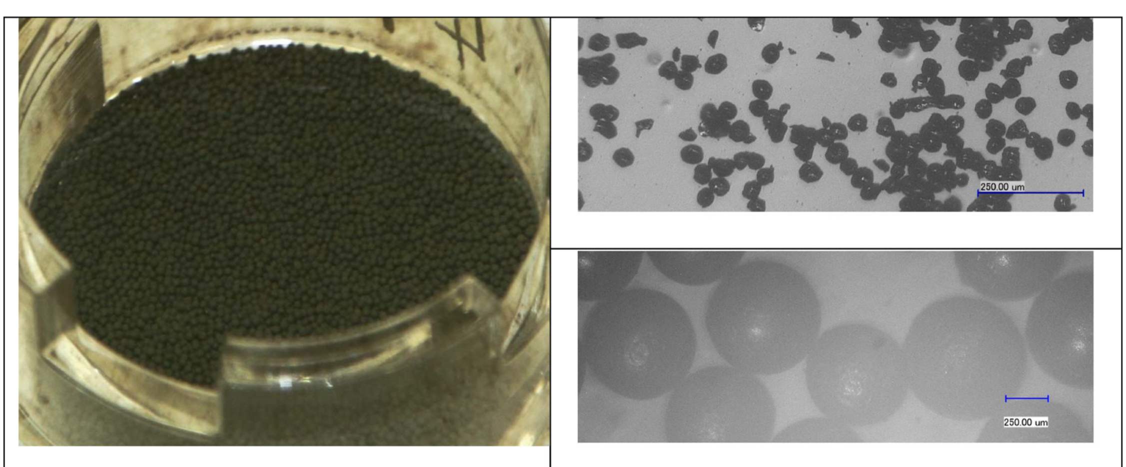

Fig. 4. Am-bearing MOX spheres for the SPHERE irradiation in two size fractions: small (≈60 μm, top right picture) and large one (≈800 μm, bottom right picture).

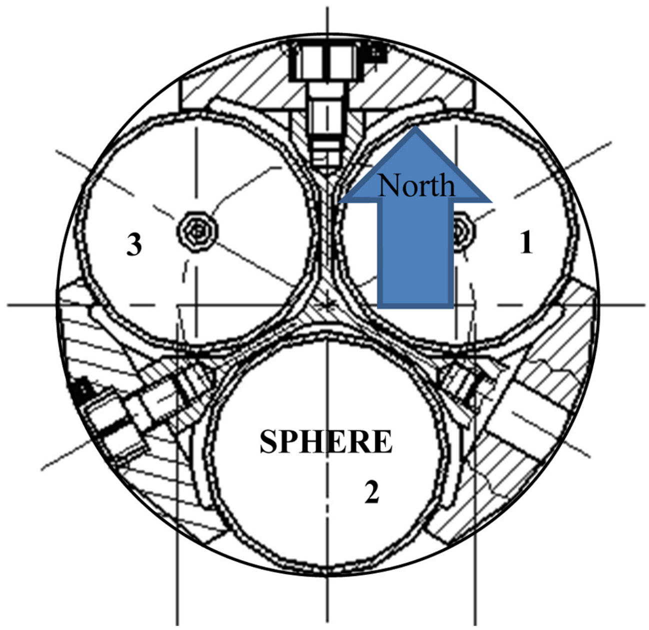

Fig. 5. TRIO-131 DWD capsule for experiment (North orientation on top). Channel 2 (bottom position) is the wet channel.

In contrast to a (standard) dry TRIO channel, water is flowing through the wet TRIO channel, which provides a means to directly cool the sample holder containing the experiment with primary HFR coolant. This solution was adopted to cool the hafnium which shields the experiment and hardens the neutron spectrum, in order to reach a maximum linear power of 300 W cm^{-1}.

The in-pile section holding the pins consists of three elements:

- The assembly which comprises two sample holders, one inside the other. The two sample holders constitute the 1st and 2nd containment for the irradiation experiment. The internal sample holder contains the two pins.
- The TRIO-131 wet channels contains the double wall sample holder;
- The rig head, representing the transition between the in-pile section and out-of-pile installation, carries all instrumentation leads and gas tubes.

The other two TRIO-131 channels are dry and filled with dummy sample holders made of aluminium.

Table 3 shows the radial dimensions of the TRIO-131 channels and the sample holders:

In order to reach the required average temperature in each pin, the radial gas gap between the 1st and the 2nd sample holder has been axially tailored (see Table 4).

The assembly consists of three main sections (see Fig. 6), namely:

(a) the lower section comprising:

- A tube of AISI 316L (external sample holder) containing another tube (internal sample holder) of the same material, which inside contains the irradiation experiment.
- An open tube made of TZM (a Molybdenum alloy), the shroud, containing pins 1 and 2. The TZM shroud contains also some scientific instrumentation, such as thermocouples and neutron fluence detector sets.
- The sealed pins of 15–15 Ti steel cladding tubes with the fuel pellets and sphere-pac column.

Both pins, as well as the TZM shroud, are immersed in a Na bath for enhanced thermal bonding. The Na fills the 1st containment and is in contact with the shroud, with the fuel pins and with the AISI 316L internal sample holder containing the shroud and the pins. See Fig. 7 for a schematic view.

A gas gap between the internal sample holder and the external sample holder is used to tune the temperature of the fuel and to create a barrier between the Na and the water of the cooling system.

The Hf shield surrounding the 2nd containment is of 0.8 mm thickness and consists of 2 tubes of 200 mm length. The tubes were made from sheet material, rolled and welded along its length (see Figs. 8 and 9). The total length of the shield is thus 400 mm.

The design, and the temperature reached in the sample holders, guarantees that the Na remains liquid during operation to improve the heating transfer and avoiding solid formation (too cold working temperature) or sodium boiling (too hot working temperature). The temperature above and just below the Na surface will be monitored by six dedicated thermocouples. In order to prevent oxidation of the Na, the plenum of the 1st containment is filled with high-purity He at 0.1 MPa, sealed after final assembly and kept closed during in-pile operation (no gas circulation in the 1st containment). The heat generated by fission and gamma absorption in the materials will be radially dissipated through the Na bath, the structural materials and the gas gaps by conduction and radiation to the downstream primary coolant of the TRIO wet channel.

The vertical position of the sample holder may be adjusted by means of a remotely operated vertical displacement unit (VDU) to optimise the sample holder position with respect to the neutron flux buckling in the HFR core such that the two fuel stacks produce the same linear power. The temperature in the two sample holders can also be adjusted by changing the gas mixture in the gap between the two containments. While the gap is initially filled with 100% He, the decrease in heat generation with increasing fuel burn-up can be compensated with Ne addition (Ne has a thermal conductivity lower than He and thus better insulates thermally).

As the irradiation proceeds, one (or more) of the tailoring options cited above (e.g. vertical positioning or gas composition

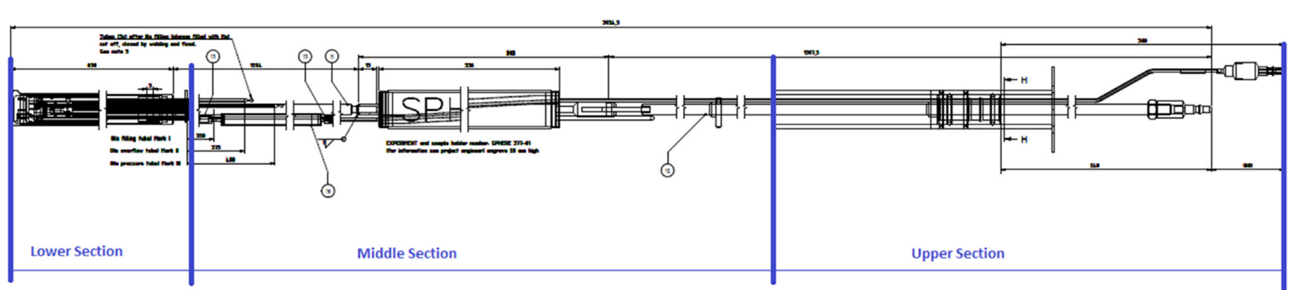

Fig. 6. Technical drawing of the assembly.

Table 3
Main dimensions of sample holders and TRIO channels (at room temperature).

Part	Outer ⌀ (mm)	Inner ⌀ (mm)	Tube thickness (mm)	Material
TRIO channels	33.5	31.5	1	Al. Open to primary coolant
External sample holder	24	22	1	AISI 316L
Internal sample holder	See Table 4[a]	18	See Table 4[a]	AISI 316L

[a] The outer dimension of the internal sample holder has been tailored to match the required fuel temperature.

Table 4
1st containment outer radius and resulting gas gap dimensions (at room temperature).

Axial location (m)		Diameter (m)	Radius (μm)	Gap dimension
Bottom	−0.175	0.0214[a]	0.0107	307.5
−0.175	−0.16	0.0216[a]	0.0108	207.5
−0.16	0.028	0.0218[a]	0.0109	107.5
0.028	0.043	0.0216[a]	0.0108	207.5
0.043	Top	0.0214[a]	0.0107	307.5

[a] As built dimensions.

variation in the gap) can be applied to achieve the final experimental objective within the foreseen irradiation time.

(b) The middle section of the assembly (shown in Fig. 6) consists of the shielding plug, the dust filters in all capillary tubes and one filter with activated charcoal in the down-stream of the second containment. The function of this filter is to adsorb gaseous fission products which might be released from the first or the second containment.

(c) The upper section of the assembly (shown in Fig. 6) consists of the penetration plug with the dynamic O-ring sealing, the connector for the thermocouples, the snap-tight connectors of gas lines and one extension rod with a snap connector suspension for the mechanical coupling with the Vertical Displacement Unit in the rig head. The dynamic sealing is necessary to maintain a leak-tight TRIO channel. The scientific instrumentation of the SPHERE experiment consists of 24 thermocouples (TCs) and 6 fluence detector sets (FD), 3 per pin. The fluence detector sets contain: A nickel–cobalt wire piece (1% Co), an iron wire piece, a titanium wire piece and a niobium wire piece. The TCs used in the experiment are: 24 Type K thermocouples produced

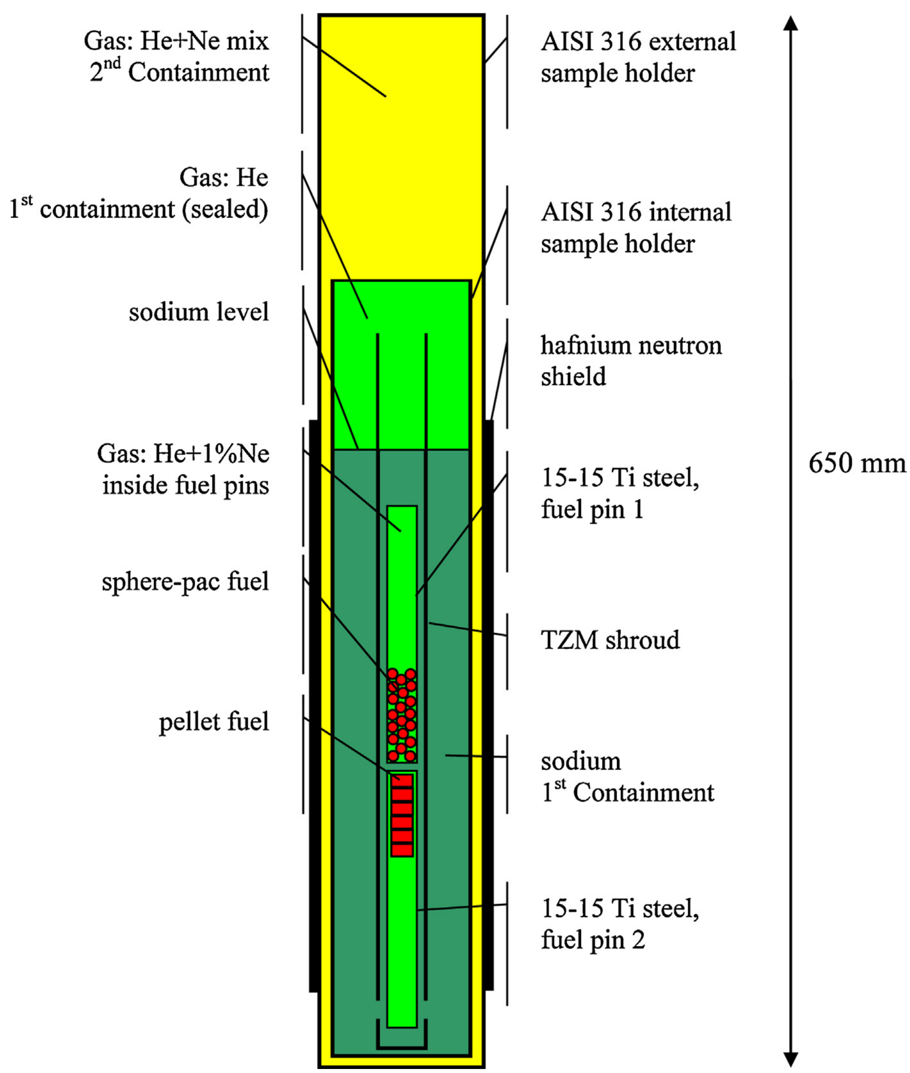

Fig. 7. Schematic view of the SPHERE irradiation experiment.

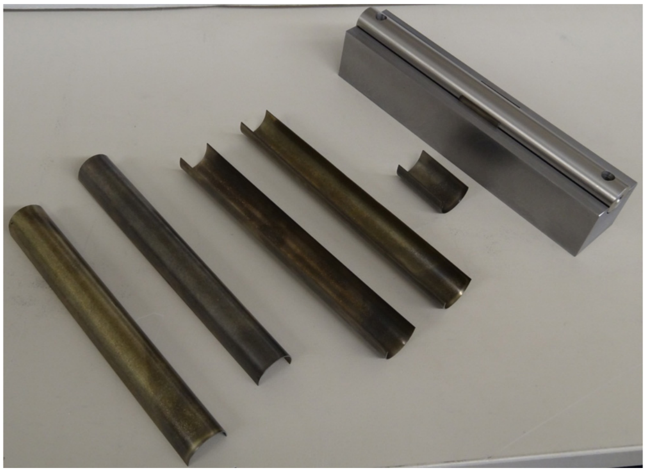

Fig. 8. Hafnium shield rolled and ready to be welded on the external sample holder.

by Thermocoax to measure the temperature field at the Na level and above the Na level as well as to measure the cladding temperature of the pins. These TCs feature MgO as insulation material and AISI 316L as sheath material. Their operating temperatures range from −200 up to 800 °C. The TCs are located inside grooves milled along the outer diameter of the TZM tube and the upper part of the AISI 316L tube. Six TCs are positioned at different levels to monitor the Na level and to detect leakage. Fig. 10 shows the TCs ready to be assembled in the TZM shroud and the plugs of the internal and external sample holders.

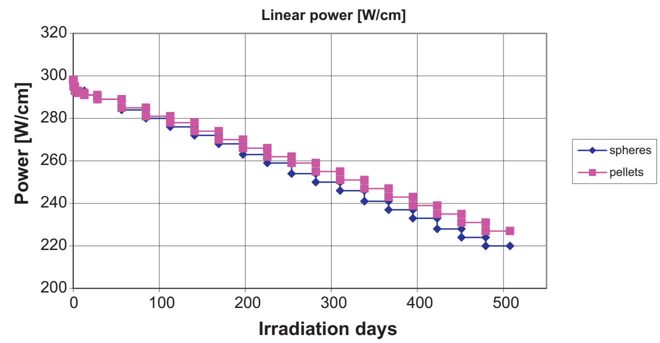

Fig. 11. Predicted power history of the Am-MOX fuel based on MCNP/FISPACT burn-up calculations.

4. Nuclear and thermal design

4.1. Nuclear assessment

The nuclear calculations have been done by the Monte Carlo N- Particle code MCNP-4C3 (Briesmeister, 2001), using a representative HFR core model. The models for the TRIO-DWD containing SPHERE was placed in this core model in position G7 south orientation (as shown in Fig. 5). The burn-up evolution of the two pins of SPHERE was calculated with the OCTOPUS code package (Oppe and Kuijper, 2004), which alternates spectrum calculation (using MCNP) and depletion calculation (using FISPACT-2007 (Forrest, 2007)).

Fig. 11 plots the expected power history (fission + neutron and gamma heating) of the SPHERE pellets and sphere-pac fuel. It shows a decrease of linear power with burn-up due to the consumption of Pu present in both types of fuel.

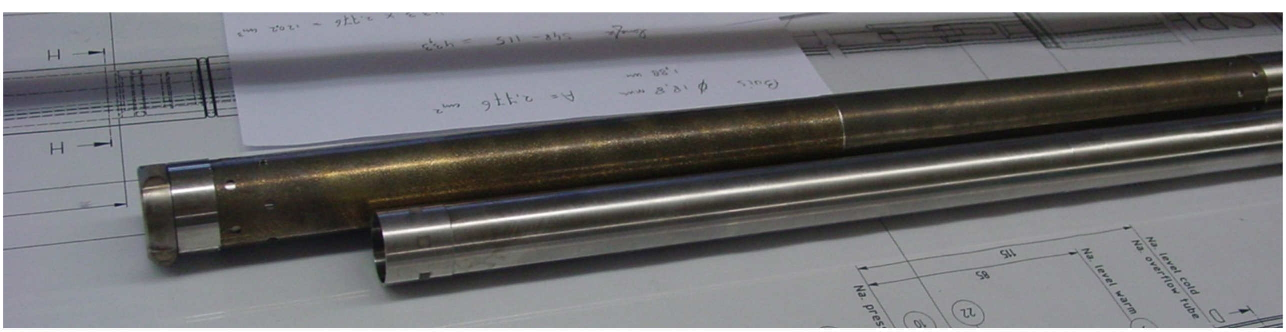

Fig. 9. Internal sample holder and external sample holder (clad with the hafnium shield) ready to be assembled.

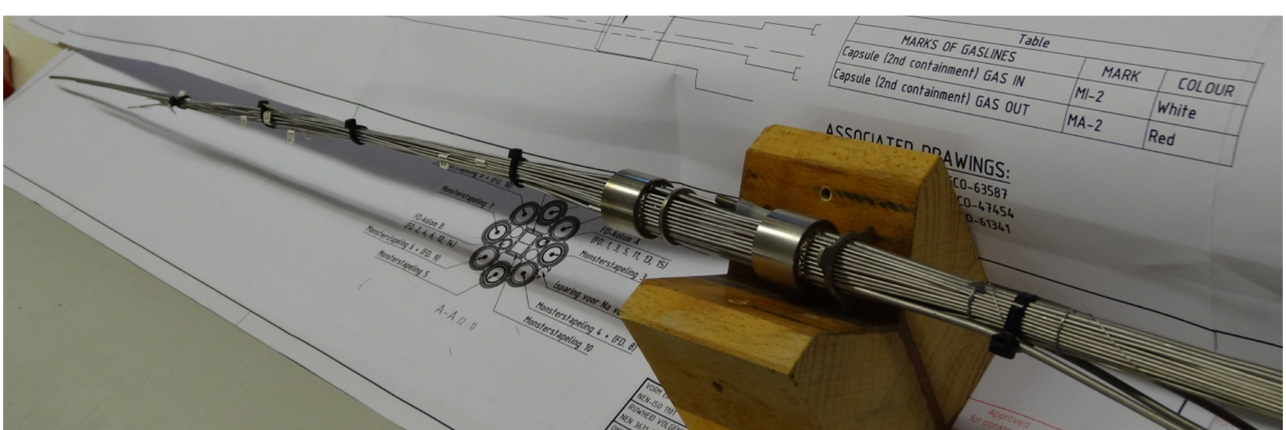

Fig. 10. Thermocouples ready to be assembled in TZM shroud.

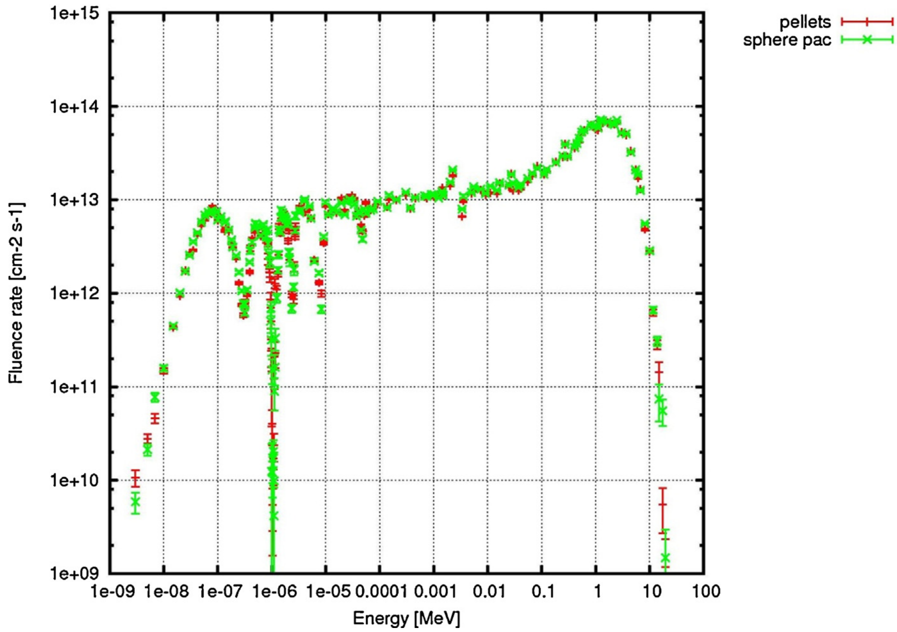

Fig. 12. Neutron spectra in the pellets and sphere-pac fuels.

The position-averaged fluence rates calculated by MCNP have been collapsed to the OSCAR3 7-group structure, which is applied for the HFR cycle calculations. The results are summarised in Table 5. All flux values are averaged over the fuel height (±0.300 m from the core centre-line). The statistical uncertainty from nuclear analyses (standard deviation, 1σ) is of the order of 1–2%.

More in detail, the Fig. 12 shows the neutron spectra directly in the fuel stacks.

The neutron spectra in the pins, as explained in the introduction, is not representative for fast reactor and looks more similar to a thermal spectrum but with an higher amount of fast neutrons.

Table 5
Position-averaged fluence rates for SPHERE.

	Energy boundaries (eV)	Fluence rates (10^{18} m^{-2} s^{-1})
Group 1	$8.208 \times 10^5/1.96 \times 10^7$	0.729
Group 2	$5.53 \times 10^3/8.208 \times 10^5$	0.990
Group 3	$4.00/5.53\ 10^3$	0.714
Group 4	0.625/4.00	0.154
Group 5	0.248/0.625	0.082
Group 6	0.058/0.248	0.257
Group 7	0.0001/0.058	0.258
Total		3.180

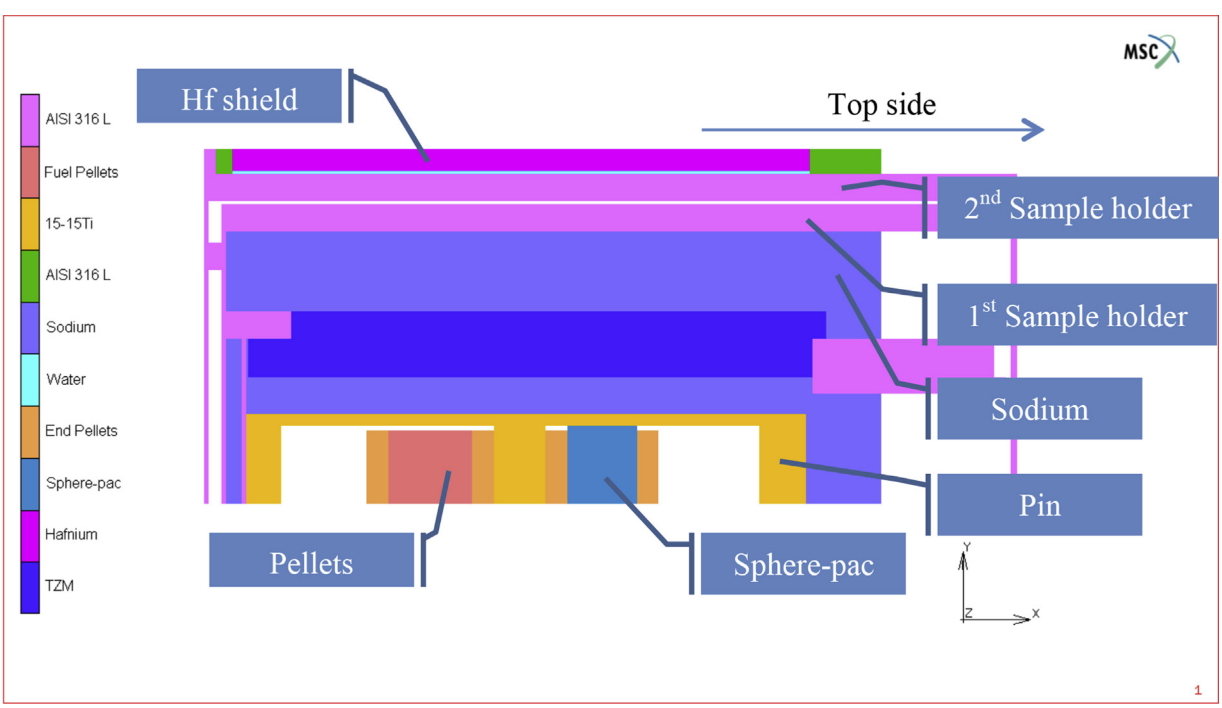

Fig. 13. Axisymmetric FE model of SPHERE.

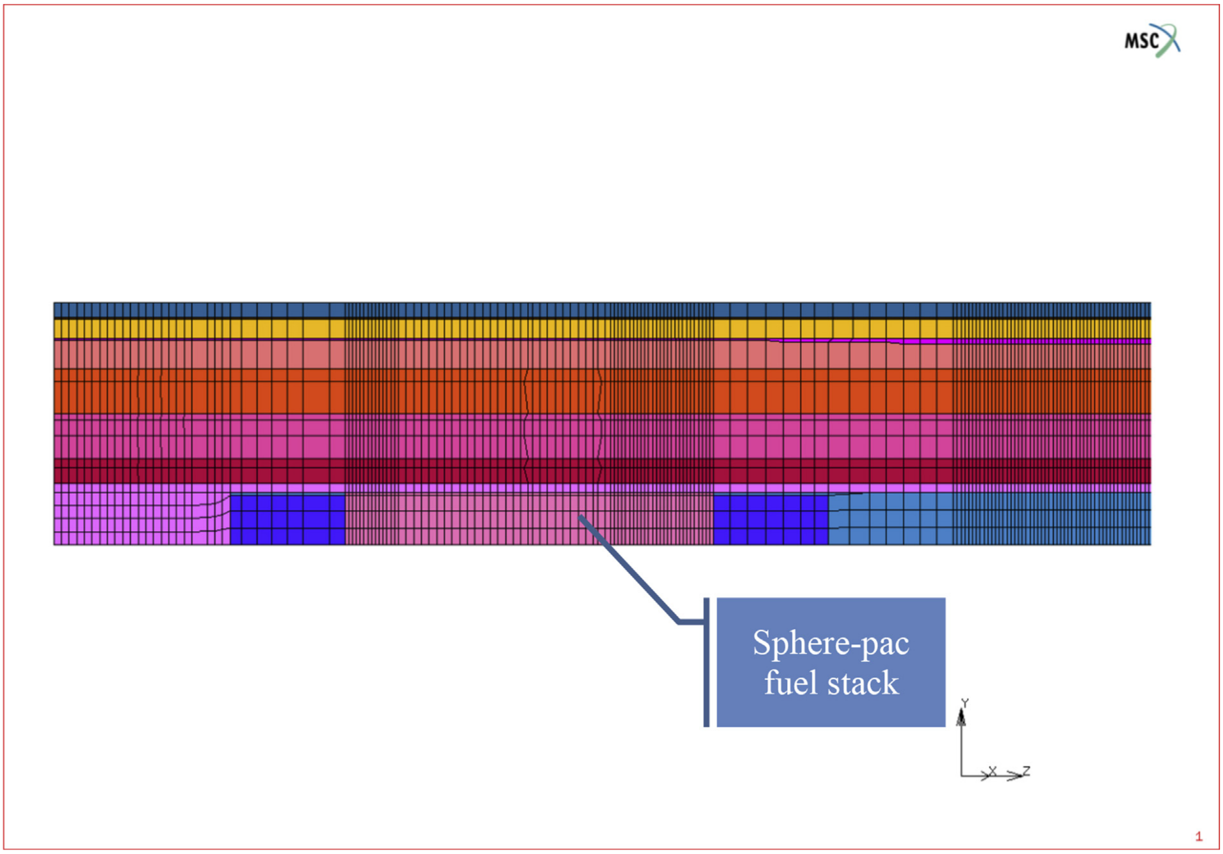

Fig. 14. Mesh distribution at sphere-pac location.

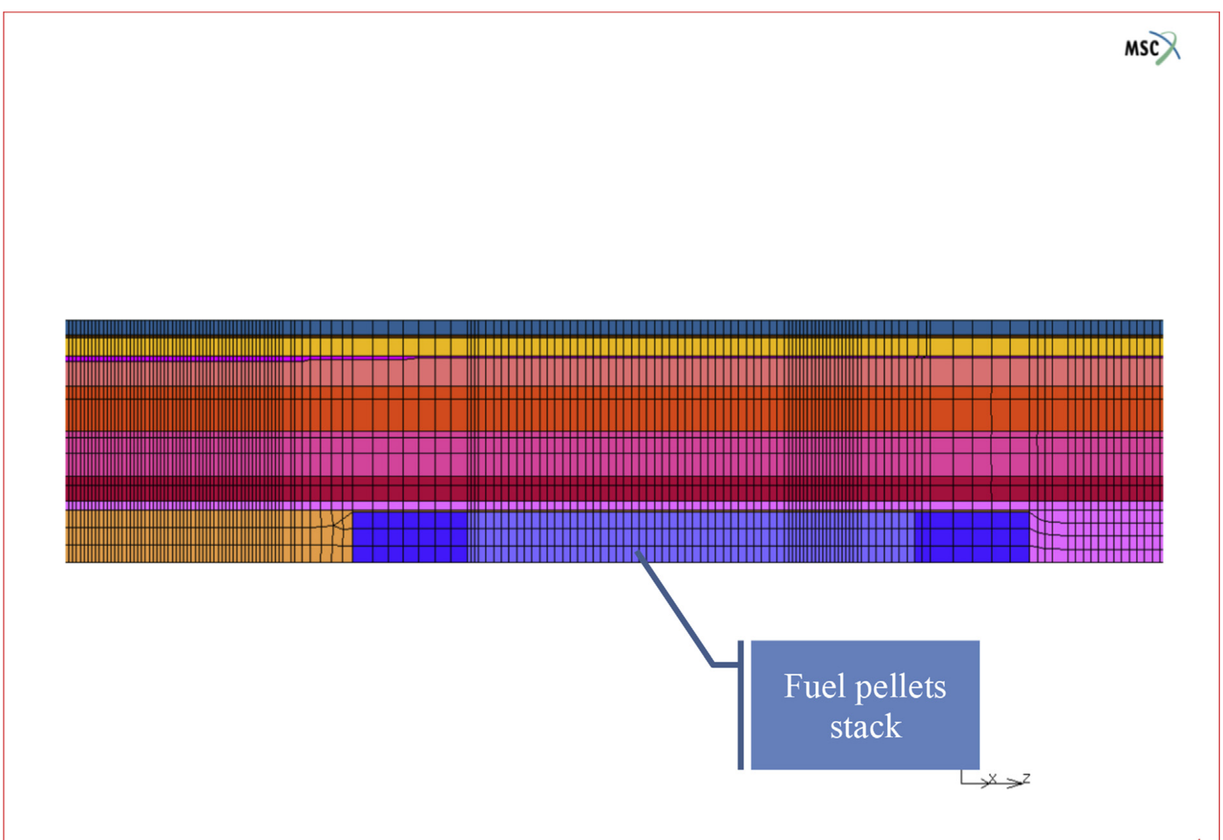

Fig. 15. Mesh distribution at pellet location.

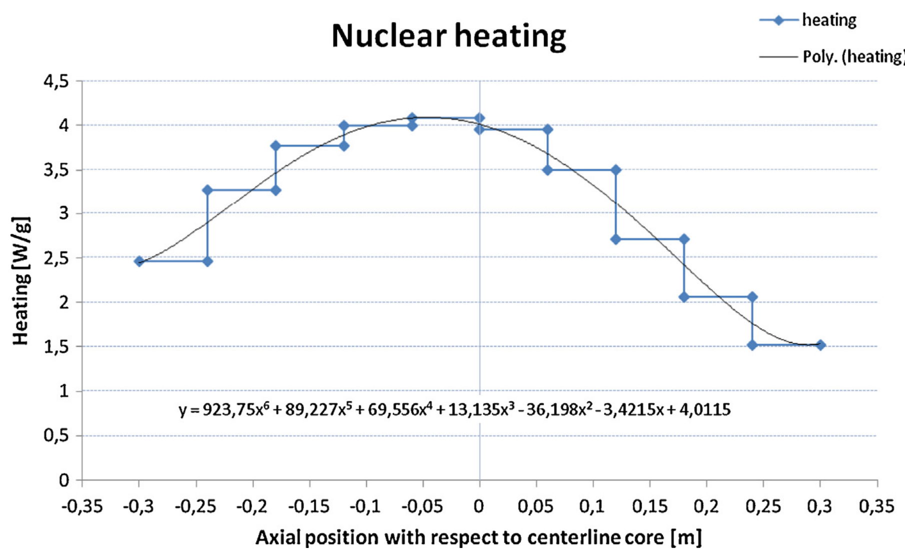

Fig. 16. Nuclear heating (gamma + neutron) for position G7.

Table 6
Estimated maximum plenum pressure in the fuel pins after 18 cycles.

Pin nr.	Total gas (FP + He) (mol)	Temperature (K)	Plenum volume (cm^3)	Maximum pressure at 100% release (MPa)
1 (Sphere-pac)	1.39E−3	900	1.9	6.72
2 (Pellets)	1.86E−3	900	1.64	10.2

One of the objectives of the SPHERE experiment is to study the role of fuel microstructure and irradiation temperature on gas release. The maximum He production was calculated by neutronics: 0.25 mmol for the sphere-pac fuel and 0.3 mmol for pellet fuel after 507 irradiation days (18 cycles). In Table 6 the maximum plenum pressures at the end of the irradiation are conservatively estimated on the basis of full release of He and fission gases in the plenum volume at an estimated average plenum temperature (900 K). The column with the maximum pressure in Table 6 includes also the initial pressure due to the presence of the helium filled during assembly of the pins (0.1 MPa at 298 K results in 0.302 MPa at 900 K). The maximum pressure expected in the pin containing the pellets is 10.2 MPa.

4.2. Thermo-mechanical assessment

In order to understand the behaviour of the experiment, thermal analyses for the beginning (BOI) and the end of irradiation (EOI) have been performed. The cases reported refer to BOI and to the design EOI (i.e. after 507 days of irradiation, 18 cycles). The design allows tuning the temperature by changing the gas mixture in the outer containment (i.e. between the internal and external sample holder). To determine the safety margin, the analyses were repeated with the gas gap completely filled with He or Ne.

For these calculations the FEM code MARC version 2005 (MSC Software Inc.) was used. To optimise the dimensions, an axisymmetric finite element model of the SPHERE experiment was prepared.

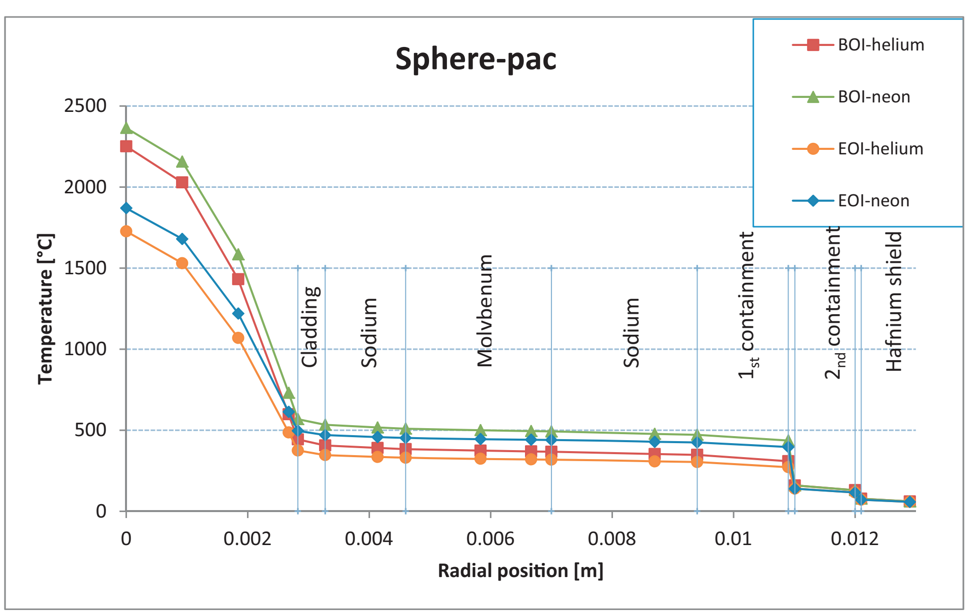

Fig. 17. Comparison of radial temperature distribution for the different load cases, sphere-pac.

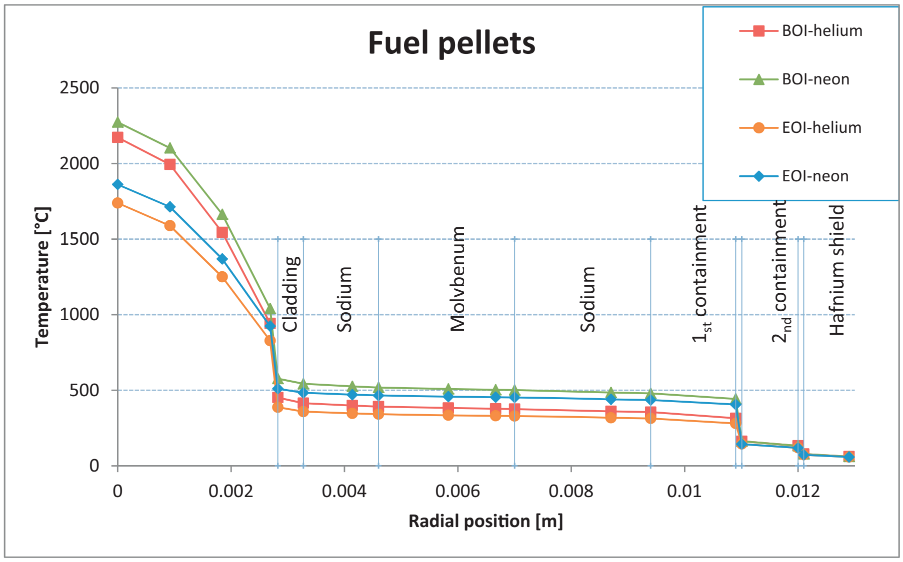

Fig. 18. Comparison of radial temperature distribution for the different load cases, fuel pellets.

The TRIO tube and gap around the external sample holder were not modelled because all the heat is assumed to be transferred into the water of the primary cooling system flowing in the wet TRIO channel. The temperatures and stresses were calculated using a single axisymmetric model coupling a thermal and a mechanical analysis. The model used can be seen in Fig. 13.

The different colours shown in Fig. 13 refer to the different materials used in the analysis. The mesh is too dense in axial direction to be shown in a single image. Therefore, Figs. 14 and 15 show the mesh distribution at the pellet fuel and the sphere-pac respectively. The complete mesh contains a total of 12,098 nodes and 10,694 elements.

Initially the temperature of the entire assembly is set to room temperature (293 K). Thermal expansion effects have been inferred on the basis of this reference temperature.

The nuclear heating (gamma + neutron) in position G7 depends on the axial position and is based on MCNP calculations. Fig. 16 shows the heating profile resulting from these MCNP calculations with a 6th order polynomial regression.

In each element of the FE model (except for elements comprising the nuclear fuels), the heat generated due to neutron capture and gamma heating was calculated by using the polynomial in a user subroutine (the MARC subroutine FLUX).

In the fuel pellets, besides nuclear heating, additional heat is generated due to fission heating.

The fission average heating for the sphere-pac is 298 $W\,cm^{-1}$ (1.19×10^9 $W\,m^{-3}$) at the beginning of irradiation and 220 $W\,cm^{-1}$ (0.88×10^9 $W\,m^{-3}$) at the end of the 18-cycle irradiation, if the experiment stays in the chosen HFR position. For the fuel pellets the fission average heating is 298 W cm (1.31×10^9 $W\,m^{-3}$) at the beginning of irradiation and 227 $W\,cm^{-1}$ (1.00×10^9 $W\,m^{-3}$) at the end of irradiation.

The convection heat transfer coefficient was assumed to be 30,000 $W\,m^{-2}\,K^{-1}$. The bulk water temperature was assumed as a constant 45 °C.

As the temperatures in the experiment are relatively high, heat radiation can have a significant influence on the thermal behaviour of the system. Heat radiation between the outer surface of the pellets and the inner surface of the fuel pin tubes has been included in the model. Heat radiation has been incorporated in the model by adjusting the thermal conductivity of the gas mixture present in the gap. An effective thermal conductivity is calculated, taking into account temperature-dependent conductivity, expansion effects and wall temperatures. This effective thermal conductivity is implemented through the user subroutine ANKOND for all gas volumes present. For all solid materials an emissivity coefficient ε of 0.8 was used.

The model was verified for radial heat transfer by comparison with a 1D model.

Four design cases have been considered: case 1 BOI-helium and case 2 EOI-helium describe the situation for the beginning of irradiation and end of irradiation when using 100% He in the gas gap between the 1st and 2nd containment. Case 3 BOI-neon and case 4 EOI-neon describe the situation for the beginning of irradiation and end of irradiation when using 100% Ne in the gas gap.

The Figs. 17 and 18 show the radial distribution of the temperature, which are possible to reach during the irradiation by changing the gas mixture in the gas gap. Figs. 17 and 18 show, respectively, temperature distribution at sphere-pac and pellet fuel location.

From the figures above, it is clearly visible that the model predicts fuel temperatures approaching 2500 °C in absence of fuel restructuring. The temperatures of the cladding will always remain well below 650 °C which is considered a safe limit for 15–15Ti steel.

5. Conclusions

Minor Actinide bearing Driver Fuel (MADF) is an option to burn minor actinides homogeneously inside the core of a sodium-cooled fast reactor. The results of the SPHERE experiment will provide better understanding of the comparative irradiation behaviour of sphere-pac and pelletised fuel with respect to helium release/trapping and to fuel swelling and fuel-cladding interaction. Moreover, SPHERE will give also useful information on the restructuring process of sphere-pac fuel and on actinides radial migration.

The extent of fuel restructuring will be determined after the first irradiation cycle by neutron radiography. Most probably, only the presence or absence of a central hole and the possible occurrence of fuel melting can be determined. If it is concluded from the neutron radiography that central hole formation and restructuring have not occurred, fuel central temperatures should be increased by repositioning SPHERE to a higher flux position in the HFR.

Although the experiment was designed for 18 HFR cycles, the irradiation could be shortened if sufficient production of helium and a clear restructuring of the sphere-pac fuel is reached. At the end of the experiment, the analysis of the fluence detector sets will confirm the exact fluence which the experiment has received. Then, post-irradiation neutronic simulations to reassess total helium production will be performed within the European project PELGRIMM. These values will be compared with the values obtained by post-irradiation gas puncturing (to determine the released He) + annealing test (to measure He retained in the fuel). A comparison of this data will confirm the amount of helium produced and released which will be then correlated with the fuel temperature, thus enabling a direct performance comparison between pellet and sphere-pac fuel.

Some other investigation will be performed during the Post Irradiation Examination planned within the European project PELGRIMM started in January 2012 and planned to finish in December 2015: profilometry, gamma-scanning and spectrometry, sample metrology, ceramography as well as Scanning Electron Microscopy and Electron Micro-Probe analysis to determine the microstructure evolution during irradiation.

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