IRRADIATION EFFECTS ON 6061-T6 ALUMINIUM ALLOY USED FOR JHR INTERNAL STRUCTURES

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ABSTRACT

The Jules Horowitz Reactor (JHR) is a new irradiation reactor that will replace the OSIRIS reactor sometime in the next decade. For most of the 21st century, it will be used to conduct a large number of irradiation experiments that will study the behaviour of materials and fuels under irradiation.

JHR is intended to irradiate samples at levels up to twice those of OSIRIS. The reactor will be slightly pressurised, and its internal structures will be made from specific neutron-transparent materials to achieve these high levels of irradiation. Many of these structural materials will be subjected to high fluence, such as the reactor vessel, which serves as the core-reflector interface and must therefore resist major mechanical and thermal loads.

Precipitation-hardened 6061-T6 aluminium alloy was chosen for these internal structures (core vessel, rack, etc.) in order to provide safe, reliable operation with an economically feasible lifespan. This alloy is considered to have better post-irradiation properties than AG3-NET(O). The main risks associated with this material and its components are:

- Reduced ductility, resulting in a lower total tensile strain,
- Reduced fracture toughness, resulting in a material more likely to undergo sudden failure,
- Irradiation creep and swelling, resulting in a change of the component dimensions.

As part of the first two levels of containment, the mechanical properties of the critical components that are subject to irradiation must be guaranteed during the design phase, and they must be able to be monitored during operation.

Two irradiation programs focusing on these materials have been implemented with the goal of reducing these risks:

1) The **RAJAH** program involves the irradiation of Al 6061-T6 and AG3-NET(O) samples in OSIRIS in the core reflector position. This program studies their tensile behaviour, fracture toughness, and impact strength under a high thermal neutron flux. It started in April 2008 and should end with the shutdown of OSIRIS.

The goals of the program are to:

- Achieve a thermal fluence in the range 1.5 to 2 EFPY (Equivalent Full Power Years) (JHR) on a base material representative of the JHR core vessel in order to assess changes in its mechanical properties (tensile strain, fracture and impact strength),
- Demonstrate that the mechanical behaviour of welds on the core vessel skirts are not affected by the irradiation at 17 EFPY (JHR), based on the assumption that they are located furthest from the maximum flux area.

Microstructural examinations will be conducted on the irradiated samples to identify any changes in their mechanical properties.

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2). The **FLOREAL** program involves the irradiation of AA-6061-T6, AG3-NET(O) and AlFeNi alloys in the OSIRIS core to study the behaviour of metal blades subjected to stress relaxation under irradiation. This program started in December 2006 and will end in late 2012.

The goals of the program are to study the stress-relaxation behaviour of these alloys under neutron flux, both in the as-fabricated state and in a second stage after pre-irradiation in unbended configurations. Relaxation is measured between cycles using laser profilometry. Additional microstructural observations will be conducted using transmission electron microscopy.

Once the JHR has reached criticality, these two irradiation programs will help us to better understand the mechanical properties of aluminium alloys used for the internal structures by examining their microstructural changes. At the same time, these programs will be useful for anticipating the behaviour of these materials under flux, thereby rendering these components more reliable during operation.

1. Introduction

The Jules Horowitz Reactor (JHR) is a MTR which will replace the OSIRIS reactor in the next decade and will offer a large number of irradiation experiments. To achieve high levels of irradiation, the reactor will be slightly pressurized, and its internal structures will be made from specific neutron-transparent materials.

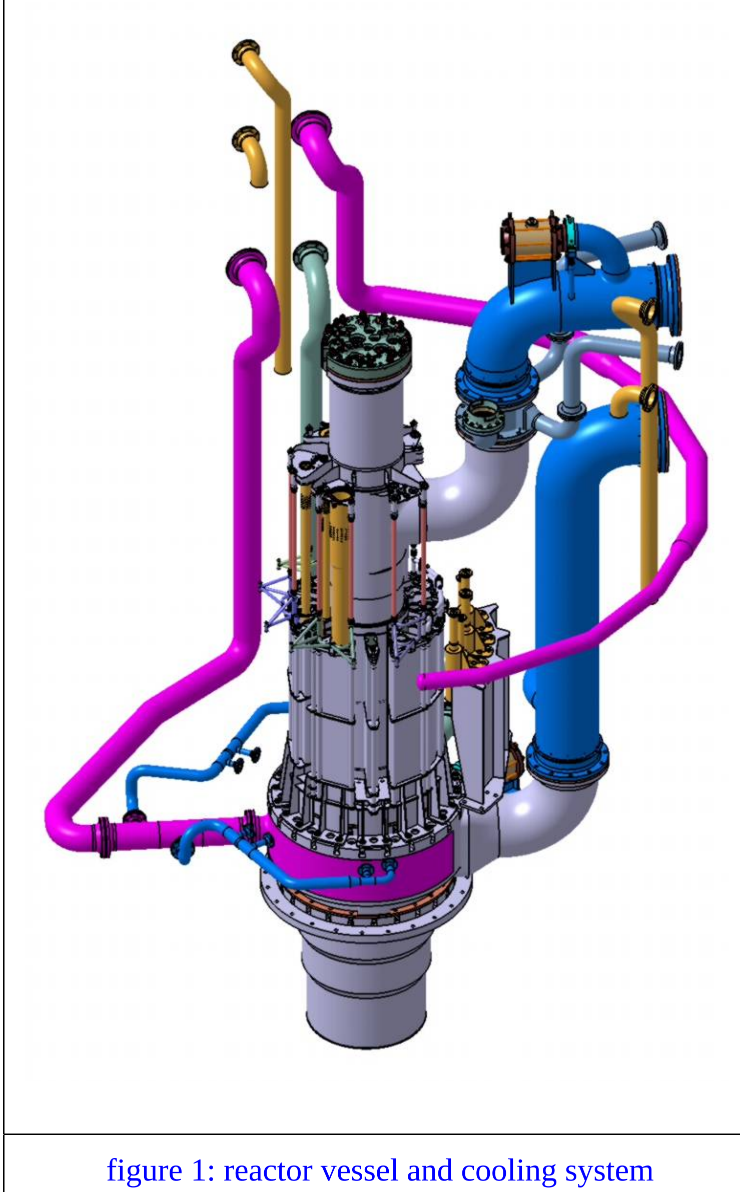

figure 1: reactor vessel and cooling system

In order to limit neutron absorption, achieve high levels of neutron flux (over 8 10^{14} n/cm^2.s^{-1} at the core center in the mid-plane), and limit the gamma heating and the component temperatures, aluminium alloys have been chosen for a wide range of core components :

- the precipitation-hardened alloy 6061-T6 (Al-Mg-Si system) will be used for the subcomponents of the core vessel (main skirt, tee, upper and lower skirts and base flange) and for the rack supporting the fuel elements (fig. 2). This alloy is widely used in the American research reactors (HFBR, HFIR).
- The AG3-NET(O) alloy, a non heat-treatable alloy of the 5000 series (Al-Mg), could be used in the annealed temper for the external tube of experimental devices. The chemical specifications of this alloy (cf table 1) have been derived from the AA-5754 alloy by reducing the contents in specific elements in order to limit neutron absorption, activation, and corrosion for use in water in a nuclear environment at moderated temperatures. AG3-NET is widely used for the core components and the experimental devices in the European research reactors.
- An Al-Fe-Ni alloy (8000 series) that is already used as fuel cladding in some European research reactors will be used for the JHR fuel clad after annealing and bending of the fuel plates to build the cylindrical fuel elements (fig. 4). This alloy was designed at the end of the 1960's, in response to a need for fuel cladding that can resist corrosion in water at high temperatures (over 250°C).
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Chemical element	AG3-NET	6061	AlFeNi
Si	≤ 0.30	0.40-0.8	< 0.3
Fe	0.2-0.40	≤ 0.7	0.8-1.2
Cu	≤ 0.008	0.15-0.40	≤ 0.008
Mn	≤ 0.70	≤ 0.15	0.2-0.6
Mg	2.5-3,0	0.8-1.2	0.8-1.2
Cr	≤ 0.30	0.04-0.35	0.2-0.5
Ni	-	-	0.8-1.2
Zn	≤ 0.03	≤ 0.25	≤ 0.03
Zr	-	-	0.06-0.14
Ti	≤ 0.02	≤ 0.15	0.02-0.08
Other specified	Fe+Si ≤0.5	-	B, Li, Cd ≤0.001 Fe+Ni > 1.8
Other non specified (each)	≤ 0.03	≤ 0.05	≤ 0.03
Other non specified (total)	≤ 0.15	≤ 0.15	≤ 0.5

Table 1 : Chemical specifications in wt% of the aluminium alloys used in the JHR

The 6061-T6 alloy (table 1) was chosen for the pressurized vessel because of its high yield and tensile strengths and its good mechanical stability under neutron flux. A review of post-irradiation mechanical data and microstructural evolution under irradiation was performed by Farrell in 1995 [i]. Irradiation effects on tensile properties have been extensively studied [ii-iii iv v vi], and some data have been published on fracture toughness by Alexander [iv], on impact toughness and microstructures by Weeks [v], on post-irradiation creep by King [vii], and on swelling by Farrell [i]. Post-irradiation data for this alloy at high fluences show a loss of ductility, a reduced fracture toughness, and swelling leading to a change of the component dimensions. No irradiation creep data have been published yet. According to the published data on different products (rolled plates, tubes) there is a great scatter in the measured properties. The wide data range measured at high fluences seems to be in large part attributed to different fabrication processes and to the T6 heat treatment parameters (cooling rate, aging temperature and time). Indeed, the different irradiation conditions alone do not explain the wide scatter of the data.

The AG3-NET(O) alloy (table 1) is a potential candidate for the experimental devices because its neutron transparency is much better than that of steel. But like the 5000 series Al-alloys, the AG3-NET undergoes a severe loss of ductility at high fluences [viii]. Moreover, very little data exists for the mechanical properties of this alloy after several years of neutron irradiation. There is no fracture toughness data because the geometry of the tested components often does not allow appropriate samples to be fabricated. Likewise, there is little swelling data.

The AlFeNi alloy, whose chemical specifications are given in Table 1, has been chosen for the JHR fuel plate cladding because it has lower creep strains than the AG3-NET(O) in the intermediate temperature range (50 to 150°C) for stresses between 50 and 70 MPa corresponding to fuel plate operation conditions. Moreover, the AlFeNi alloy has a better corrosion behaviour than the 6061-O alloy in water at high temperatures (over 250°C), which is appreciable in case of accident. AlFeNi cladding is already used and appears to work well in some high-flux research reactors like the RHF (France) and FRM2 (Germany). But a lack of mechanical data on the irradiated alloy limits a generalized use of this alloy in the MTRs.

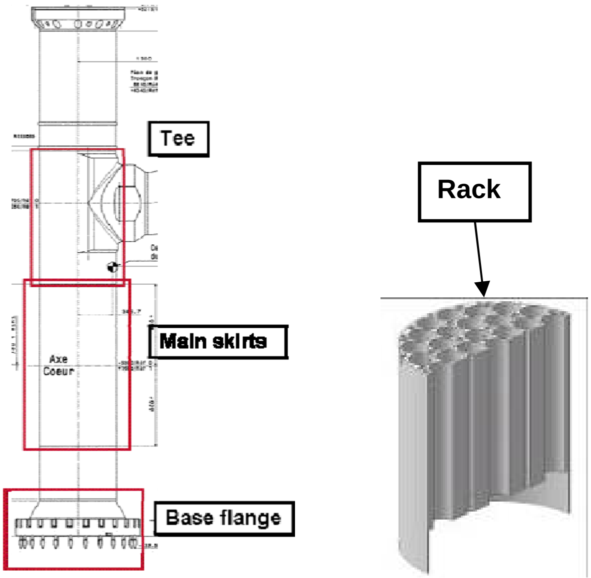

Figure 2 : Main subcomponents of the vessel and the internal structures

A qualification program of the as-fabricated aluminium alloys was implemented in 2000, aiming in a first step to develop the fabrication and welding processes of the critical components, then to define their receipt criteria, and finally to qualify the relevant processes.

After the definition phase, which aimed to assess the reactor industrial feasibility, a second step began in 2006 concerning the fabrication process qualification with the following objectives:

- Test and validate different forging and welding methods for the vessel (cylindrical skirts, tee), the base flange and the fuel rack,
- Understand the relations between microstructure, fabrication process and mechanical properties,

- Help the industrial companies to master the fabrication conditions.

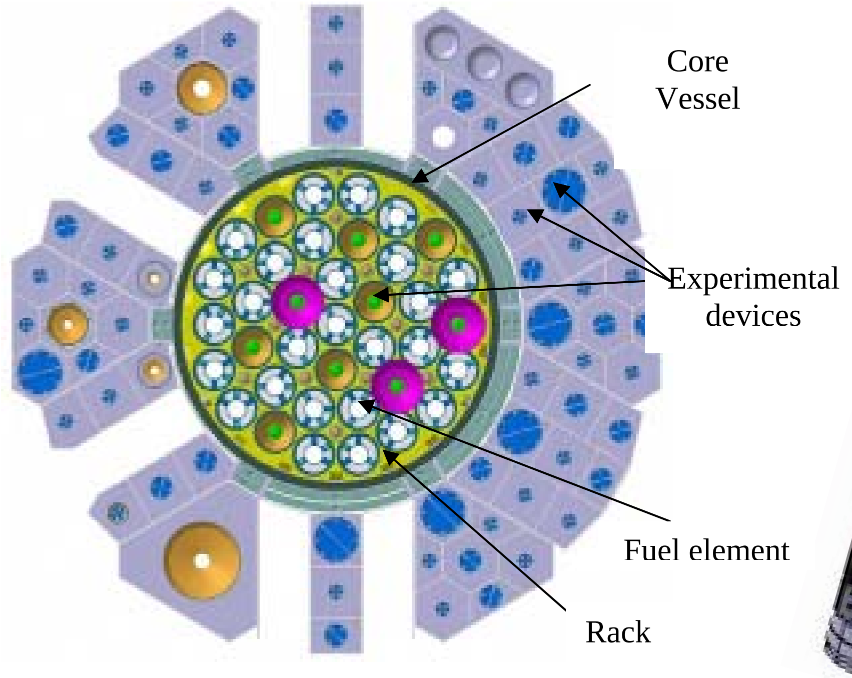

Figure 3 : Reactor core, and reflector

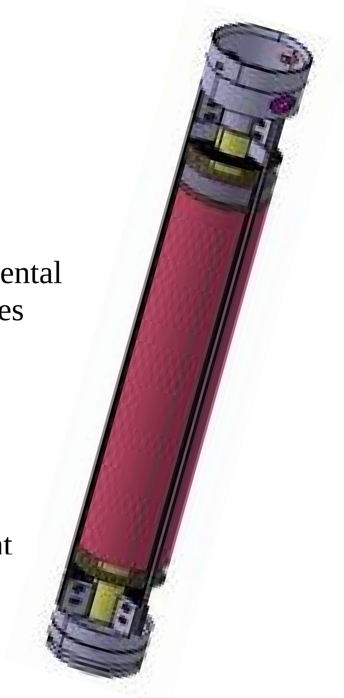

Figure 4 : Fuel element

In order to validate the mechanical properties of the critical components during the design phase and operation, two irradiation programs focused on these aluminium alloys have been implemented in the OSIRIS Material Testing Reactor in Saclay : the RAJAH irradiation (**A**luminium **A**lloys for **RJH**) started in 2008 and the FLOREAL irradiation started in 2006.

2. Vessel fabrication process

- Forging process

The aluminium 6061 alloy contains Silicon and Magnesium that form homogeneously dispersed Mg2Si precipitates that improve the mechanical properties of the material (yield and tensile strength). The manufacturing process therefore has a strong impact on the microstructure, and hence on the mechanical properties and probably on the evolution under neutron flux.

That is why we tested different forging methods (hammer forging, circular forging) and different conditions for the T6 heat treatment. These tests aim to identify a manufacturing process that produces not only appropriate total tensile strain, but also an acceptable behaviour in fracture toughness. We therefore have to avoid excessively large Mg_2Si precipitates and iron intermetallics. The key parameters are the chemical composition and the fabrication history of the component (forging temperature and heat treatment). Figure 5 depicts a core vessel demonstrator.

- Welding process

Several welding and repairing processes suited for an industrial scale have been tested. Test coupons were welded by different certified experts holding a WPQ (Welding Procedure Qualification) for aluminium. Welding was performed with the electron beam (fig. 6) or the arc welding process, with or out filling metal. The European standards EN 15614-11 and EN 15614-2 have been respectively used for these tests, with soundness control and destructive acceptance tests. A metallographic analysis has been performed to determine the minimum Silicon concentration with regard to the cracking phenomenon.

Figure 5: Core vessel demonstrators

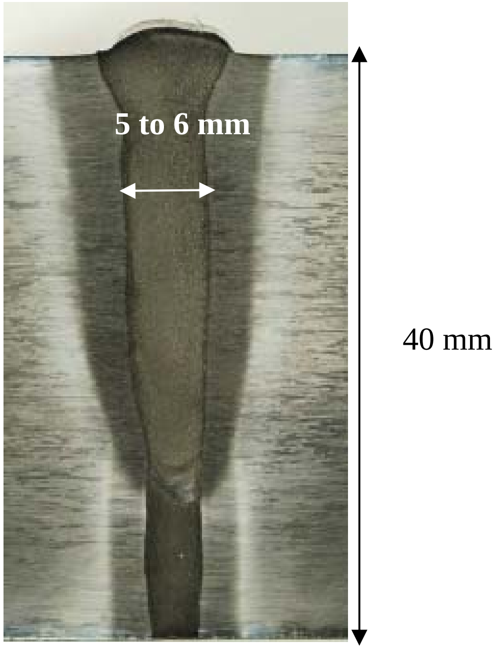

Figure 6: Optical macrography of an electron beam soldering

3. RAJAH irradiation

The RAJAH irradiation of aluminium alloys is performed in the first range of devices outside the Osiris core (fig. 8), to have a ratio of thermal conventional (E=0,0254 eV) to fast neutron flux (E >1 MeV) between 5 and 10. Because the thermal neutron flux contributes to an increase in the mechanical strength and a decrease in strain, the selected ratio was a conservative choice in regard to the mean reactor vessel conditions, and it envelopes local high ratios.

In the reactor mid-plane, the samples receive a conventional thermal neutron flux of $2{,}2\text{x}10^{14}$ $n/cm^2.s^{-1}$, namely a fluence of about 10^{22} n/cm^2 in 24 Osiris cycles of 23 days. The samples designed for mechanical tests are maintained in 15 baskets that are stacked in a tray (fig.7), which is inserted into the experimental device.

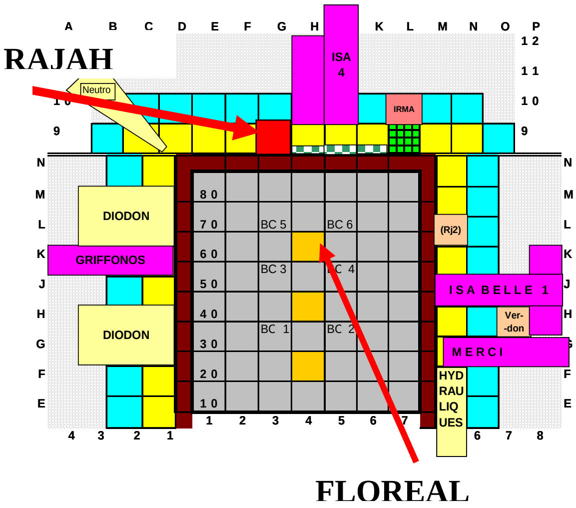

Fig. 7 : up : Tray containing baskets

down : tensile and fracture toughness baskets

Fig.8 : Irradiation place in OSIRIS

The samples are cooled by the reactor cooling light water, which flows downwards through the tray, so that their irradiation temperature is in the range 40°C to 50°C. In order to get homogenous fluences on the different baskets, the device is turned 180° at each cycle, and a permutation of the baskets is made every 4 cycles, except for the 3 central baskets which remain in the mid-plane for the whole irradiation phase to receive a higher fluence. This irradiation consists of three phases:

- The first phase, which started in April 2008, aims to obtain mechanical data on forged AG3-NET alloy, on wrought 6061-T6 alloy fabricated by different processes up to a moderated fluence of 1.5 10^{22} n/cm^2, and on several welded 6061-T6 samples fabricated by different welding processes at low fluences. The irradiation of welded samples at fluences representative of 17 years operation at full power aims to show that the mechanical properties of the vessel welding joints are not degraded by the irradiation. Three sample types were introduced in the device in order to perform tensile, impact, and fracture toughness tests after irradiation (fig.7 down). This first phase will provide some information on the link between the as-fabricated microstructures and the mechanical properties evolution under neutron flux, particularly regarding the ductility loss and the decrease of the fracture toughness. The information gained from this program will validate the chosen fabrication methods.

- The second phase, which is scheduled to start in March 2010, aims to obtain mechanical post-irradiation data on the 6061-T6 alloy fabricated with the process chosen for the vessel and the rack. On the basis of an OSIRIS shutdown date in late 2015, the maximum conventional fluence will reach about 1.5 to 2 10^{22} n/cm^2. This irradiation is a validation phase of the vessel fabrication and welding processes. Tensile and fracture toughness tests will be performed at room temperature and at 75°C to represent the operating conditions of the JHR vessel, and at 125°C to cover the temperature excursions on the rack.

- The third phase, which should start at the middle of 2011, is both a JHR vessel qualification irradiation and a pre-surveillance program. At the close of 24 reactor cycles, the thermal conventional fluence will reach a maximum of about 10^{22} n/cm^2, which is approximately the fluence achieved by the JHR vessel after one year of operation. A few samples will then be tested, and most of the irradiated samples will be transferred into the JHR reactor for a surveillance program. These pre-irradiated samples will then be used in a monitoring program to characterize the effects of irradiation on the JHR vessel material. They will receive the equivalent of one year of additional fluence relative to the JHR vessel.

4. FLOREAL irradiation

Some post-irradiation mechanical data have been published on the aluminium alloys AG3-NET and 6061-T6, but there is no irradiation creep data in the literature. In order to measure the strain rate under irradiation, the "FLOREAL" irradiation campaign is performed in the French Material Testing Reactor OSIRIS. In this experiment, the in-flux relaxation behaviour is assessed using a bending relaxation technique. Constitutive laws allow the relaxation to be determined under fast neutron flux, and the irradiation creep behaviour can be predicted. The relationship between in-reactor stress relaxation and irradiation creep has never been shown in austenitic stainless steels[ix].

This experiment started in December 2006 and will end in late 2012. The device is in the core center as shown in figure 8. The thermal to fast flux ratio in the Osiris core is similar to that of the JHR core vessel (ϕ_{th}/ϕ_f ~2). The maximum fast neutron flux is 2.10^{14} $n_f/cm^2.s^{-1}$ (E>1MeV) and the thermal neutron flux is 4.10^{14} $n_{th}/cm^2.s^{-1}$ (E=0,0254 eV). In this experiment, three aluminium alloys are tested : 6061-T6, AG3-NET(O), and the AlFeNi.alloy. The strip-shaped specimens are irradiated at a temperature of 40-45°C in 7 baskets stacked .in a device through which the reactor cooling water flows (fig. 9). On each basket, 4 samples are in a 3-point-bending position and 4 are in unbended positions (fig. 10). Hence the device contains 28 bended samples and 28 flat samples. There are two types of bended positions (0,6 mm deflection and 1 mm deflection) in order to set 2 different stresses in the strips. The length of the strips and baskets is adapted to the alloy grade in order to impose stresses under the yield strength on each alloy : low stress around 45% of the yield strength, and high stress around 75% of the yield strength.

The experiment is divided in two parts of 8 irradiation periods, whose length increases from 3 days at the beginning to 3 reactor cycles at the end. Each part consists of 2 periods of 3 days and 13 full reactor cycles. The first part, which ended in June 2009, aimed to measure the relaxation behaviour of as-fabricated material. The second part aims to measure the relaxation behaviour of pre-irradiated specimens. In the first part, the bended samples were periodically unloaded and the residual deflections, as well as the shape of the initially flat samples, were measured in hot cells with a laser beam.

In the second part of the experiment, some of the bended specimens stay in bended positions to increase their fluence. And most of the bended positions are reserved to irradiate some of the unbended samples irradiated in the first part. This will allow us to measure the relaxation strain rate under irradiation of specimens pre-irradiated to a thermal fluence of 13. $10^{21}n_{th}/cm^2$. For each part, the irradiation fast fluence at the end is about 5.25. $10^{21}n_f/cm^2$.

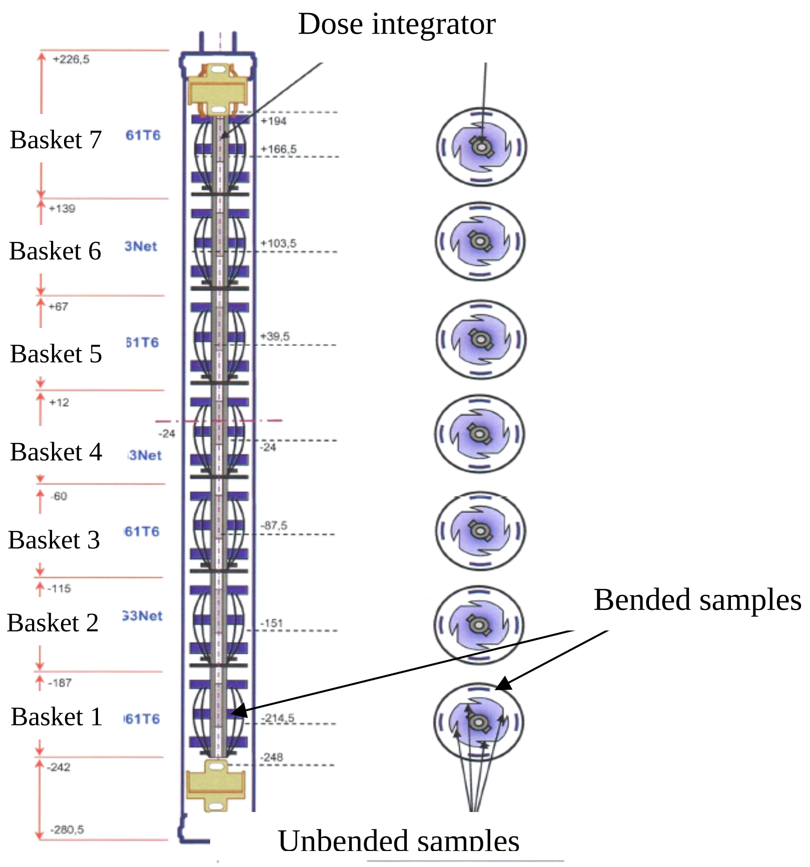

Figure 9 : Irradiation device with the 7 baskets

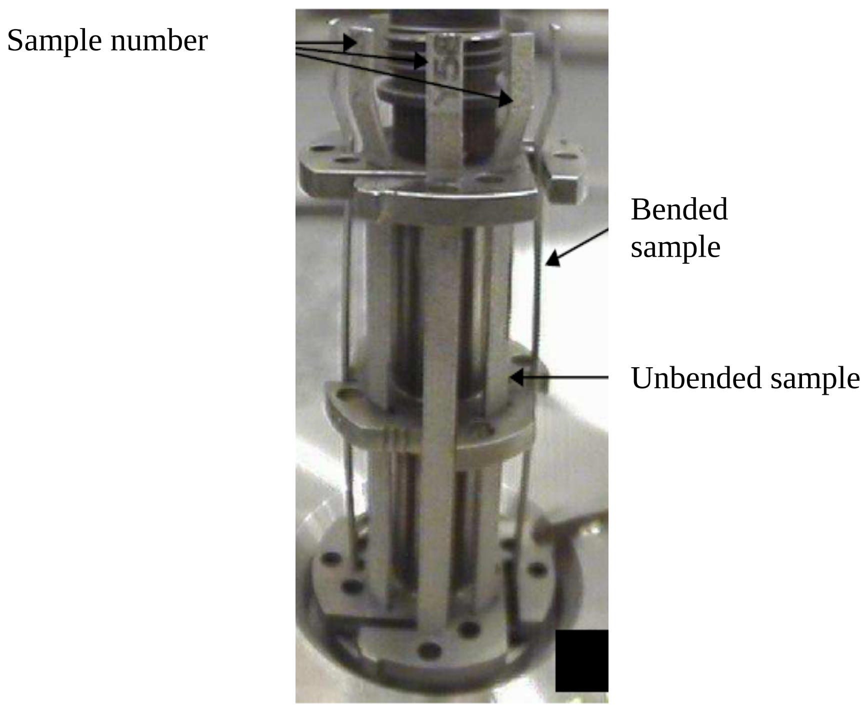

Figure 10: Experimental device with 4 unbended and 4 bended samples

5. Conclusions

The Materials Testing Jules Horowitz Reactor (JHR) will replace the French OSIRIS reactor in the middle of the next decade. JHR will allow irradiation of materials, metallic structures, and fuel at neutron fluxes reaching up to twice those of OSIRIS : $6x10^{14}$ $n_f/cm^2.s^{-1}$ (E>1 MeV) and $4x10^{14}$ $n_t/cm^2.s^{-1}$ (E<0,625 eV).

To achieve these high neutron fluxes, aluminium alloys were chosen for critical components, because their low neutron absorption rate and their low density allow little gamma heating and hence a limitation of the operation temperatures. Precipitation-hardened 6061-T6 alloy was chosen for the vessel and the rack, AG3-NET(O) for the experimental devices, and AlFeNi for the fuel clad.

In 2000, a qualification program of the as-fabricated aluminium alloys was launched. The first step was the reactor definition phase, which aimed to assess the reactor's industrial feasibility. The second step, which began in 2006, consists of the qualification of the fabrication and welding processes for the critical components. Different forging and welding methods were tested and validated.

In the frame of this critical component qualification program, two irradiation programs of aluminium alloys are underway in the Osiris material testing reactor : RAJAH irradiation, which started in April 2008, and FLOREAL irradiation, which started in December 2006.

The great scatter in the mechanical properties measured after irradiation on 6061-T6 is not only due to the variable irradiation conditions but also to differences in the fabrication process and the thermal treatment. The RAJAH irradiation aims to obtain swelling, tensile, and fracture toughness post-irradiation data on the forged AG3-NET-O and on the 6061-T6 alloy fabricated with the process chosen for the vessel and the rack. The samples are irradiated at 40 to 50°C with a conventional thermal to fast neutron flux ratio in the range 5 to 10. On the basis of an OSIRIS shutdown date in late 2015, the maximum conventional fluence will reach up to 2 10^{22} n/cm^2 which corresponds to 2 years of operation of the JHR vessel. Moreover, some welded samples will be irradiated at low fluences representative of 17 EFP years to show that the mechanical properties of the vessel welding joints are not degraded by the irradiation.

The third phase of RAJAH, which should start at the middle of 2011, is both a JHR vessel qualification irradiation and a pre-surveillance program. Most of the irradiated samples will be transferred into the JHR reactor for a vessel monitoring program. In this manner, these monitoring samples will benefit from the equivalent of one year of additional fluence relative to the actual JHR vessel.

Since no irradiation creep data are available for the aluminium alloys, the FLOREAL experimental irradiation has been launched in the Osiris core center in a fast neutron flux of 2.10^{14} $n_f/cm^2.s^{-1}$ (E>1MeV) at a temperature of 40-45°C. This program consists of measuring the relaxation strain rate of AG3-NET(O), 6061-T6, and AlFeNi alloys under irradiation using 3-point-bending specimens. The experiment started in December 2006 and will end in late 2012.

The relaxation behaviour of the as-fabricated samples was measured in the first part of the experiment up to a fast fluence of $5.2.10^{21}$ n/cm^2. In the second part, which starts in October 2009, the pre-irradiated material relaxation will be studied. The relaxation strain rate under irradiation of specimens pre-irradiated to a thermal fluence of 13. $10^{21} n_{th}/cm^2$ will be measured. Some bended samples of the first irradiation part will pursue their irradiation in bended positions to achieve a fast fluence of about 10^{22} n/cm^2.

These relaxation measurements will be used to predict the irradiation creep behaviour of aluminium alloys.

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