Irradiation effects on 6061-T6 aluminium alloy used for the JHR internal structures

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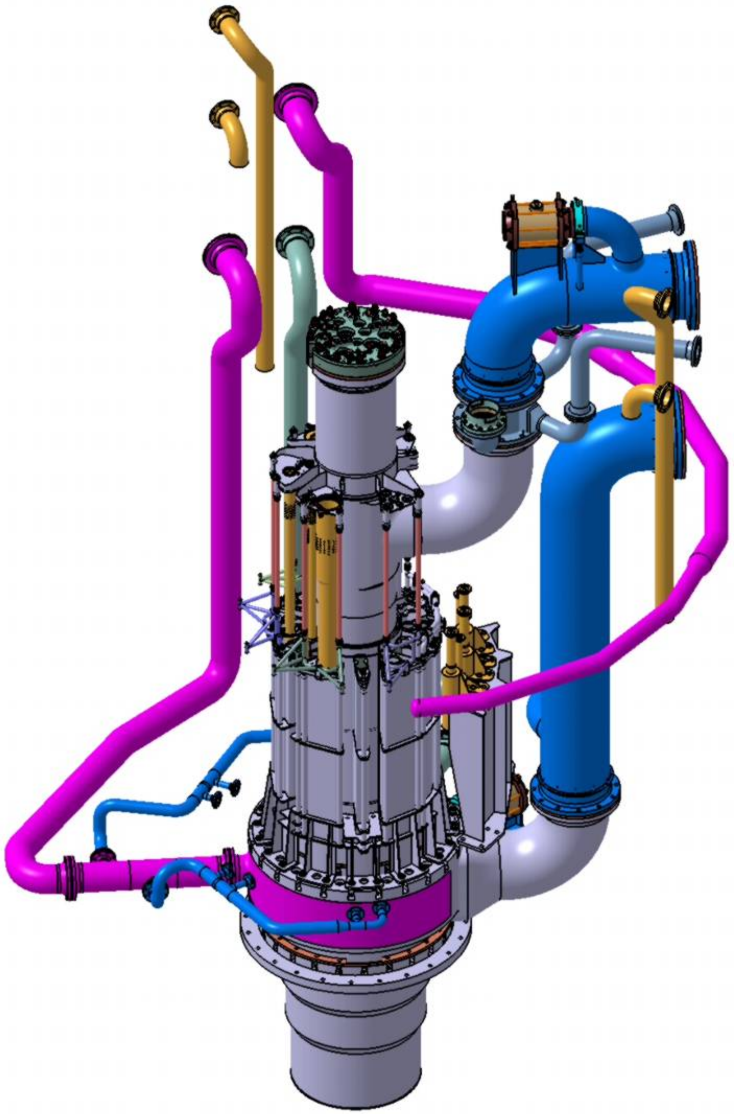
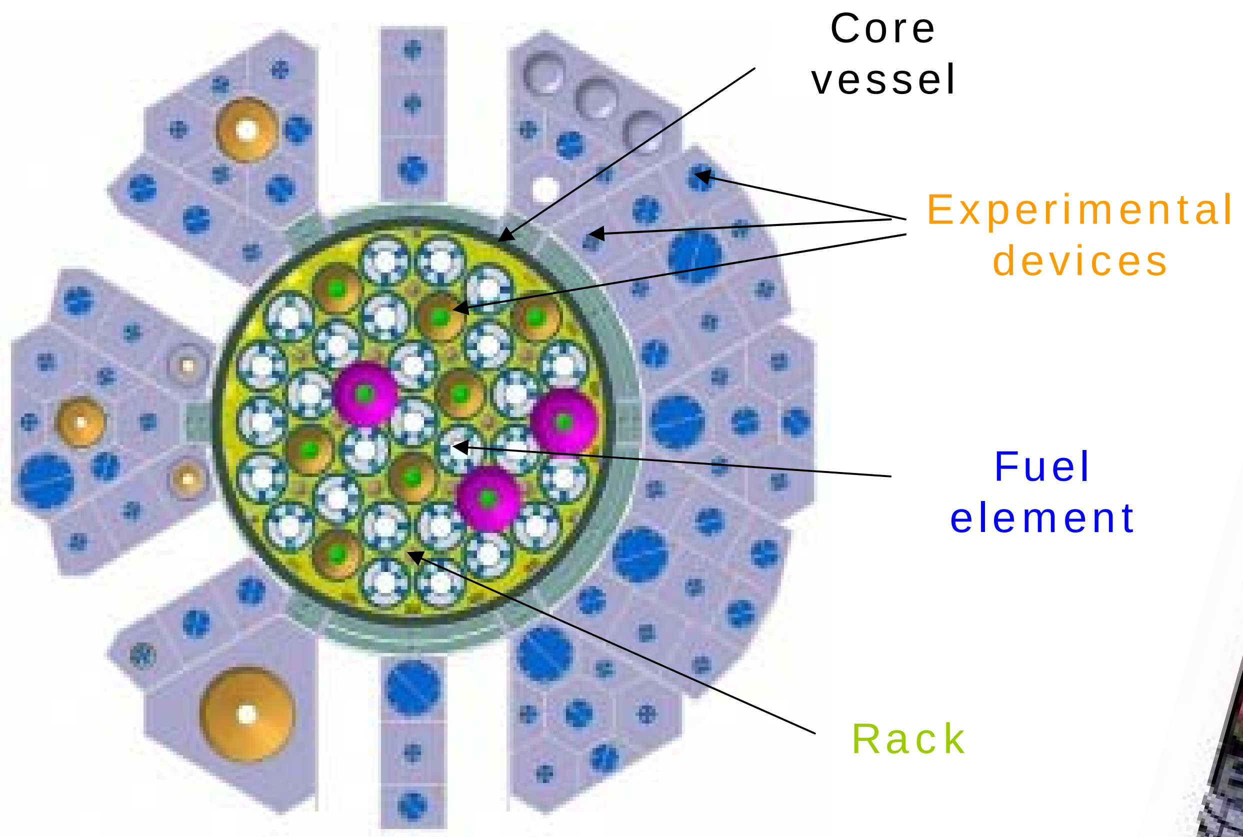
Reactor block



Reactor aimed features

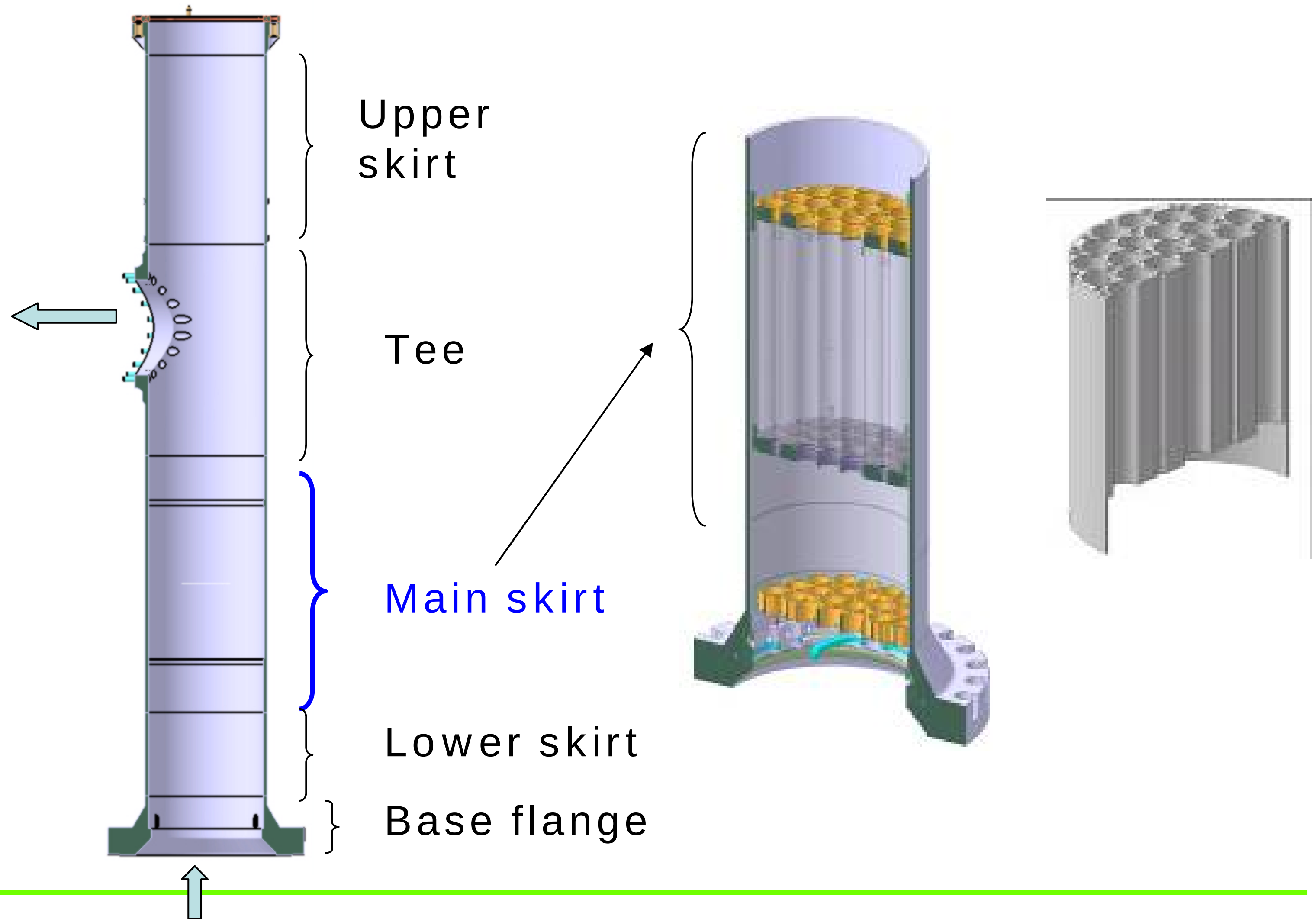
- Neutron flux $\Phi > 8.10^{14}$ n.cm^{-2}.s^{-1} in core center
- Φ_{th} / Φ_f
  - ~ 0.6 in core center
  - ~ 13 in first periphery
  - ~ 2 in the vessel
- Gamma heating in core center : 16 W/g
- Core slightly pressurized : max 16 bars
- Cooling : light water
- Water velocity : 15 m/s
- Inlet/outlet temperature : 29° C/39° C

Reactor core section



Fuel element

Vessel subcomponents and rack



How to get high neutron flux?

- **Choice of Aluminium alloys for the core components :**
  - Low neutron absorption ⟹ high neutron flux
  - Low density ⟹ low gamma heating ⟹ limited temperatures in the core ⟹ moderation/absorption rate ↗ ⟹ neutron flux increase

- **Core slightly pressurized :**
  - P = 16 bars ⟹ moderation increase ⟹ neutron flux increase

Aluminium alloys used for the critical components

- Core vessel : 6061-T6
- Fuel rack : 6061-T6

1%Mg –0,6% Si–Fe-Cu

high R_m,$R_{p0,2}$, widely used in USA

good stability under neutron flux

- Fuel cladding : AlFeNi-O 1%Fe-1%Ni-1%Mg

good corrosion resistance up to 250° C

low creep strains, used in RHF, FRM2

- Experimental devices : possibly AG3-NET(O)

2.7% Mg, Mn, Fe → derived from AA-5754 (3% Mg)

widely used in Europe

Status of knowledge on post-irradiation properties

➢ 6061-T6 : impact of fabrication process

Tensile and fracture toughness data ⟶ great scatter

Impact toughness, post-irradiation creep, swelling

But no irradiation creep data

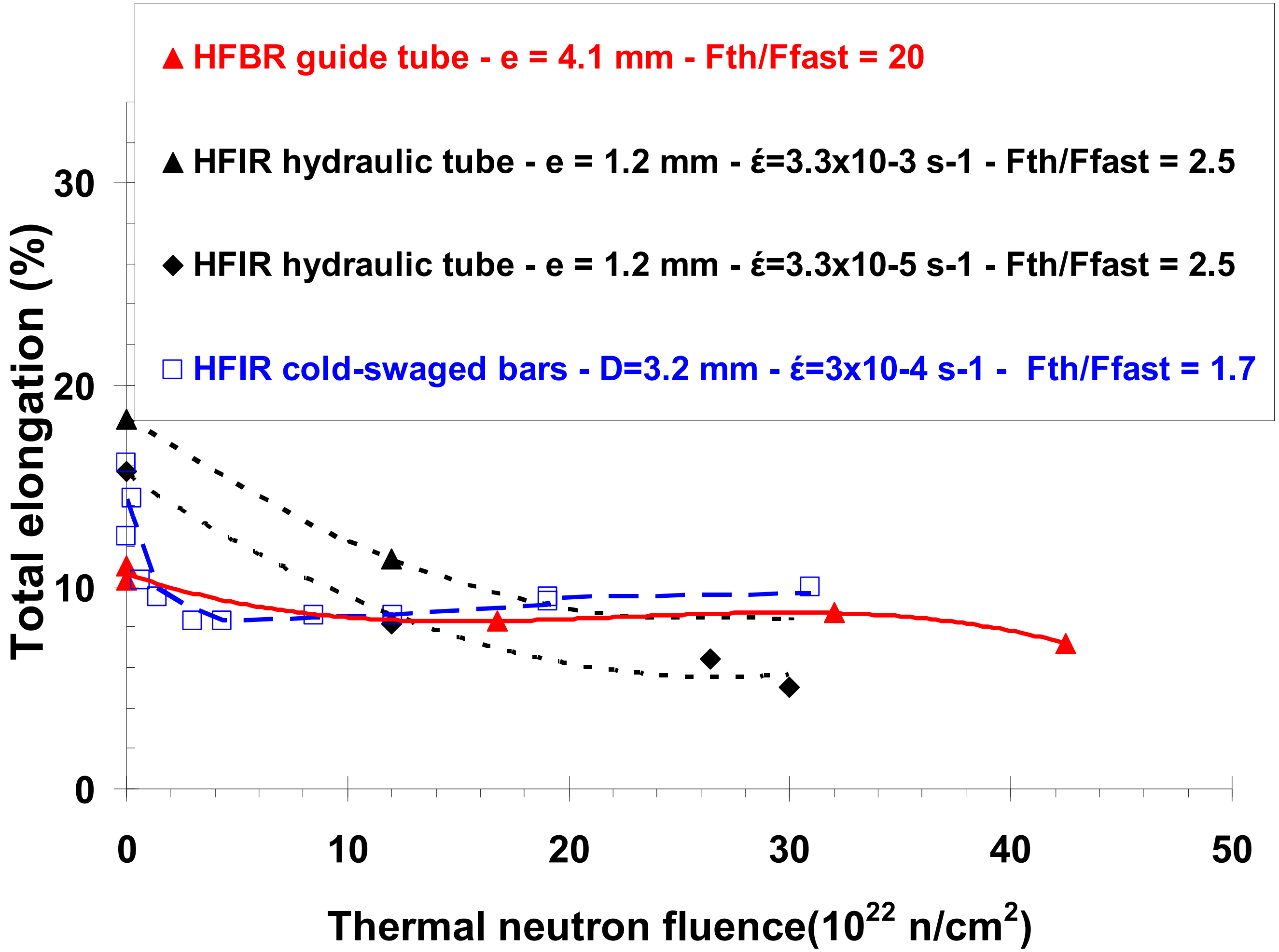
➢ AlFeNi-O : lack of mechanical data

➢ AG3-NET(O) : little data at high fluence

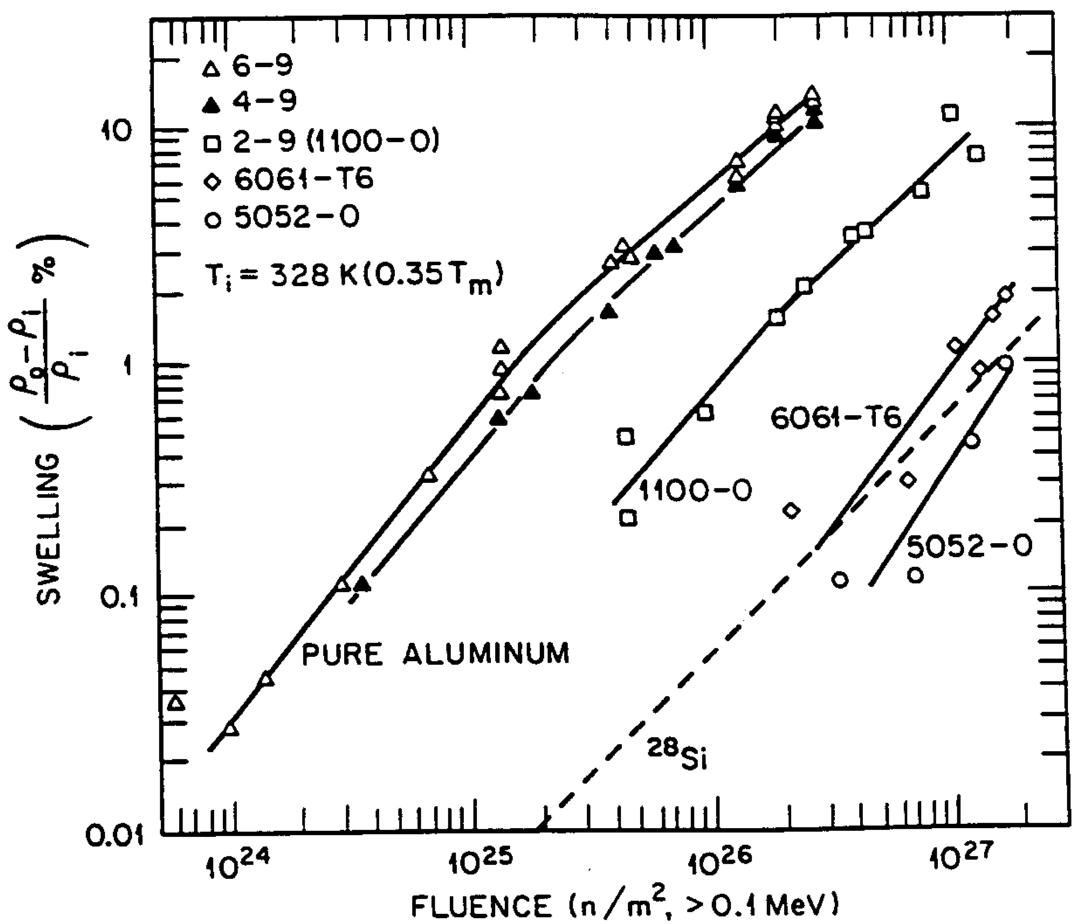
Tensile data : severe loss of ductility at high fluence

No fracture toughness, no irradiation-creep and no swelling

6061-T6 : fabrication impact



Swelling of aluminium alloys



K.Farrell, 1995

ORNL/TM-13049

Qualification program of aluminium alloys for the critical components

➢ 2000-2005 : definition phase

- Development of fabrication and welding processes

  ⇒ to assess the industrial feasibility

➢ Since 2006 : qualification of fabrication processes

- Definition of receipt criteria
- Qualification of relevant processes : forging, welding

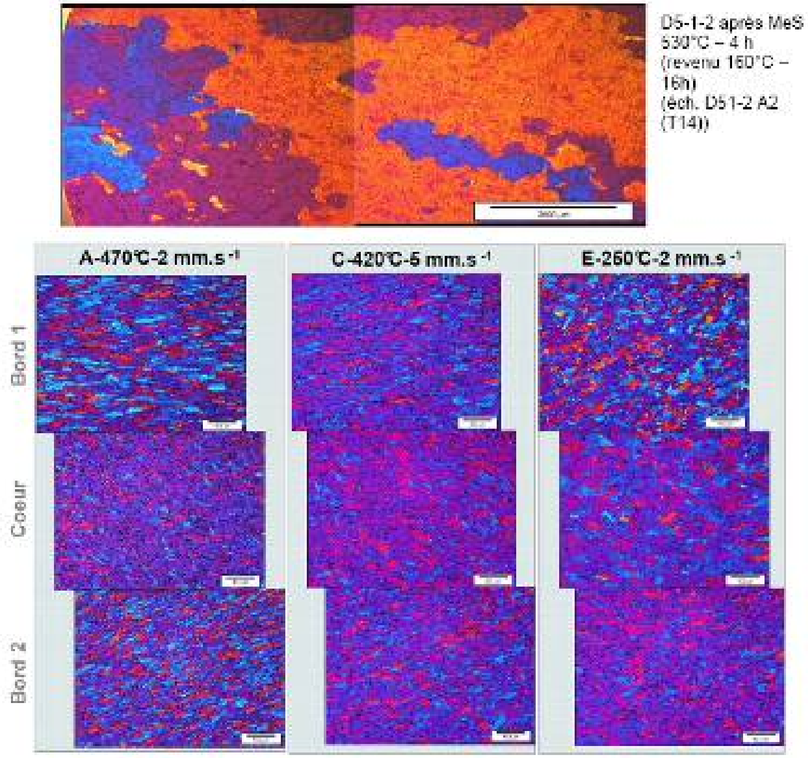
  ⇒ validate different methods, link process/properties

- Implementation of two irradiation programs in OSIRIS

  ⇒ validate mechanical properties during design and operation

Forging process

Core vessel demonstrators



Microstructures obtained on Servotest samples in different conditions (T, strain rate)

Welding process

Electron beam soldering
with filling metal

✓ Use of a Welding Procedure Qualification for aluminium

✓Several welding and repairing processes tested : electron beam, arc welding, with or out filling metal

✓ Use of European standards EN 15614-11 and 15614-2

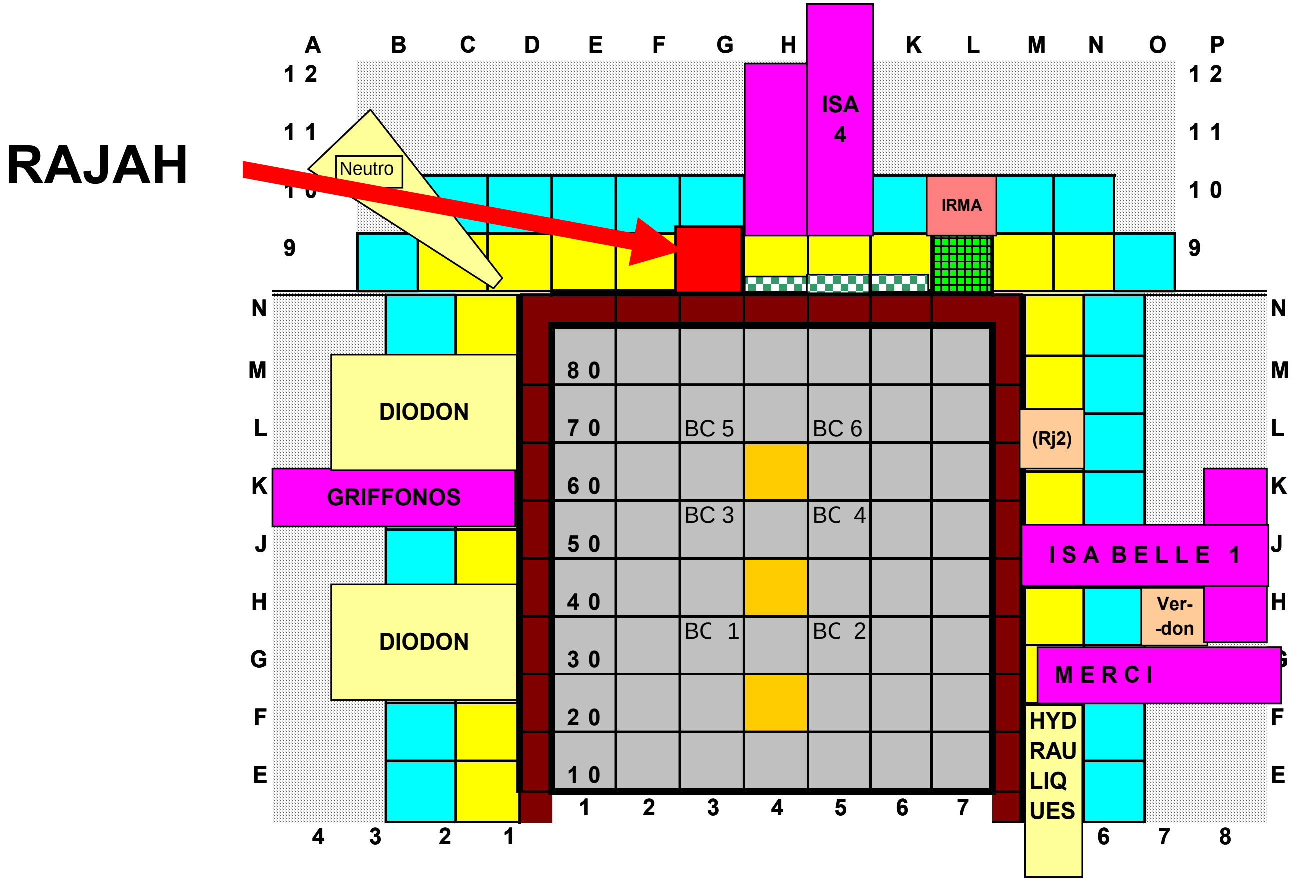
✓ welding control : Soundness control, destructive tests, metallographies

RAJAH irradiation in Osiris

- Started in April 2008
- Alloys irradiated : 6061-T6 , AG3-NET(O) and 6061-T6 welded samples
- 3 sample types : tensile, impact and fracture toughness
- Neutron spectrum : $5 < \Phi_{th} / \Phi_{fast} < 10$
  (conservative in regard to JHR vessel)
- Irradiation temperature : 40° C < T < 50° C
- Thermal neutron flux in mid-plane (E=0.0254 eV): $2.2\text{x}10^{14}$ $n.cm^{-2}.s^{-1}$
- 15 baskets containing 154 samples
- To get homogenous fluences : permutation of the baskets every 4 cycles, and device turned 180° at each cycle
- To get samples at higher fluence : 3 central baskets remain in the mid-plane

RAJAH device

Irradiation place in Osiris



RAJAH irradiation targets

➢ First phase, started in April 2008 :

- Forged 6061-T6 : different fabrication processes

  ⟹ impact on the mechanical properties evolution up to 1.5×10^{22} $n_{th}.cm^{-2}$

- Forged AG3-NET(O) : get data up to 1.5×10^{22} $n_{th}.cm^{-2}$
- Welded 6061-T6 samples : different welding processes

  ⟹ show that the vessel welding joints are not degraded by the irradiation at a fluence representative of 10 years operation

➢ Second phase, to start in March 2010 :

- 6061-T6 fabricated with the process chosen for the vessel :

Irradiation up to ~ 1.5×10^{22} $n_{th}.cm^{-2}$; 3 test temperatures : 20° C, 75° C (JHR vessel) and 125° C (rack T excursions)

⟹ validation of the vessel fabrication process

➢ RAJAH third phase, scheduled to start at the middle of 2011

- JHR vessel qualification irradiation + presurveillance program
- Thermal fluence received in Osiris (24 cycles) :

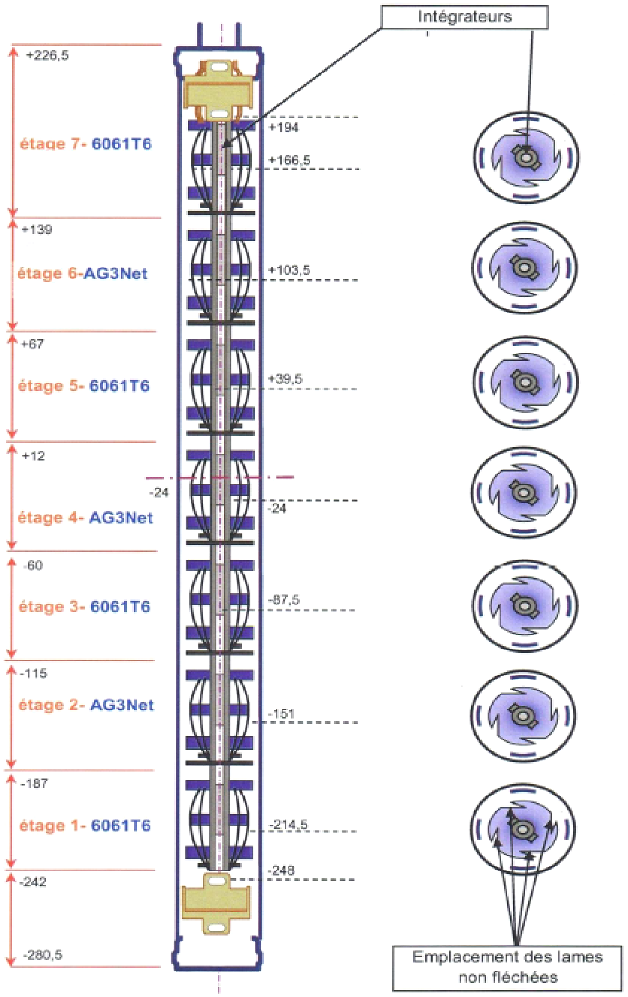
  max 10^{22} n.cm^{-2}

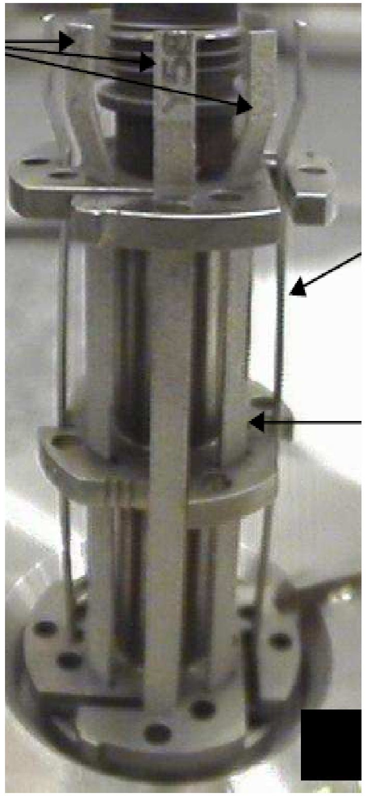
  (equivalent of ~1 year operation of the JHR vessel)
- A few samples tested : vessel qualification
- Most samples transferred into the JHR reactor for a vessel surveillance program

FLOREAL irradiation in Osiris

- Started in December 2006
- Aims to assess the in-flux relaxation behaviour of aluminium alloys and to predict their irradiation creep behaviour
- Alloys irradiated : 6061-T6, AG3-NET(O) and AlFeNi(O)
- Sample types : strip shaped ; 3-point-bending relaxation technique
- Neutron spectrum : $\Phi_{th}/ \Phi_{fast} \approx 2$ similar to that of JHR core vessel
- Fast neutron flux : $\Phi_{fast} = 2x10^{14}$ $n.cm^{-2}.s^{-1}$ (E>1MeV)
- Irradiation temperature : 40° C < T < 45° C
- 7 baskets containing 56 samples
- 2 types of bended positions to set 2 different stresses : 45% and 75% of yield strength
- Bended samples periodically unloaded and measured in hot cells with a laser beam → residual deflection → relaxation strain rate

FLOREAL device



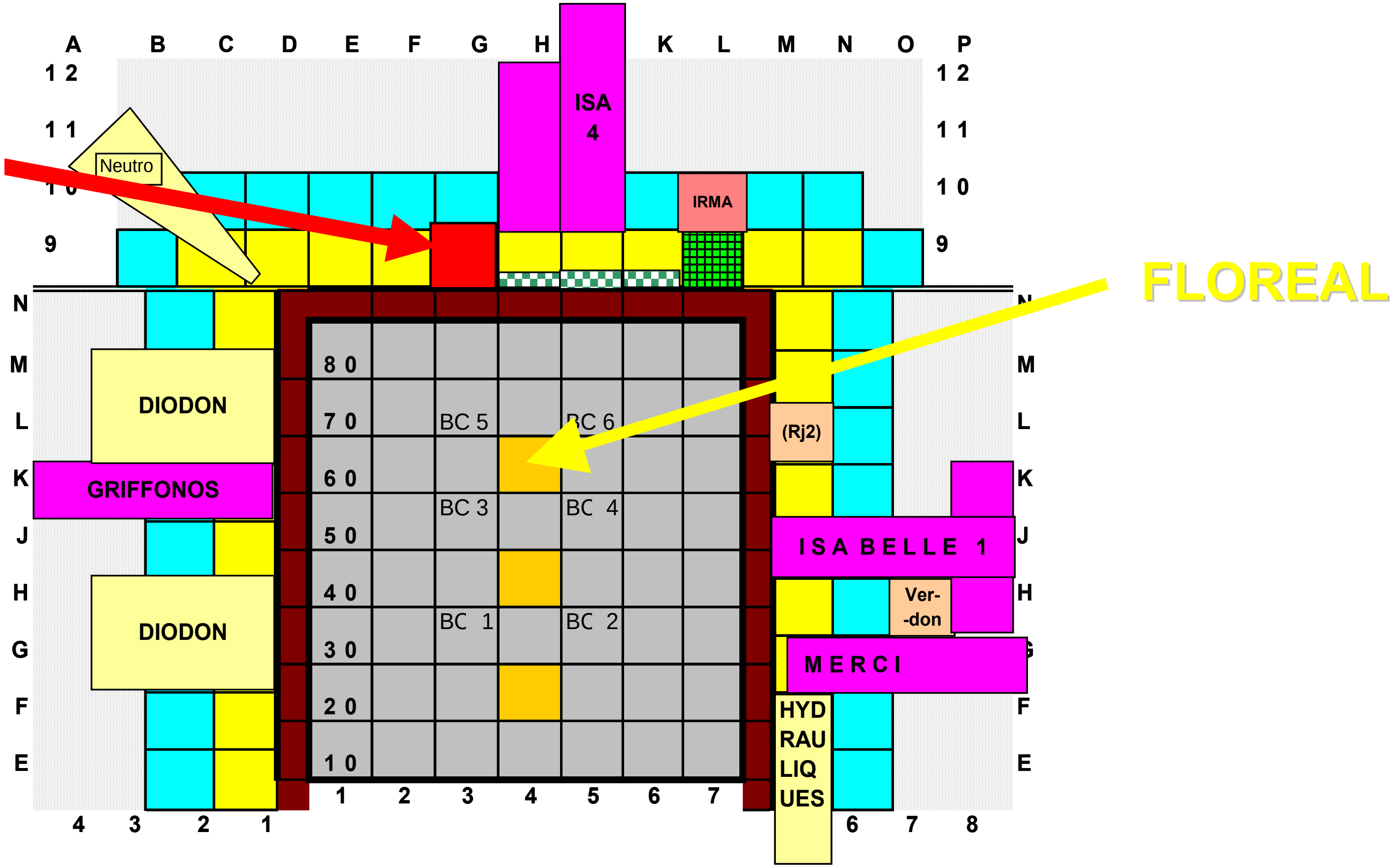


Bended sample

Unbended sample

Basket containing 4 bended +
4 unbended samples

Irradiation place in Osiris



FLOREAL irradiation

- First part, from December 2006 to June 2009 :
  - Aimed to measure the relaxation behaviour of as-fabricated alloys
  - 8 irradiation periods (3 days up to 3 cycles)
  - Fast fluence received : 5.25×10^{21} $n.cm^{-2}$ (E>1 MeV)

- Second part, from October 2009 to the end of 2012
  - Aims to measure the relaxation behaviour of samples pre-irradiated in unbended positions to $\Phi_{th} = 1.3 \times 10^{22}$ $n.cm^{-2}.s^{-1}$
  - Some of the bended samples (first part) stay in bended positions to increase their fluence up to ~ 10^{22} $n_{fast}.cm^{-2}$
  - 8 irradiation periods (3 days up to 3 cycles)
  - Fast fluence received : 5.25×10^{21} $n.cm^{-2}$ (E>1 MeV)