POST IRRADIATION EXAMINATIONS OF GAIA LEAD FUEL ASSEMBLIES

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ABSTRACT

To address further demands of the PWR utilities worldwide, Framatome has developed the GAIA fuel assembly design. GAIA fuel assembly provides more resistance to fuel assembly bowing, higher thermal hydraulic performance, an intrinsically safe behaviour under seismic conditions, more burnup capability and more Uranium loaded in fuel assembly thanks to its High Performance Fuel Rod. The development of the GAIA fuel assembly took benefit from improvements and upgrades in codes & methods and computational capabilities that made the fuel design optimization faster and more secure.

In 2009, GAIA lead fuel rods were loaded in host assemblies for a 5 year irradiation program at the Ringhals nuclear power plant, unit 4, in Sweden. This program was completed in 2014 and post-irradiation examination results from rods extracted after 4 irradiation cycles are already available. Growth and oxide are identical to standard M5 clad rods and diameter change confirms the intended earlier pellet to clad gap closure. The pin pressure measurement performed at 52 GWd/tHM burnup confirms that fission gas release in the High Performance Fuel Rod is in the lower bound compared to standard UO_2 fuel rods, thus providing a higher burn-up capability. The program was completed after 5 cycles in 2016.

GAIA lead fuel assemblies, completely loaded with GAIA fuel rods, have been in operation since 2012 at the Ringhals nuclear power plant, unit 3. During the reactor outages in 2013, 2014, 2015, 2016 and 2017, visual inspections and post-irradiation examinations of the lead fuel assemblies have been performed at burn-ups from 20 (2013) to 58 GWd/tHM (2017). The various examinations covered: cladding oxide thickness, fuel rod axial and radial dimensions, fuel assembly growth, fuel assembly bow, spacer growth, spacer and guide tube corrosion. The results of the rod inspections are in line with the expectations and fully consistent with the 2009 GAIA lead fuel rod program. The growth behaviour of the GAIA lead fuel assemblies lies within the expected range of the experience feedback already available on similar structures irradiated in various types of reactors covering 15x15 to 18x18 lattices. This is true for both designs: the one with PCAm structural tubes as reference to the design of the resident HTP assemblies delivered by Framatome in the same reactor, and the one with Q12 guide tubes, which corresponds to the reference structural design for GAIA batches. The GAIA lead fuel assembly distortion measurements are on the same low level as resident HTP assemblies. The post-processing of the video records confirmed that the fuel rod bow performance was as expected at the end of each of the 5 cycles.

1 Introduction

The Ringhals 4 lead fuel rod irradiation program that started in 2009 consisted in irradiating 6 different test rod designs in two HTP host assemblies during 5 cycles. Among the test rods, the high performance GAIA fuel rod (larger pellet, reduced pellet to clad gap, Cr_2O_3 doping, see [1]) was present together with variants, making it possible for Framatome to decouple the effect of several design features like the reduced gap, initial He pin pressure, pellet diameter and presence of Cr_2O_3 doping in UO_2 pellets. After each cycle the lead rods were inspected according to the Post Irradiation Examination (PIE) program agreed with Vattenfall: growth, oxide and rod diameter changes were measured. The results of the 5th cycle examination are available since 2016.

In 2012 the first four GAIA lead fuel assemblies were introduced in the reactor of Ringhals unit 3. These assemblies feature 6 GAIA mixing spacers and 3 intermediate flow mixers, all cladding made of M5, a GRIP bottom nozzle and a HMP lower end grid. Their guide thimbles and instrumentation tube were reinforced compared to the standard products and have an outer diameter of 12.6 mm. For two of the lead assemblies, the guide thimble material is PCAm, and the top end grid is an M5 GAIA spacer. The structure of these two assemblies is similar to the one of the HTP reloads delivered by Framatome to the same reactor. The two other lead assemblies use Q12 as structural tube material and an upper HMP spacer with reduced spring forces. Except the enrichment, the characteristics of the fuel rods are identical to the high performance fuel rods previously introduced in the GAIA lead fuel rod program in Ringhals-4. A description of the GAIA design and supporting testing performed to justify GAIA technology can be found in [2].

Irradiation and examination planning is depicted in Figure 1. Examination results are available for the 5 cycles of the Ringhals 4 lead fuel rod program and for the 5 cycles of the Ringhals 3 lead fuel assembly program.

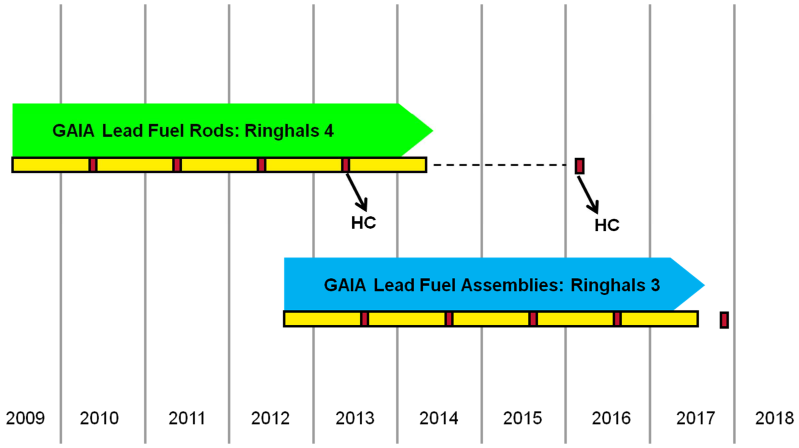

Fig 1. Irradiation and examination planning:
yellow = irradiation periods; red = PIEs during outages; HC = Hot Cell examinations

The results of the measurements performed on GAIA high performance rod are detailed in chapter 2, the examinations performed on the GAIA lead fuel assemblies are shown in chapter 3.

2 High performance fuel rod examination results

2.1 Growth

Fuel rod axial growth shall be taken into account to justify that no interference between nozzles and fuel rods will occur during the operation of the fuel assembly. New fuel rod designs might grow differently than previous fuel rods. Therefore, measurements of the fuel rod growth kinetic are mandatory to validate the high performance fuel rod design.

Figure 2 shows the results of the growth measurements performed after the five irradiation cycles on the high performance lead fuel rods of Ringhals 4 (red diamonds) as well as the measurement performed on the GAIA lead assembly peripheral fuel rods after their five cycles (blue circles) as a function of the fuel rod burn-up. Some scattering is observed on the GAIA fuel assembly rods after the 2nd cycle, which is due to the burn-up gradient associated with the loading history of the assemblies.

The growth of these high performance fuel rods lies within the overall M5 cladding rods database. These results show that the advanced fuel rod designs are not inducing any penalty regarding the axial clearance requirement, thus allowing using them in place of the current M5 rods, for the same design burn-ups and without any additional axial dimensioning concern on the structure.

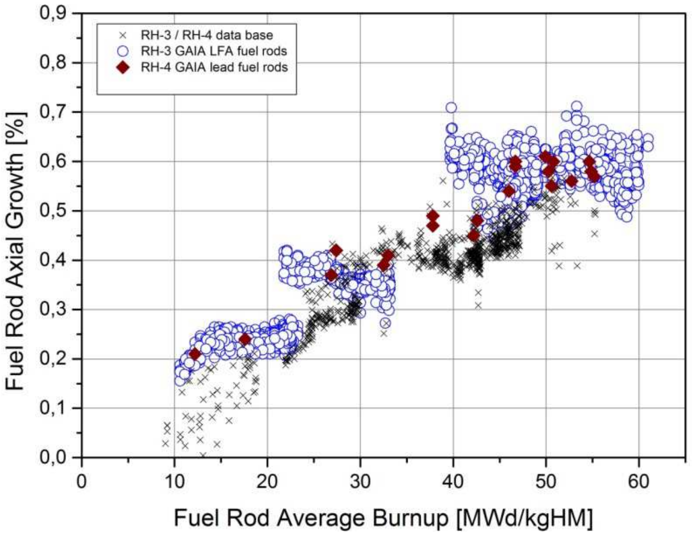

Fig 2. High performance fuel rod axial growth behaviour

2.2 Oxide

The corrosion of the fuel rod can become a limiting factor for fuel assembly operation, typically restricting the operation range (e.g. maximum allowed burn-up) since oxide and hydrogen build-up affect the mechanical properties of the cladding. For a new fuel rod design, it is required to verify that corrosion remains acceptable.

Oxide thickness was measured on the surface of all the peripheral test fuel rods of the Ringhals 4 program and at several axial elevations. The maximum was systematically recorded for each rod and the results can be seen on Figure 3 where they are compared to the database obtained in the same reactor on M5 claddings. The maximum oxide thickness measured on some peripheral fuel rods of GAIA lead fuel assemblies at Ringhals 3 were below or equal to 26 µm for rod burnups up to 59 GWd/tHM, fully consistent with the previous observations despite the increased power of the Ringhals 3 reactor.

The oxide build-up on M5 does not depend on the type of rods since oxide thickness measurements are corresponding to the now well-known behaviour of this advanced cladding material. Therefore the high performance fuel rod still benefits from the full M5 oxidation resistance in operation (see [3]).

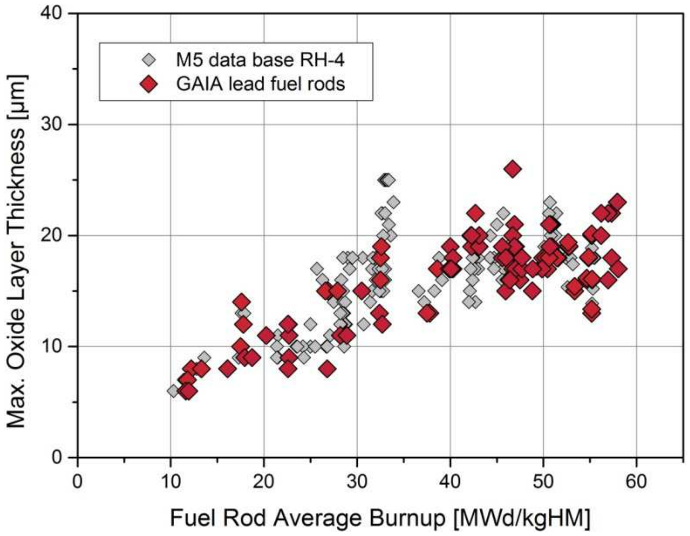

Fig 3. High performance fuel rod maximum measured oxide thickness

2.3 Diameter

Fuel rod cladding strain must be shown to be limited in order to rule out any risk of cladding defect. The normal operation strain is essentially consisting in tangential deformation that can be quantified by fuel rod diameter measurements.

Figure 4 shows the results of the rod diameter measurements performed after the five irradiation cycles on the high performance lead fuel rods of Ringhals 4 (red diamonds) as well as the measurement performed on the GAIA lead assembly peripheral rods after their five cycles (blue circles) as a function of the rod burn-up. Both data sets appear to be very consistent. These data reflect the early pellet to clad gap closure, which was anticipated for the large pellet (with already reduced pellet to clad gap per design at begin of life) of the high performance rod design: the contact occurs during the first irradiation cycle. Diameter evolution of the rod doesn't show any risk of reaching excessive strain.

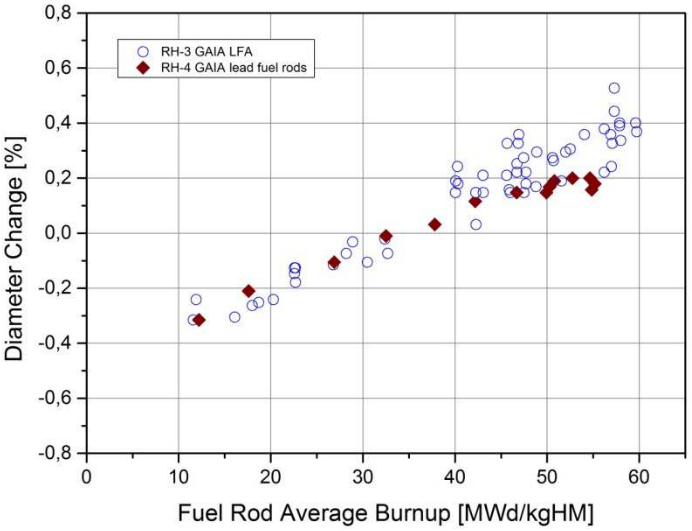

Fig 4. High performance fuel rod diametric behaviour

2.4 Fission gas release

The internal rod pressure increases progressively during operation as a consequence of the production of gaseous fission products. Excessive pressure increase could lead to internal overpressure with potential consequences of too fast cladding strain increase.

Two GAIA lead fuel rods of a host assembly were extracted for hot cell examinations after having reached an average burn-up of 52 GWd/tHM. On these two rods, following examinations were performed in hot cell:

- Fuel rod internal pressure

- Fission gas release and analysis
- Gamma scan and burnup evaluation (after cutting in 4 pieces)

The GAIA high performance fuel rod fission gas release measurements are coherent with the experience feedback already acquired on the doped fuel, i.e. in the lower bound of the UO_2 database (see Figure 5).

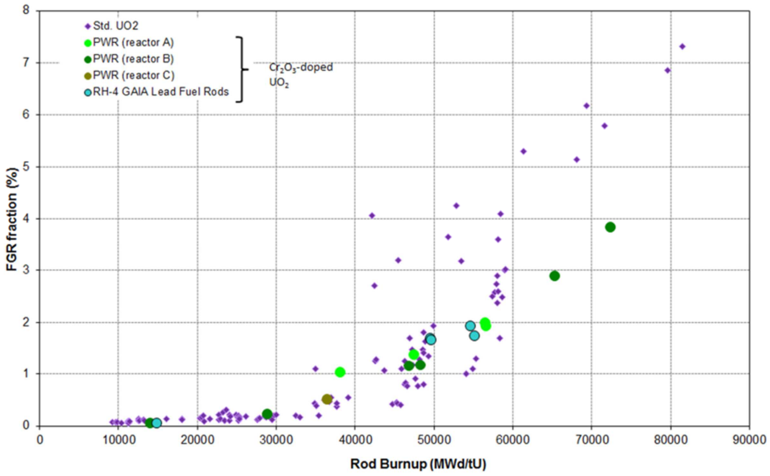

Fig 5. Fission gas release (FGR) of Cr_2O_3-doped fuel (green / blue circles) compared to standard UO_2 fuel (violet diamonds)

3 GAIA lead fuel assemblies examination results

3.1 Fuel assembly growth

The fuel assembly length evolution must be taken into account in order to verify that no lift-off will occur during normal operation and that positive clearance between assembly and reactor internals is ensured during the assembly lifetime.

The growth behaviour of the GAIA lead fuel assemblies lies within the expected range of the experience feedback already available on similar structures irradiated in various types of reactors covering 15x15 to 18x18 lattices. This is true for both design variants: the one with PCAm structural tubes as reference to the design of the resident HTP assemblies delivered by Framatome in the same reactor, and the one with Q12 guide tubes (see definition of Q12 in §3.2), which corresponds to the reference structural design for future GAIA batches.

The small and positive growth of the GAIA structures contributed to refine the growth law that has been used for reloads licensing.

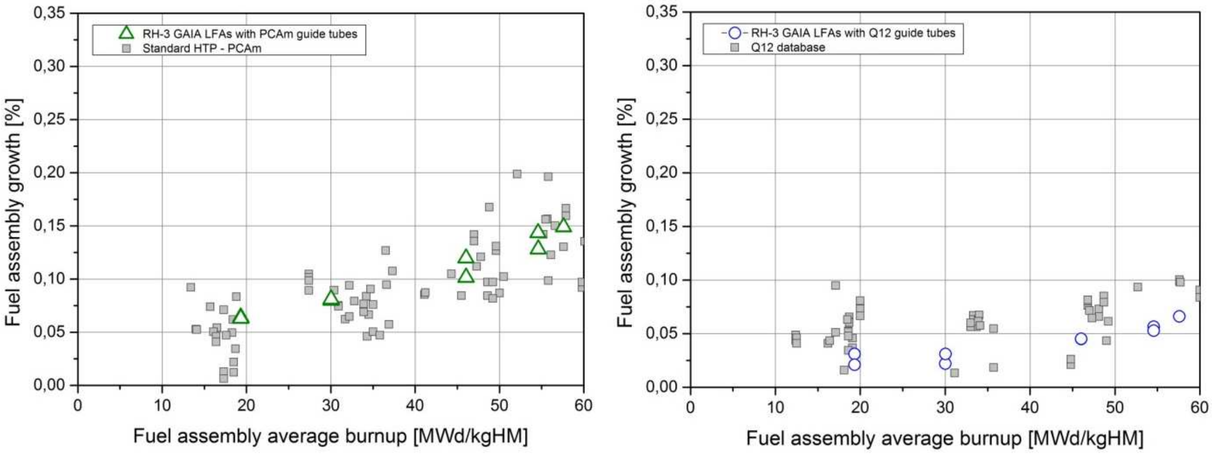

Fig 6. Growth of GAIA lead fuel assemblies: PCAm Guide tubes (green triangles on the left, compared to the overall PCAm growth database) and Q12 (blue circles on the right, compared to the overall Q12 growth database)

3.2 Fuel assembly resistance against lateral deformation

The GAIA fuel assemblies were developed with the objective of improving the fuel assembly resistance against lateral deformation:

- Reinforcement of guide tube geometry : thick guide tube with enlarged cross section increasing lateral stiffness while reducing creep response by reducing stresses in the guide tubes;
- Additional enhancement of guide tube creep resistance by the deployment of so-called Q12 material (Zr1Nb0.5Sn0.1Fe Ultra Low Tin Quaternary alloy, see [4]);
- Further increase in lateral stiffness by reinforcing spacer to guide tubes connections.

The distortion behaviour of lead fuel assemblies in a reactor cannot be assumed representative of the resistance against lateral deformation of the new design. Indeed, the distortion is known to be a result of interactions between all fuel assemblies present in the core and the flow. Four or eight lead fuel assemblies – even reinforced – are a too limited amount to show a measurable impact on the core deformation pattern.

Straightness measurements were performed on all four GAIA fuel assemblies after each irradiation cycle and have been compared to the data available on the Ringhals 3 reactor. The GAIA LFAs show in the same low level of fuel assembly bow as resident HTP assemblies. GAIA fuel assemblies inserted in reloads quantities will decrease the bow level of the core further.

3.3 Fuel rod wear measurements

Fuel rod wear measurements were performed at the end of 4th and 5th cycles. At the end of the 4th cycle, wear measurements were performed on one GAIA LFA and on one resident HTP (reference design wrt fuel rod wear). At the end of the 5th cycle, wear measurements were performed on the two GAIA LFAs. Both measurements campaigns confirmed the expected excellent behaviour of the GAIA fuel assembly design: the maximum wear marks had depths of 30 μm with no progression of wear in the 5th irradiation cycle.

3.4 Fuel assembly visual examinations

The visual appearance of the components shows no anomaly and no crud deposition was detected on the surface (see photos on Figure 7). The rod axial position evolution shows that the upper end grid design plays a major role. These observations correspond to the experience already acquired on similar structures.

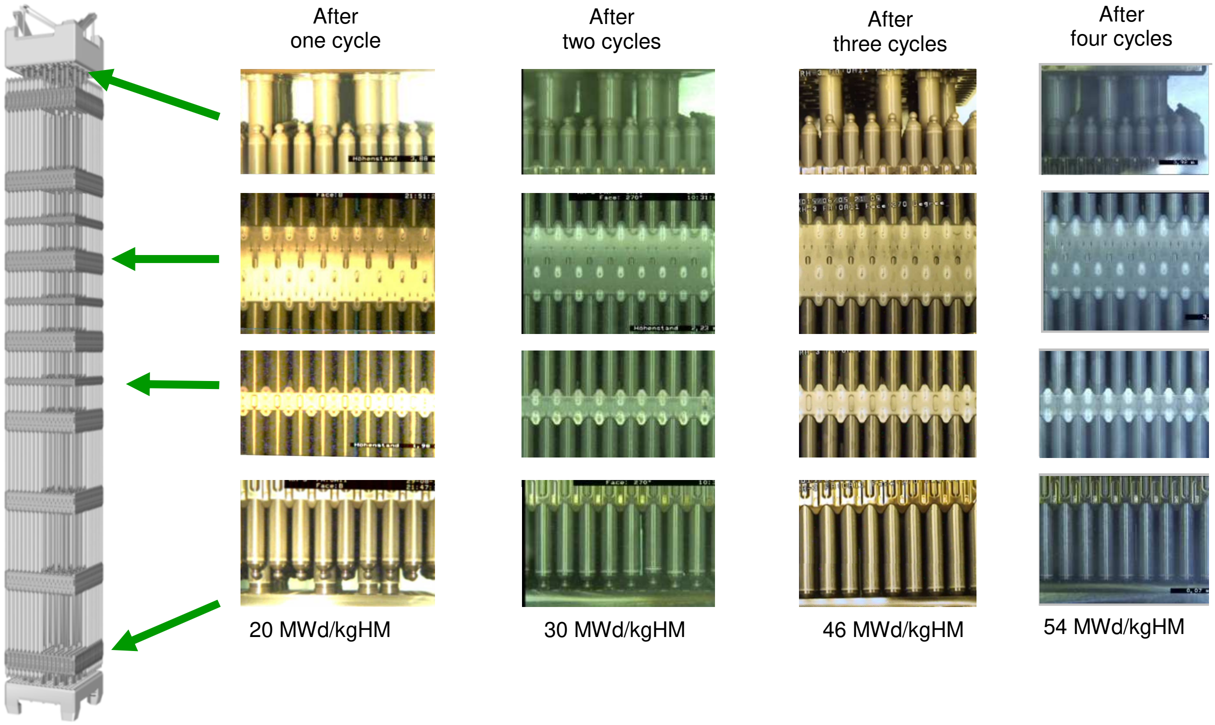

Fig 7. GAIA fuel assembly visual examinations

The video records were post-processed to derive rod to rod gap closure statistics on peripheral rods in the three lowermost spans, non-equipped with intermediate flow mixers. Excessive gap closure could induce thermal-hydraulic penalties on the fuel assembly design. The gap closure ratio (GCR) is determined according to the following formula:

$$\mathrm{GCR}\,[\%] = \frac{M_0 - (M - K \cdot \sigma)}{M_0}$$

With:

- M_0 nominal rod-to-rod distance;
- M average rod-to-rod distance;
- K Owen coefficient taken from statistical table, dependent on sample size;
- σ standard deviation of rod-to-rod distance;

The gap closure ratios evaluated at each span of each GAIA fuel assemblies are all below the design limit, which demonstrates the absence of fuel rod bow after 5 cycles corresponding to 58 GWd/tHM. No significant difference can be seen between the Q12 and PCAm GAIA designs.

4 Conclusion

The GAIA lead fuel rod program in Ringhals 4 has been completed in 2014. The irradiation of four GAIA lead fuel assemblies has been completed in 2017 in Ringhals 3. The post-irradiation examination results on these two programs are consistent with experience obtained on similar products and validate the GAIA high performance fuel rod design until burnup of 62 GWd/tHM and the GAIA assembly behaviour until burnup of 58 GWd/tHM.

A comparable lead fuel assemblies program is being realized in the USA in a 12ft reactor: 8 GAIA fuel assemblies are being irradiated from 2015 in 18 month campaign. They are currently experiencing their third cycle and shall reach end of life in 2019. The results of the PIEs performed after 2 cycles, at a burnup of 48 GWd/tHM, are fully in line with the results from the Ringhals 3 LFA program.

5 Future irradiation plans

Full reloads of GAIA 12ft fuel assemblies will start their irradiation in 2020 in Europe and 2021 in the USA.

GAIA 14ft LFAs will start their irradiation in 2018 in Europe in order to support the qualification of the advanced Framatome fuel assembly design technology and make it available for all 17x17 reactors.

6 Acknowledgments

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M5, Q12, GRIP, HMP and HTP are registered trademarks or trademarks of FRAMATOME in the USA or other countries.

7 References

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