FRAMATOME MODERN FUEL DESIGNS

NICO VOLLMER
Strategic Marketing Manager
FRAMATOME FUEL DEPARTMENT

PETRA-BRITT HOFFMANN
Materials and Thermal-Mechanics Department Head
FRAMATOME FUEL DEPARTMENT

NORMAL GARNER
Technical Sales Manager
FRAMATOME FUEL DEPARTMENT

GUY GENTET
Senior Product Line Manager, PWR Fuel
FRAMATOME FUEL DEPARTMENT

ELMAR SCHWEITZER
Metallic Alloys & Irradiation Programs Responsible
FRAMATOME FUEL DEPARTMENT

DANIEL DE LORENZO
Project manager and Business Development
FRAMATOME FUEL DEPARTMENT

Framatome has a record of over six decades of continuous innovative design and delivery of state of the art nuclear fuel for the power generation market. The rate of innovation and new product introduction has accelerated over the past two decades as reactor operators worldwide have seen increased demand to reduce generation costs and increase protection against accident conditions.
The present article gives a high level overview about the performance of the lastest Fuel Assembly Designs for BWR and PWR as well as about PROtect, the leading enhanced accident tolerance fuel (EATF) program by Framatome.

Figure 1. Overview of modern Fuel.

GAIA – THE NEW PWR FUEL ASSEMBLY DESIGN

To address the demands of the PWR utilities worldwide, Framatome developed the GAIA fuel assembly design (Figure 2). 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 the possibility to have 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.

The operational experience with GAIA design started in 2009 when GAIA lead fuel rods were loaded in host assemblies for a 5-year irradiation program at the a Swedish nuclear power plant. 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 $M5_{Framatome}$ clad rods and diameter change confirms the intended earlier pellet-to-clad gap closure. The pin pressure measurement performed at 52 MWd/kgU 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 burnup capability. The program was completed after 5 cycles in 2016.

GAIA lead fuel assemblies (LFA), completely loaded with GAIA fuel rods, have been in operation since 2012 at another Swedish nuclear power plant. During the reactor outages in 2013, 2014, 2015, 2016 and 2017, visual inspections (Figure 3) and post-irradiation examinations of the lead fuel assemblies have been performed at burnups from 20 (2013) to 58 MWd/kgU (2017) (Figure 4). 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 cor-

DISEÑOS INNOVADORES DE COMBUSTIBLE NUCLEAR FRAMATOME

Durante las últimas seis décadas Framatome ha venido desarrollando diseños innovadores y suministrando combustible nuclear de última generación para el mercado de la generación de energía. La frecuencia con la que las innovaciones y los nuevos productos se han introducido se ha acelerado en las últimas dos décadas según los operadores a nivel mundial han visto incrementada los requisitos de reducción de costes y de incrementar la protección frente accidentes.

EL presente artículo da una visión general del funcionamiento de los últimos diseños de elementos combustibles para plantas PWR y BWR, así como sobre PROtect, el más avanzado programa de elementos combustibles de elevada resistencia a accidentes (EATF) de Framatome.

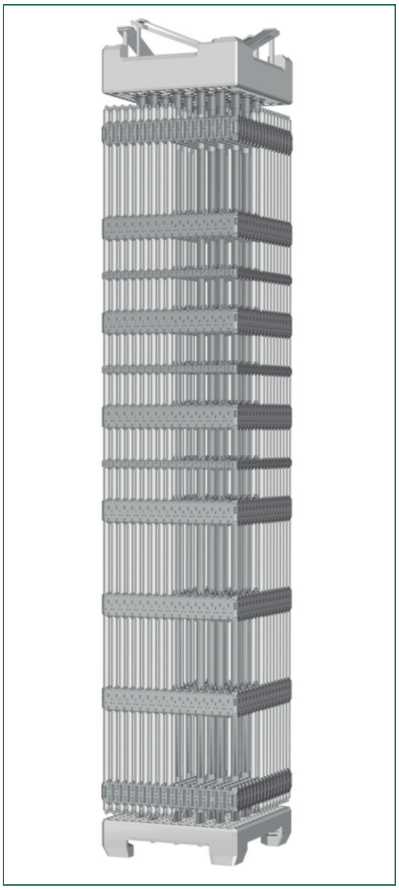

Figure 2. GAIA Fuel Assembly.

rosion. 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 behavior 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.

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]

The global GAIA implementation continues currently with 2 LTA programs in the US, one LTA program is already partly with PROtect fuel. In France one LTA program is underway (GAIA 14ft) in a N4 plant from November 2018.

ATRIUM 11 – THE NEW BWR FUEL DESIGN

The ATRIUM 11 fuel assembly has been developed by a dedicated team of international experts for several years in order to set a new standard in reliability, performance and economics.

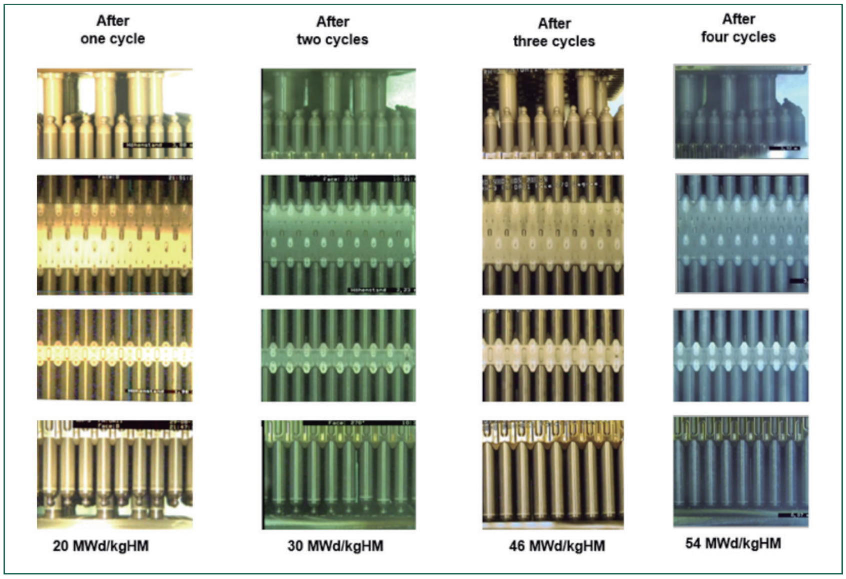

Figure 3. Visual inspection of GAIA LFA after 1st, 2nd, 3rd and 4th cycle.

The 11x11 rod array is the consequent response to a demand of operating problem-free and high performing fuel in an environment of power uprated nuclear power plants (see Figure 5 and Figure 6). The increased power load with the wish for sufficient margins for high operating flexibility can be optimally provided with more fuel rods per bundle. Less linear heat generation rate per fuel rod together with an improved pellet geometry and composition reduce risk of failure in general, especially PCI, and provide margins for further performance optimization.

The common feature of all ATRIUM fuel assemblies is the square inner water channel transferring the weight of the fuel rods to the handle as part of the upper tie plate. As a central element the water channel also serves to position the spacers axially. It occupies 3x3 lattice positions and contains non-boiling water.

- The internal water channel increases and equalizes neutron moderation leading to a flatter distribution of the thermal neutron flux across the fuel assembly.
- Fuel utilization is improved since the flatter thermal flux distribution permits a flatter distribution of ^{235}U enrichment levels.
- The void coefficient is lowered which improves the performance characteristics in a pressure transient and with respect to the coupled neutronic and thermal-hydraulic stability.

The ULTRAFLOW spacer grids, which are closer spaced in the upper part of the assembly, significantly improve the Minimum Critical Power Ratio (MCPR) margin. Besides the highly efficient swirl vanes, this spacer type has flow tabs at the spacer periphery that especially improve the cooling of the outermost fuel rod row. This feature contributes further to an excellent fuel utilization of the assemblies, allowing the placement of relatively highly enriched fuel at the high thermal flux region in the bundle periphery without losing MCPR performance.

The part length fuel rods of the ATRIUM fuel assemblies, which are mainly introduced for pressure drop and stability reasons, also result in a favorable axial distribution of fuel and moderator.

Whereas the higher amount of fuel in the less voided lower region of the core is efficiently burned, the higher water-to-fuel ratio in the upper core region additionally contributes to the good shut down margin performance.

The offered ATRIUM 11 fuel assembly base design features all of Framatome's advanced BWR design solutions:

- 112 fuel rods in a symmetric lattice providing 21% lower linear heat generation rate and 11% lower heat flux compared to ATRIUM 10XM;
- Centrally positioned square water channel maintaining the favorable and easy-to-handle ATRIUM load chain concept. 12 short and 8 long part length fuel rods for best thermal-hydraulic behavior;
- 9 Alloy 718 spacer grids with reduced mass, low pressure drop and reduced debris catching susceptibility;
- Fuel rods with high density Cr_2O_3-doped fuel
- Pressure drop optimized "Advanced Fuel Channel" made of β-quenched Z4B;
- 3rd Generation FUELGUARD.

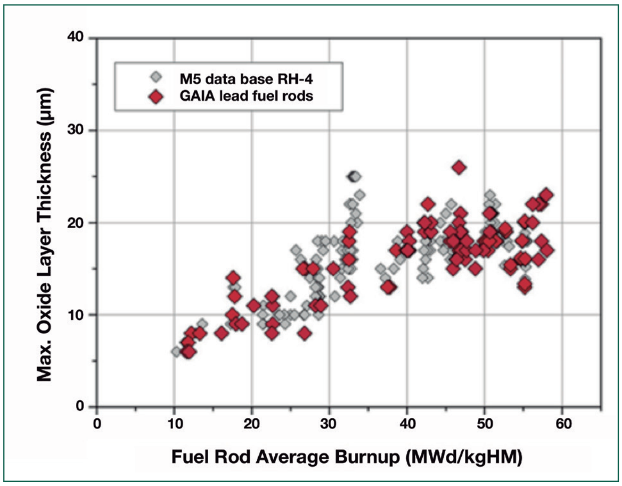

Figure 4. Oxide measurement.

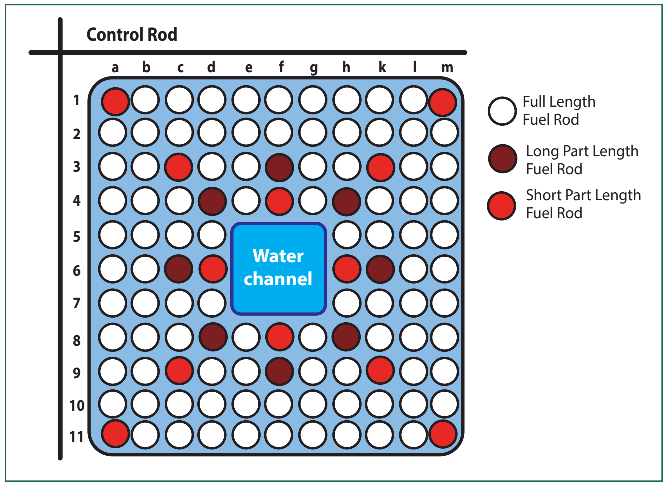

Figure 5. ATRIUM 11 scheme.

The spacer grid features integrated spring elements resulting in a reduced risk of loose parts and less parasitic material. The excellent pressure loss coefficients of the new spacer grid, the chosen part length fuel rod (PLFR) design and the geometry of the fuel channel ensure a low pressure drop and thermal-hydraulic compatibility to other designs. The 3rd Generation FUELGUARD combined with the reduced debris catching susceptibility of the spacers provides an optimal protection against debris fretting.

There have been several LFA programs in Europe prior to the insertion of the first reload batch of ATRIUM11 in a Swedish Nuclear Power Plant in 2018. In 2019, the first LFAs will be inserted in Cofrentes Nuclear Power Plant core.

PROTECT – THE LEADING EATF PROGRAM

As a result of the Fukushima accident in 2011, the nuclear industry was challenged to research, develop and design nuclear fuel products that would provide more enhanced safety margin in accident scenarios than available products today. We are focused on researching and developing comprehensive near and long term solutions under the PROtect program.

Hereby we follow a two-step approach: a near-term solution consisting of a Cr-coated M5F$_{ramatome}$ cladding associated with Cr_2O_3-doped fuel pellets and a long-term solution based on silicon carbide as the cladding material.

This contribution will give an high level view into Framatome's PROtect program. The benefits of these EATF concepts are discussed.

With new development funding to expedite EATF commercialization, Framatome will also adapt coated cladding and Cr_2O_3-doped fuel pellets for BWR applications

The first approach is considered as the near-term solution as it is based on an already proven and licensed cladding tube concept with only slight modifications.

For Framatome this so called evolutionary EATF solution consists of an M5$_{Framatome}$ cladding tube coated with a metallic Cr-layer in combination with chromia-doped UO_2 pellets. This is considered as the most promising technique to bring fuel with EATF properties to market with limited licensing efforts.

A more ambitious approach utilizes silicon carbide, i.e. SiC infiltrated SiC fiber fabric, as the cladding material in combination with a metallic liner. The ceramic tube shall provide mechanical rigidity whereas the metal liner shall provide the tightness of the structure. This material concept is currently being developed with CEA. An irradiation test program with SiC samples in various shapes is currently being performed to assess the in-pile behavior of SiC under realistic PWR conditions [4].

CONCLUSION

Modern nuclear fuel is continuously implemented by Framatome worldwide, and the results of the LFA Programs confirm the expected improved performance of the new designs.

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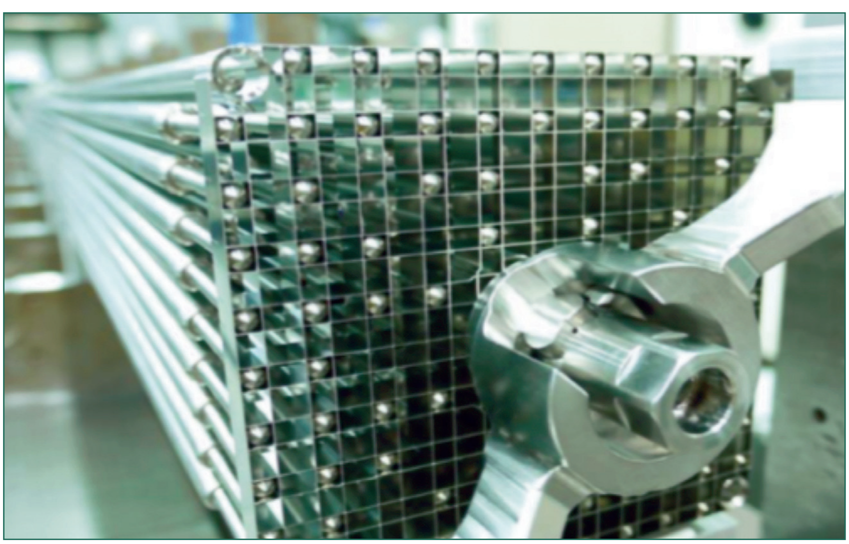

Figure 6. ATRIUM 11 Fuel Assembly.

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