Framatome’s evolutionary ATF solution: Feedback from the irradiation programs on PROtect’s Cr-coated M5\textsuperscript{Framatome} cladding

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ABSTRACT

A key point for licensing Framatome’s near-term solution is to evaluate the Cr-coated cladding’s behavior under irradiation. Framatome has launched a series of irradiations in both research and commercial reactors to investigate the behavior of the Cr-coated cladding under irradiation and confirm the excellent behavior observed during the out-of-pile testing. The IMAGO irradiation, which was launched in the Gösgen reactor in 2016, was the first irradiation of EATF concepts in a commercial reactor. The goal of the IMAGO program is to irradiate coated cladding samples to doses similar to high Burnup fuel. This program was followed by the insertion of fueled Cr coated M5\textsuperscript{Framatome} rodlets in the PWR ATF-2 loop of the Advanced Test Reactor (ATR) in 2018 and the GOCHROM irradiation program featuring the insertion of 20 full-length fueled Cr coated M5\textsuperscript{Framatome} rods in the Gösgen commercial reactor in 2019. In parallel, 52 full-length fueled Cr coated M5\textsuperscript{Framatome} rods have been inserted in two US commercial reactors.

1. Introduction

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 accident scenarios than available products today. Framatome’s strategy for Enhanced Accident Tolerant Fuel through its PROtect program is based on a two-phased approach balancing each solution’s benefits with speed to market [1]:

- A near-term “evolutionary” solution, provides margin gains with regard to activity release in case of leakers, resistance to chipping of pellets, Design Basis Accidents and coping time under severe accidents. This design consists of an evolution of the existing ones through the deposition of a few µm-thick chromium (Cr) coating on the surface of a M5 tube [2], associated with Chromia enhanced UO\textsubscript{2} pellets [3];

- The other solution is a long-term “revolutionary” solution, which provides a drastic increase in margin during Design Basis Accidents and significant coping time under severe accidents. This design replaces current metallic cladding with a ceramic matrix composite cladding which shows an outstanding dimensional stability at high temperature [4].

The near-term Cr-coated solution shows improved behavior when facing severe accidental conditions [5]. In addition of the good corrosion behavior at nominal temperature (which is around 350°C), the deposition of Chromium significantly improves its high temperature oxidation behavior.
2. Overview of Framatome’s Cr-coated cladding irradiation plan

Within the last 4 years, Framatome’s irradiation campaigns have been split between Switzerland and the United States, and an accelerated plan has been implemented for a 1st reload of Cr-coated fuel rods to be inserted in a commercial reactor in the 2023-2025 timeframe (Figure 1).

In that view, the 2015-2018 irradiation program focused on unfueled materials irradiation, with the insertion of coated samples in OSIRIS French reactor (2015), Gösgen in Switzerland (2016) and Halden (2017) in Norway. The IMAGO irradiation in Gösgen is the 1st irradiation of Cr-coated samples in a commercial PWR reactor, and is still ongoing [6]. First representative fueled rodlets were then inserted in representative PWR conditions in the ATR in 2018. Thanks to excellent preliminary irradiation feedback, Framatome inserted Fueled Lead Test Rods in 3 commercial reactors in 2019, representing a total of 52 Cr-coated fueled rods which will be irradiated until 2024 in PWR commercial reactors. In addition, a total of 176 Lead Fuel Rods have been delivered to Calvert Cliffs commercial reactor for the irradiation of the first PROtect Lead Test Assembly, and the first cycle of irradiation has begun in March 2021. This paper summarizes the irradiation feedback on Cr-coated fueled rods and unfueled cladding samples in the Gösgen Swiss reactor (KKG) as well as visuals from irradiations in the US Advanced Test Reactor (ATR) and the Unit 2 of Vogtle commercial reactor.

3. Irradiation framework in Gösgen (IMAGO) – since 2016

The objective of the IMAGO program is to assess the integrity of Cr coating under PWR operating conditions, while evaluating the corrosion kinetics and the evolution of the microstructure under irradiation.
3.1 Materials and irradiation conditions

The irradiation started in June 2016 and is planned for a total of seven 1-year cycles, finishing in 2023. The samples were placed in a Material Test Rods device inserted in the guide tubes of 2 fuel assemblies, allowing all the samples to be exposed to the PWR coolant. A number of tubes and plates, with a variability on substrate composition and Chromium deposition thicknesses, has been under irradiation for the last 4 years.

3.2 Hot cell examination after 1 cycle

3.2.1 Pre-bent samples examination

Some of the samples inserted in Gösgen for the IMAGO program were pre-bent, so as to check the impact of a static deformation on the integrity of the coating through time. As shown in Figure 2, no delamination was observed on the samples nor any cracking or deterioration after 1 cycle. The elastically pre-bent relaxation samples showed no cracking suggesting that the coating behaves well under small elastic stress in irradiation for this level of stress.

![Figure 2 - pre-bent samples hot cell examinations after 1 cycle in KKG](image)

3.2.2 Focus on the $M5_{\text{Framatome}}$ / Cr interface

Cross sections of flat samples have been prepared in order to perform hot cells examinations of the $M5_{\text{Framatome}}$ / Cr interface after one irradiation cycle in KKG (Figure 3).

![Figure 3 - Focus on the $M5_{\text{Framatome}}$ / Cr interface](image)

The Cr-Zr interface is smooth with no defects. Additionally, there is no visible oxide layer on the surface of the coating. Overall, the optical metallography shows no evolution of the coating or the Cr-Zr interface, suggesting the good stability of the coating under irradiation, and confirms the very low corrosion kinetics of the Cr-coated samples.
3.2.3 Pre-damaged samples transition behavior

Pre-damaged samples (created by a calotest sphere) were also inserted in order to evaluate the transition between the Zirconium oxide and the Chromium coating (Figure 4). The oxide formed on the uncoated region is about ~2µm thick as for the uncoated inner surface of the tube sample, thus showing no accelerated corrosion of the underlying substrate in the location of a coating defect. Furthermore, the zirconium oxide layer stops where the undamaged Cr layer starts and the formation of this layer does not lead to coating delamination. Those results confirm out-of-pile observations, as they demonstrate a good stability of the coating and a very low corrosion kinetics after 1 year of irradiation.

![Figure 4 - Pre-damaged samples cross section hot cell examination](image)

3.3 Visual inspections after 2 to 5 cycles

A visual examination of the bottom span of the remaining MTRs (Material Test Rods) was performed during the outages after cycles 1 to 5. The visual inspections in June 2018 and 2019 were performed using a HD color camera, which enables the observation of very fine features and is used to compare the visual aspect of specific areas after 2 to 5 cycles of irradiation to evaluate the evolution of the coating with irradiation exposure (Figure 5).

![Figure 5 - Visual inspections of Cr-coated cladding after 2 to 5 cycles in KKG](image)
The picture shows the same area, identified with superficial linear features, after 2 to 5 cycles of irradiation. The same features are visible in both cases with no significant evolution, which demonstrates the good behavior of the Cr-coating during irradiation, and lack of visible deterioration. The only difference observed is a slight change in color, moving from light golden color to slightly darker purple. This evolution is linked with the growth of the nanometric chromium oxide, which remains below 1μm when such colors are seen. Finally, no delamination was observed over the length of the MTRs inspected, which confirms the excellent adherence of the coating in normal operating conditions after 5 years of PWR commercial irradiation.

3.4 Global IMAGO irradiation feedback and further work

IMAGO program feedback of the irradiation of Cr-coated samples in Gösgen Swiss commercial pressurized reactor shows:

- an excellent irradiation behavior of Cr-coated samples with no defects, delamination or other degradation of Cr-coating layer after 5 years of irradiation;
- a good behavior of the coating when elastically strained during irradiation;
- a good stability of the coating and very low corrosion kinetics under irradiation.

This irradiation feedback results in Gösgen’s confidence for the insertion of fueled Lead Test Rods of Framatome’s Cr-coated solution.

4. Irradiation feedback of Cr-coated Fuel Rods in Pressurized Water Reactors

Within the last years, Framatome inserted fuel rods in Pressurized Water Reactors (PWR) either in the form of rodlets (Advanced Test Reactor campaign) or Lead Fuel Rods (GOCHROM campaign in Gösgen commercial reactor and irradiation in Vogtle Unit 2, ANO and Calvert Cliffs).

4.1 Fueled rodlets Irradiation in the Advanced Test Reactor

Framatome is currently irradiating its near-term Cr-coated cladding and Chromia-doped fuel (Cr-Cr$_2$O$_3$) ATF solution along with standard M5$_{\text{Framatome}}$-UO$_2$ fuel pins in the ATF-2 test rig of the Advanced Test Reactor (ATR) at the Idaho National Laboratory (INL).

4.1.1 Materials and irradiation conditions

The rodlets are nominally 15.24 cm (6 inches) long and were discharged from ATR at a burn-up of ~15 GWd/MTU. Fuel pins consist of M5$_{\text{Framatome}}$-UO$_2$ fuel system and Cr-coated M5$_{\text{Framatome}}$ and Cr$_2$O$_3$-doped UO$_2$ fuel system. The calculated displacement per atom (dpa) on the cladding material (M5$_{\text{Framatome}}$ and Cr-coated M5$_{\text{Framatome}}$) is ~3.5 dpa.

4.1.2 Irradiation feedback

Baseline non-destructive examinations which include visual examination, neutron radiography, gamma scanning and profilometry were completed on four fuel pins that were discharged from ATR in January 2020. The surface of all the rodlets appeared slightly tarnished due to accumulation of crud deposits. These deposits were seen on all the rodlets in the ATF-2 test train suggesting that the source of these deposits could be the test train itself which was made of stainless steel. In general, Cr-coated rodlets showed golden appearance indicating that the corrosion is significantly lower for coated rodlets compared to uncoated fuel rodlets.
Figure 6 shows the visual of uncoated and Cr-coated fuel rodlets taken through the hot cell window. Overall, no unusual features were observed in any of the fuel pins and the Cr-coated cladding fuel pins showed excellent coating adherence with no sign of coating delamination.

Diameter measurements were collected with ±5µm accuracy. No localized increase of cladding diameter was observed at the pellet-pellet interface or in other locations, as shown in Figure 7 where red dotted lines indicate cladding upper and lower outer diameter tolerance. Since the diameter change is within cladding outer diameter tolerance, it was concluded that there is no difference between Cr-coated and uncoated rods with respect to creep down.
4.2 GOCHROM Irradiation campaign of Cr-coated Lead Fuel Rods in Gösgen commercial reactor

While IMAGO program is still ongoing until 2023, Framatome inserted 20 Cr-coated Lead Fueled Rods in Gösgen PWR reactor. The irradiation campaign, so-called GOCHROM, started in June 2019 for 5 annual cycles. The objective of the GOCHROM campaign is to demonstrate Framatome’s ability to deliver full-length fueled rods of their PROtect solution and collect representative data for licensing needs. A preliminary irradiation feedback was recently received after the first year of irradiation.

4.2.1 Materials and irradiation conditions

Framatome inserted 20 full length Cr-coated fueled rods in Gösgen PWR commercial reactor, containing either classical UO$_2$ pellets or doped-UO$_2$ pellets. The conditions of the irradiation are the same as the IMAGO program.

4.2.2 Irradiation feedback after 1 cycle

Figure 8 shows a Lead Fueled Rod just before the beginning of the GOCHROM irradiation. The 20 fuel rods have been allocated at different emplacements in the core, and have been placed on the sides of the assembly so that they can be easily looked at. Figure 8 (left) shows a rod inserted between to classical Zirconium alloy rods, and Figure 8 (right) shows a zoom on the visual aspect of a Cr-coated rod before insertion. One can see that there is a superficial helical marking on the surface of each rod, which is due to the contact point with a camera for measurements before insertion.

![Figure 8 - Cr-coated fuel rod before KKG irradiation](image)

Recently, the first feedback of on-site visual check of the assembly containing PROtect full length solutions was received. Figure 9 shows a full length rod after 1 year of irradiation, and present no sign of degradation, delamination or accelerated corrosion.
As a matter of fact, all inspected rods show a bright metallic appearance, the initial helical surface features caused by the individual rod measurements before insertion are still visible after one cycle of operation and there are no indications of corrosion in visual inspections. Moreover, the transition from the rod to the end plug does not reveal any peculiarities (Figure 10).

These positive results after a year of irradiation confirm the IMAGO results obtained on unfueled samples. Moreover, the 2nd cycle has just finished and the preliminary diameter and length measurements after two cycles of irradiation (34.8 MWd/kgU equivalent burnup) is in good agreement with the development of the uncoated M5 in the same conditions. Consolidated GOCHROM results of the 2nd cycles should be available later in 2021.
4.3. Irradiation feedback from Vogtle Unit 2 US commercial reactor

Four-face visuals were collected from four GAIA LTAs, each of them containing four Cr-coated full-length cladding. These LTAs have completed one irradiation cycle in Vogtle. The results were quite promising, as no unusual features were observed on the Cr-coated fuel rods. The Cr-coated is very adherent to the underlying M5\textsubscript{Framatome} cladding and no signs of coating delamination were observed. Cr-coated rods showed lustrous-gold appearance suggesting that the oxide formed on the surface of the cladding is very thin (see Figure 11). These results confirm the excellent performance of the Cr-coated cladding which was demonstrated in the out-of-pile tests and other in-pile programs.

![Cr-coated cladding](image)

Figure 11 - Cr-coated fuel rods after 1 cycle in Vogtle Unit 2

5. Conclusion

The IMAGO campaign showed that unfueled Cr-coated cladding irradiation feedback is excellent after 3 years of PWR irradiation in Gösgen commercial reactor, with a good stability of the coating and very low corrosion kinetics under irradiation.

Fueled Cr-coated rodlets irradiation feedback after 15 GWd/MTU in the ATR showed excellent coating adherence with no sign of coating delamination, with no localized increase of diameter all along the pins.

Through the GOCHROM campaign, 20 Lead Fueled Rods have been irradiated in Gösgen with excellent visual inspection results after 1 year of irradiation, while the 2\textsuperscript{nd} cycle out of 4 foreseen cycles is on-going. Late results from Vogtle Unit 2 irradiation also confirm the excellent performance of the Cr-coated cladding.

As a result, Framatome is on track for the 2023-2025 reloads, that will be justified thanks to the LFRs in-pile data, and with the intermediate irradiation results from the Lead Test Assembly (LTA) irradiation of 176 LFRs in a single GAIA assembly coming at Calvert Cliff in 2021.
REFERENCES


