INSPECTION CAPABILITIES AND IN-PILE EXPERIENCE WITH INNOVATIVE AND ENHANCED ACCIDENT TOLERANT FUEL MATERIALS AT KKG

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ABSTRACT

The Gösgen nuclear power plant in Switzerland (KKG) has launched, in close collaboration with its fuel supplier Framatome, several R&D projects to develop and license new ceramic and metallic materials. Through these R&D programs, Gösgen has created and further developed new methodologies, irradiation capabilities and equipment to support innovative fuel and cladding material characterisation, which are now being applied for the development of enhanced Accident Tolerant Fuel (eATF) materials.

It is in this context that a new five-year irradiation program called IMAGO was launched in 2016 to test the in-pile behaviour of eATF with samples of SiC/SiC and Cr-coated zirconium alloys. The paper presents the in-pool measurement capabilities at KKG along with first results of the visual inspections of eATF samples, together with the utility's perspective on the implementation of eATF solutions in view of operating the reactor beyond 60 years.

1. Introduction

KKG has been operating a KWU (Kraftwerk Union AG) 3-loop pre-Konvoi type Pressurised Water Reactor (PWR) with a thermal power of 3002 MW_{th} for a period of ca. 40 years. KKG has launched over that period, in close collaboration with its fuel supplier Framatome, several R&D projects to develop and license new fuel materials. Since then, KKG supported the development of advanced materials and their irradiation in the core as well as their inspection out-of-pile in its pools.

At first, the goal was to develop more corrosion-resistant cladding materials than the standard Zircaloy-4 fuel cladding; a need that appeared already a few cycles after the commissioning of the reactor in 1979. A second development program was to extend the fuel utilisation and performance with a high-burnup program, achieving a maximum fuel-rod-average burnup license limit of 75 MWd/kg_{HM} (and peak-pellet of 82 MWd/kg_{HM}) for UO_2 fuel. Through these R&D programs, KKG has created and developed unique methodologies and equipment to support innovative fuel implementation, which are now being applied for the development and testing of eATF.

KKG uses a two-way methodology, whereas test materials (TMs) are inserted in the core during the outage depending on whether they contain fuel or just non-fuel materials. In the case of non-fuel TMs, they are normally introduced in the core in the form of Material Test Rods (MTRs) containing the TMs inside, in different possible forms (rodlets, plates, etc.). The geometrical limitation is the size of the guide thimble tubes. MTRs are placed in selected guide thimble tubes of an otherwise standard fuel assembly (FA) that works as host assembly; these MTRs are fixed to flow restrictors without affecting the FA mechanical design.

In the case of TMs based on ceramics containing fissile material, KKG inserts these TMs in the form of sintered pellets inside segmented rods or Lead Test Rods (LTRs), which are positioned in a host FA replacing a standard fuel rod in one or several FAs. LTRs are associated with the further introduction of Lead Test Assemblies (LTAs) and advanced fuel assemblies in reload quantities, whereas segmented fuel rods or individual test rods may contain fuel samples that are part of R&D goals and not necessarily intended to become part of an immediate future reactor procurement.

TMs, both fuelled and non-fuelled, are visually inspected and characterised during the annual outage with specific semi-automatic equipment developed and improved at KKG during the last decades for these specific purposes. Section 2 describes the most important of these systems, namely the Fuel Assembly Inspection Device (so-called in the plant "ISE") in the containment pool, and the Automated Fuel Assembly Repair Device (so-called "ABERE") in the annexe loading pool. A good example of the capabilities of non-fuelled TM irradiation and characterisation is described in the context of the CRONOG programs in Section 3.

Nowadays the R&D focuses on developing and testing eATF for improved safety mostly during LOCA [1] [2]. These materials are designed to significantly reduce the water-zirconium oxidation reaction by either adding a hard corrosion resistant outer layer by means of Physical Vapor Deposition (PVD), as for example Cr-coating on a typical Zircaloy-based substrate such as M5, or by replacing Zircaloy-based alloys altogether by ceramic composite materials such as SiC/SiC. They cover in this way both evolutionary and revolutionary areas of potential interest and development for the next 20 years.

It is in this last context that a new five-year irradiation program called IMAGO (Irradiation of Materials for Accident tolerant fuel in Gösgen) was launched in 2016 to test the in-pile behaviour of eATF with non-fuelled samples of SiC/SiC and Cr-coated zirconium alloys [3]. The first samples have been already visually inspected after one irradiation cycle and irradiated samples have been shipped late 2017 to the hot cells at the Paul Scherrer Institute (PSI) in Switzerland for dimensional measurements, metallographic analysis, thermal diffusivity measurement and mechanical testing, etc. A description of the IMAGO program and first results of in-pool Cr-coated irradiated material are given in Section 4. Section 5 finalises the paper with a discussion and an outlook of the utility's perspective about the implementation of eATF solutions in view of operating the reactor beyond 60 years of lifetime.

2. Inspection capabilities

KKG benefits from a number of enhanced systems for fuel assembly and fuel rod inspections as well as for the extraction of samples or probes. On the one hand, these are placed in a corner of the containment pool, close to fuel sipping stations. These capabilities in the containment pool are continuously developed and maintained but are essentially similar to those in other German PWRs.

Specific in Gösgen is the availability of a loading pool in the ring room surrounding the metallic containment, which is connected to the inside-containment pool through a horizontal channel. This loading pool was originally designed for the fuel assembly transfers and for manual inspections. Several years after startup, it was decided to modernise and furnish the loading pool capabilities with an additional system for the fully automated replacement and inspection of individual fuel rods. This system is unique worldwide and, thanks to it, KKG participates in many fuel and cladding R&D programs. We describe these inspection capabilities in each of these two pools in the next two sections.

2.1 Inspection capabilities in the containment pool

The inspection system in the main pool inside the containment is the Fuel Assembly Inspection Device (or "ISE"). The ISE goal is to perform all necessary checks and investigations on fuel assemblies, control rods (CRs) and MTRs during the outage such that new core configuration can be safely and efficiently loaded. This means that FAs and CRs for the next cycle can be demonstrated to be failure free before the start of the next cycle. Figure 1 illustrates the layout of the ISE.

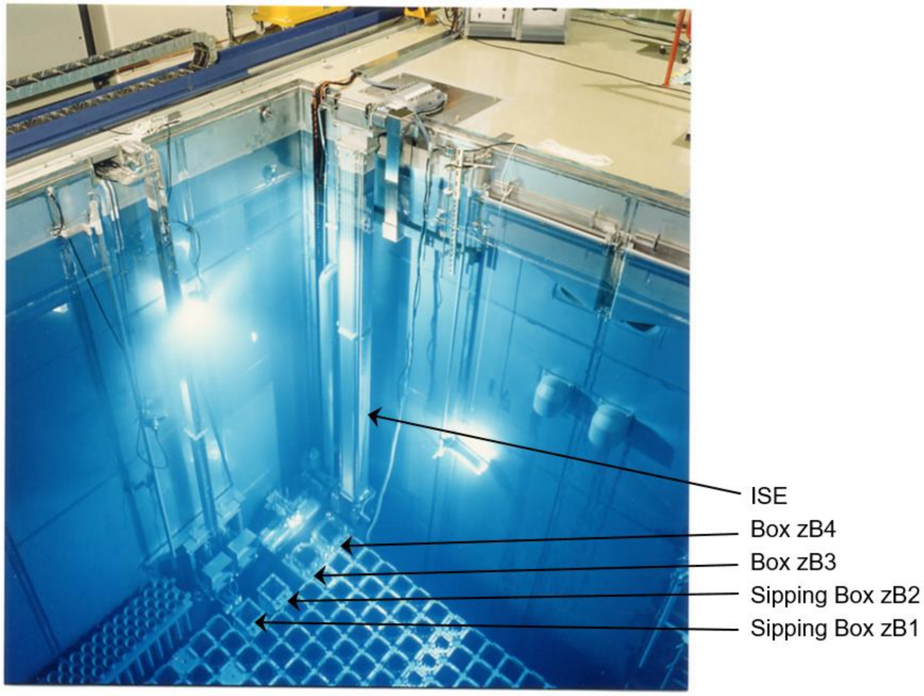

Figure 1. Fuel Assembly Inspection Device (ISE).

The most important functions and capabilities of the ISE are described in Table 1.

1	Visual inspection of fuel assemblies and control rod cluster assemblies
2	Oxide thickness linear measurement of fuel rods at the fuel assembly periphery
3	Fuel assembly geometry measurements: Length, Bowing
4	Fuel rod growth and free room measurement
5	Contour and corrosion measurement of spacer grids
6	Fuel assembly spring force relaxation measurement
7	Eddy-current measurement of all control rod fingers (48x20) and their profilometry and diameter
8	Services for MTRs and Material Test Programs such as CRONOG and IMAGO

Table 1: Enhanced capabilities of fuel assembly inspections using the ISE in the KKG main pool.

2.2 Loading pool

In the loading pool, KKG installed a fully automatised system, the Automated Fuel Assembly Repair device (or ABERE). The system can be inserted and extracted from the loading pool in the ring room surrounding the metallic reactor containment. The system ABERE is relatively sophisticated. It was designed and built with a few number of subsystems, to guarantee the easy maintenance and further modular development. The different subsystems are supported by a robust mechanical structure that gives integrity to the system and connects it to the loading pool. The ABERE uses the Fuel Rod Replacement Device (FRRD) to extract or insert an individual fuel rod vertically, from or to a FA. Figure 2 depicts the support structure and the FRRD.

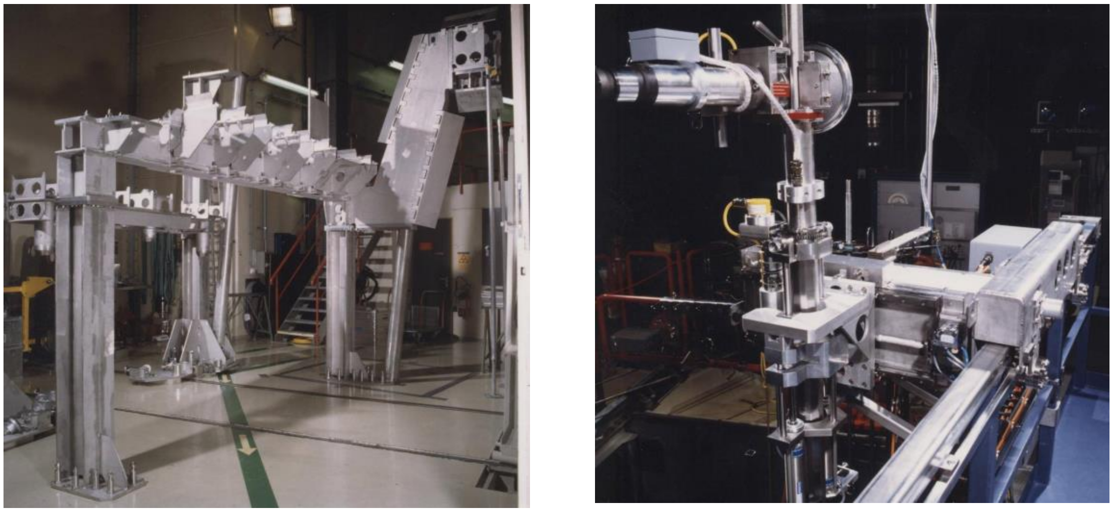

Figure 2. Left: Support structure of the ABERE out of the loading pool in the ring room. The different structures on the horizontal beam allow the positioning of up to 3 fuel assemblies or quivers. Right: The Fuel Rod Replacement Device (FRRD) for the vertical extraction of individual fuel rods.

The correct positioning of the FRRD on top of the desired assembly or quiver is materialised through the movement of two subsystems, the Positioning Wagon and the Coordinate Wagon, which work synchronically at different axial elevations. The FRRD hangs from the Positioning Wagon that drives it from an assembly or quiver to another one, meaning both X- and Y-movements to allow the accurate handling of a fuel rod.

The operation runs per se automatically, following a movement plan established in advance, depending flexibly on the movements desired. This allows if needed the total replacement of rods from one assembly to a new skeleton in not more than a couple of days. Figure 3 illustrates the Coordinate and Positioning Wagons; Figure 4 shows how the Coordinate Wagon helps to precisely move a FR from one FA to another.

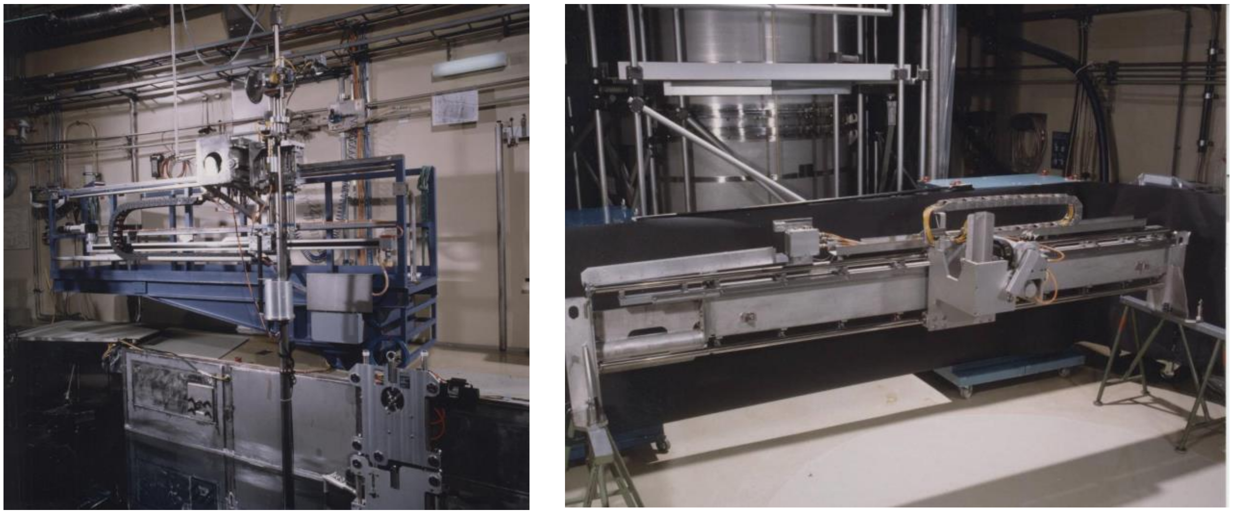

Figure 3. Positioning Wagon, placed in normal operation outside the water (left), and Coordinate Wagon, which during operation is submerged (right).

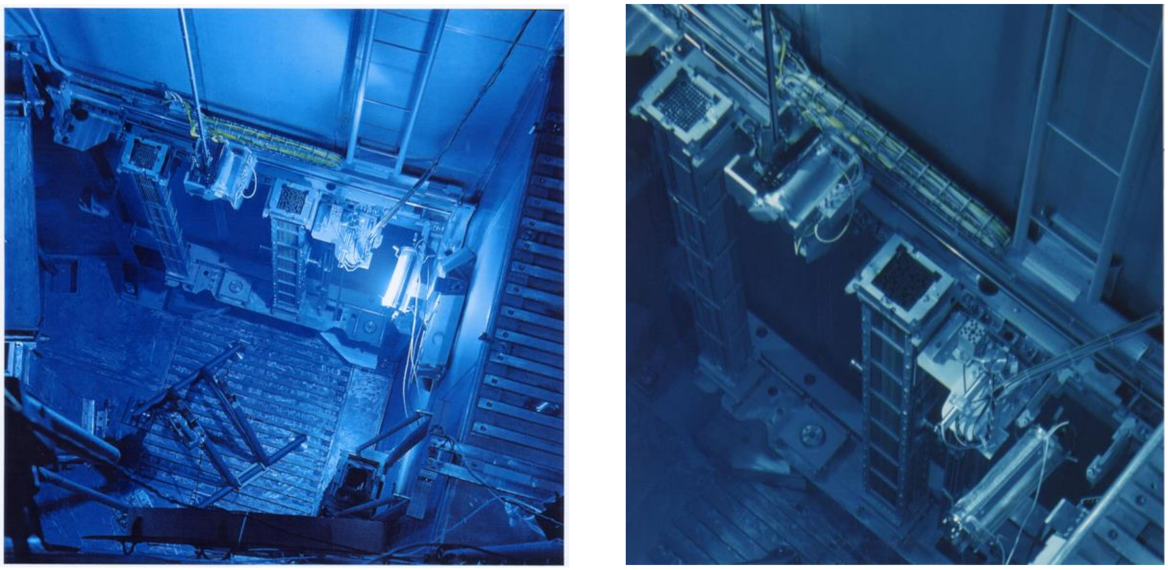

Figure 4. Coordinate Wagon driving the lower part of a fuel rod from one assembly to another in the loading pool at KKG. Right: Detail of the Coordinate Wagon between two assemblies.

The main measurements or functions enabled by the ABERE are given in Table 2. Using the ABERE, more than 1'000 fuel rods have been inspected and more than 18'000 fuel rods have been handled. Lead test rods have been irradiated up to 10 cycles, achieving in excess of 110 MWd/kg$_{HM}$ [4].

1	Repair of fuel assemblies
2	Replacement of fuel rods between assemblies or quivers
3	Replacement of an entire fuel assembly structure
4	Inspections of individual fuel rods, among others: - Eddy-Current tests - Oxide thickness measurements, linear and helicoidal - Measurement of rod geometry, diameter and length - Fuel rod brushing
5	Visual inspections
6	Local cladding deformations, integrity and analysis
7	Fuel rod diameter
8	Exchange of fuel rods
9	Oxide thickness (on a helix line)
10	Grid-to-rod friction forces
11	Preselection of ideal rods for post-irradiation examination in the hot cells at research labs

Table 2: Enhanced capabilities of fuel rod and fuel assembly interventions using the ABERE in the loading pool at KKG.

3. Material Test Programs: CRONOG

3.1 Introduction to Material Test Programs at KKG

KKG performs the irradiation of special fuel rods replacing standard ones in hosting FAs since many decades [5]. This is basically so in the context of the characterisation of LTRs for production purposes, a standard practice, that KKG expanded to other test and segmented rods.

A special feature of the KKG irradiation capabilities is, however, the irradiation of non-fuelled TMs in the context of Material Test Programs since 2001. For this purpose, MTRs are designed and constructed such that they can be seen as special flow restrictors, as if they were permanently inserted control rod fingers. These special flow restrictors allow the irradiation of up to 12 MTRs in a single host assembly. The core design needs to account for the presence of these MTRs by means of separate neutron macroscopic cross sections and flux form functions for the hosting assemblies.

The investigations of the irradiated MTRs are performed essentially in the hot cells at the Paul Scherrer Institute in Würenlingen, Switzerland, or in the hot cells at Framatome in Erlangen, Germany. The investigations include visual inspections and dimensional measurements as well as mechanical, chemical and other tests. The probes are constructed so that special effects can be measured; in this context we introduced in the core typically growth, creep and space corrosion probes. The usual materials inserted are standard zirconium alloys together with new alloys, to validate their properties and compare results.

3.2 CRONOG Programs

As an example of MTR investigations, we describe in this section the CRONOG programs. KKG and Framatome investigated guide tube materials in this context by introducing specially prepared

MTRs in the years 2008, 2013 and lately 2016. CRONOG stands for Creep of Zirconium Alloys in Gösgen.

From 2008 onwards, we characterised experimentally with the CRONOG 2008 program the neutron irradiation induced free growth, as well as the neutron irradiation induced axial creep of individual samples. Different materials, including, among which Q12 with different fabrication processes, alloying species, including cold reworked annealed, partly or totally recrystallized, have been irradiated. After seven years of irradiation, the axial creep probes have been irradiated without compression, similarly to the free growth probes, and investigated every two years instead of annually in the loading pool during the outage.

Eight further MTRs with PCAm, Q12 and M5 were inserted (CRONOG 2013) in the core. In the latter program, probes have been partly loaded in advance with 50 and 150 ppm H, to investigate the influence of the presence of dissolved hydrogen in the matrix on the atom mobility and plastic deformation revealed in their creep behaviour. In 2016 and based on already obtained comparative results of hydrogen-preloaded vs. no-hydrogen mechanical behaviour under irradiation conditions, three more MTRs were inserted in the core in 2016 (CRONOG 2016) to complement the database of 2013, with pre-loaded hydrogen concentrations of 100 and 150 ppm.

The MTRs are periodically inspected during the outage, and some of them selected for PIEs. For the hot cell investigations, round disks are cut and transported to the hot cells.

4. Material Test Programs: IMAGO

4.1 IMAGO Program

A similar concept was pursued to irradiate eATF cladding samples in the so-called IMAGO program (Irradiation of Materials for Accident tolerant fuel in Gösgen) in 2016 [6] [7] [8]. A total of nine MTRs containing different eATF cladding material samples started to be irradiated in July 2016 and will be irradiated till June 2021.

From the nine MTRs, five contain Cr-coated M5 samples designed to investigate stack, damage and bending effects. These samples are inside the MTR at different axial positions, with the exception of the lower part of the MTR, which is itself a Cr-coated M5 segment without any content or sample inside and exposed directly to the water and irradiation environment without any further barrier. The other four samples contain SiC or SiC/SiC composites and SiC/Ta/SiC sandwich probes.

The geometry and arrangement of the IMAGO probes is very sophisticated (Figure 5), with the purpose that as much information as possible can be extracted from their irradiation in one single MTR. For example, bent Cr-coated samples were inserted to evaluate the behaviour under irradiation and especially the adherence of the coating under mechanical stress. Tubular solid rod SiC segment samples have also been inserted in the MTRs to evaluate the swelling of SiC under PWR conditions.

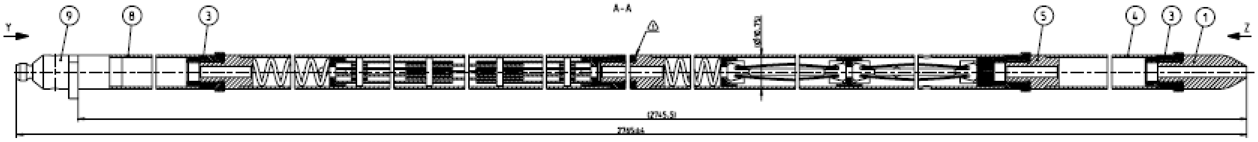

Figure 5. Layout of a IMAGO Material Test Rod irradiated since 2016 in Gösgen. Different samples are mounted inside the MTR and placed within a guide thimble tube for irradiated in a heavy duty fuel asembly. Bended and damaged samples are also included for future characterisation.

The design safety evaluation of the MTRs includes among other things, the operational integrity, the safe axial positioning and no deteroration effects on the hosting guide thimble tube. In particular, the sample surface temperature has to stay below saturation (344°C at 155 bar). For this reason, all structural parts are equiped with flow holes so that the rodlets and samples can be internally cooled. In the case of IMAGO, a MTR contains an inlet and outlet piece and lateral radial holes, allowing water flow to move within the samples and next to the guide tube. The thermal-hydraulic justification was performed with the CFD code STAR-CCM+ and 3D CAD models of the MTRs. The energy source or gamma heating into the solids is provided in the code assuming a conservative volumetric energy source derived from neutronic calculations with a realistic axial power profile of the hosting FA. The calculated flowrate of water into the guide tubes with MTRs has no impact on the by-pass/coolability of the core.

4.2 First In-Pool Results of the IMAGO Program

After one-year irradiation, the IMAGO MTRs were visually inspected (Figure 6) to verify the aspect of the Cr-coating of the lowest part of the MTRs. All MTRs, with the exception of two, were loaded again in host assemblies and are being irradiated for the second cycle. The next inspection is planned in June 2018.

The Cr-coating is very stable and the transition to the non-coated region smooth. There are no indications of delamination after one cycle. The Cr-layer showed essentially the same degree of homogeneity after one-cycle irradiation as it had before irradiation; no effects leading to operational changes or degradation could be found. The Cr-coating showed a golden colour corresponding to a very thin Cr-oxide thickness.

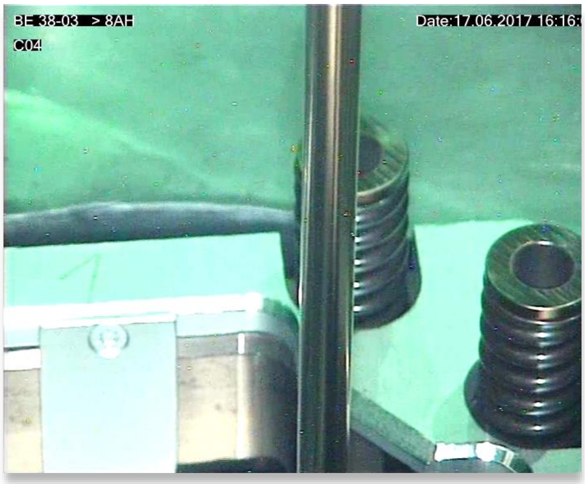

Figure 6. Visual appearance of the Cr-coated M5 lowermost segment of MTR with the denomination C04, after one cycle irradiation (maximum neutron fluence of ca. 3×10^{21} n/cm^2). The Cr-coating is best to be seen on the colour picture (top-right).

From the two definitively extracted MTRs in June 2017, the segments with Cr-coated M5 and SiC samples were transported to the hot cells at the Paul Scherrer Institute in November 2017 for detailed investigations. Additional MTRs will be extracted up to the end of the program planned for the year 2023 to evaluate their behaviour with increasing neutron fluence. At KKG, the Cr-coated MTR segments will continue to be visually inspected.

5. Discussion and Outlook

The paper has presented the two-step methodology developed at Gösgen to characterize the in-pool behaviour of test materials or lead test rods. Several R&D programs have been successfully launched with the ultimate goals to further develop nuclear grade materials for heavy-duty PWRs.

KKG possesses a unique set of systems and experienced staff that allow the irradiation and the detailed investigations of fuel and/or non-fuelled materials. KKG has used these capabilities intensively in the past and constructed, for example with the CRONOG program, a long tradition that helps this plant to identify trends and material behaviours in the core well in advance, giving the plant managers the capability to take decisions pro-actively and prophylactically before detrimental effects may occur. The insertion in the core of advanced material in the core first in small quantities is also from a licensing viewpoint very beneficial. The safety demonstration is typically done by using the collected in-pile experience obtained on the test materials.

Not surprisingly then, KKG plays an important role in the development and characterisation of eATF cladding materials with its fuel supplier Framatome. Depending on the success of Cr-coated M5 being tested and the safety benefit associated to this new material, Gösgen is looking to potentially replace its current fuel cladding with this solution.

The natural next steps would be the insertion of segmented rods or directly of full length LTRs with Cr-coated zirconium alloy substrate. At the time being, the conceptual phase is under discussion. Neutron analysis will also be performed in the near future in order to quantify the neutron penalty with the insertion of Cr-coated fuel rods. It is recognized in KKG that only evolutionary or revolutionary cladding materials will permit to operate the plant beyond the horizon of 2039, which means operation for 60+ years.

M5 is a trademark or a registered trademark of Framatome or its affiliates in the USA or other countries.

6. Acknowledgment

The authors would like to thank in particular the Fuel Service Team of Framatome in Erlangen for their support and close collaboration. Special thanks to Heinz Schwandner and his team for the active development of the tools presented in the paper and the more than 30 years passed at the KKG plant. We are also thankful to the director of the Nuclear Fuel Division, B. Zimmermann for his support.

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