BENEFITS OF FRAMATOME's E-ATF EVOLUTIONARY SOLUTION: Cr-COATED CLADDING WITH Cr_2O_3-DOPED FUEL

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ABSTRACT

Framatome is pursuing the development of Enhanced-Accident Tolerant Fuel (E-ATF) cladding concepts ranging from near-term evolutionary (Cr-coated M5 cladding) to long term revolutionary (SiC/SiC composite cladding) solutions, utilizing its worldwide teams and partnerships throughout Europe and the United States.
The technology combining Cr-coated M5 cladding with Cr_2O_3-doped UO_2 fuel provides the most mature concept. Several fuel performance characteristics are enhanced, relative to existing UO_2 fuel with uncoated Zr-based cladding alloys, both in normal operation and in accident conditions. The article describes some of the expected benefits of this fuel rod concept such as increased reliability due to enhanced wear resistance and PCI behaviour and improved behaviour in accident conditions due to reduced ballooning and high temperature steam oxidation.
Framatome is evaluating the test results demonstrating the material performance enhancement in the consideration of the value assessment of its E-ATF evolutionary concept. Value assessments should consider the full spectrum from normal operation to accident scenarios, recognizing the local safety regulations, licensed codes and methods.

1. Introduction

The accident at Fuksuhima Daiichi in 2011 highlighted the need to further increase fuel margins in the case of a severe accident. In particular, the reduction of the high temperature steam oxidation of the Zr-based components in the core was seen as a major concern. Later on, the profitability of the nuclear industry has been challenged by shale gas or by the increasing contribution of renewables in the energy mix. Thus, it appeared that the Enhanced-Accident Tolerant Fuel (E-ATF) should also improve the performance during normal operation and the fuel cycle economics.

Framatome is actively developing E-ATF cladding concepts ranging from short-term evolutionary (chromium-coated zirconium alloy cladding) to long term revolutionary (SiC/SiC composite cladding) solutions. Framatome is utilizing its worldwide teams and partnerships, with programs and irradiations planned both in Europe and the United States. In that respect, the most advanced and mature E-ATF fuel rod solution for PWR application is made of the chromium-coated M5 cladding and Cr_2O_3-doped UO_2 fuel pellets. The current efforts in terms of testing and value assessment are focused on this fuel rod product.

The value assessments must address the technical analyses results as well the economic benefits. It should be recognized the conclusions from technical analyses may depend on the codes, methods, and regulatory framework. The testing results demonstrating the material improvements along with technical analyses showing improvements in normal operation and in the accident scenario results are discussed in this paper.

2. Framatome's E-ATF evolutionary solution

In the near-term, Framatome is focusing on an E-ATF evolutionary solution with the most promising technologies: chromia-doped pellets coupled with Cr-coated M5 clad. These modifications represent an incremental change to currently licensed fuel systems thereby remaining within the existing regulatory structures and allowing for more streamlined licensing.

2.1 Chromia-doped UO_2 fuel pellets

The development of this fuel was done with the goal of increasing fuel robustness and efficiency with enhanced performance while ensuring improved safety margins, for both PWR and BWR applications [1]. This fuel has larger grains and improved viscoplasticity with respect to standard UO_2. This results in the following benefits:

- Normal operating conditions: Increased fission gas retention within the large grain microstructure reduces the internal pressure in fuel rod at high burnup, by up to 20 bars (hot conditions) with respect to the reference UO_2 rods. Higher resistance to Pellet-Cladding Interaction (PCI) leading to additional power margins will enable utilities to upgrade LWRs manoeuvrability [2]. This topic is further detailed in section 3.
  Higher density to improve fuel cycle economics is also possible with this fuel concept. Additional fuel reliability benefits stem from Cr_2O_3-doped fuel distinctive properties. Strong mechanical stability of these pellets leads to significantly reduce pellet flaws, especially missing pellet surface which can adversely affect the fuel rod performance during power transients. Furthermore, failed fuel degradation after the occurrence of primary defects can significantly affect the reactor operation or the planned outages and increase workers exposure. Namely, not only high release of fission products to the reactor coolant occurs leading to high off gas levels, but also fuel washout is observed due to the direct contact of the fuel pellets with the coolant. With respect to these phenomena, Cr_2O_3-doped UO_2 fuel pellet shows an enhanced behaviour due to improved oxidation resistance and a reduction up to a factor of 5 of the washout rate in comparison to non-doped fuel [1].
- Accident conditions: Lowering internal rod pressure due to increased fission gas retention may then reduce ballooning of cladding during a depressurization accident such as a LOCA (loss-of-coolant accident). The higher intergranular gas retention may also have a favourable impact with respect to fuel fragmentation (reducing the fuel relocation in the balloon in LOCA). Finally, a reduction in the activity released from the fuel rods that fail is anticipated thanks to a favourable change in the transient fission gas release kinetics with chromia-doped UO_2 fuel. Tests are on-going to confirm these expected benefits.

2.2 Chromium-coated M5 cladding

The coating technology is being developed by Framatome and the CEA (Commissariat à l'Energie Atomique et aux Energies Alternatives) in the framework of the French Nuclear Institute in partnership with EDF (Electricité De France). The coating is deposited using a proprietary physical vapour deposition (PVD) technique that does not modify the underlying zirconium substrate's microstructure. It forms a dense layer with no porosity at the coating-substrate interface [3]. Metallic chromium coating was selected because it provides an optimal balance between high corrosion resistance and coating adherence and reasonable neutron transparency. The coating adherence remains in various conditions including irradiation in commercial power reactor. The Cr-coating thickness is typically in the range 10-20µm. This solution results in the following benefits:

- Normal operating conditions: Out-of-pile experimental test performed at Framatome facilities highlight low corrosion kinetics under standard representative PWR environments. Cr-coating also reduces the susceptibility of zirconium alloys to corrosion in high lithiated environments which may increase operational flexibility concerning coolant water chemistry [4]. Also, as chromium is harder than zirconium the wear resistance of the Cr-coated cladding is enhanced (see section 3).
- Accident conditions: Creep and ballooning and burst tests used for LOCA performance characterizations are being performed at CEA Saclay [5]. The creep tests highlight the strengthening effect of the Cr-coating at High-temperature (HT) on the overall thermal-mechanical response of the coated clad segments under internal pressure, especially in the 600-800°C temperature range (αZr). This induces an increase by a factor 2 to 3 of the time to rupture, for any given applied internal pressure. Hence, the chromium coating induces a significant reduction of the balloon size, especially in the "low-temperature" range (αZr). This may have some positive consequences on nuclear fuel sub-assembly "flow blockage".

  For the higher creep temperature range, even if significant ballooning occurs, the rupture opening remains very small (less than 1mm²) what could result in less fuel dispersal during a LOCA event. Moreover, steam ingress inside the clad segment should be reduced, thereby limiting the extent of the inner clad surface oxidation and the associated secondary hydriding phenomena following clad burst occurrence.

  HT oxidation tests in steam show that the chromium coating significantly reduced the cladding oxidation kinetics compared to conventional uncoated materials [6]. This means that Cr-coated M5 cladding can withstand longer times at temperature before reduction in the post-HT oxidation clad mechanical properties (i.e. ductility and strength).

  As a consequence, chromium coating provide significant additional margins for LOCA scenarios and, to some extent, for beyond LOCA conditions. All these aspects are further detailed in section 4.

3. Focus on some benefits for normal operations

3.1 Pellet-Clad Interaction (PCI) resistance

The PCI performance of the doped UO_2 fuel was determined with a comprehensive power ramp test program for both PWR and BWR applications [1]. The improved behaviour of the doped fuel yields PCI margins higher than those for standard UO_2 fuel. For BWR applications, the benefit is an increase of 70 to 100 W/cm of the power increment failure threshold in comparison to the standard liner or non-liner non-doped fuel failure threshold [2]. This allows considering the Cr_2O_3-doped fuel as an attractive substitute to the present BWR liner cladding in terms of PCI protection.

For PWR applications, results with Cr_2O_3-doped UO_2 show a power increment failure higher by 40W/cm than for standard UO_2 / M5 fuel rod design. Based on these later results, a PCI technological limit has been derived with the current Framatome licensed fuel rod code COPERNIC with some limited adjustments to correctly predict clad strain and fission gas release in transient conditions. In comparison to standard fuel, the PCI technological limit is enhanced by 35% with the Cr_2O_3-doped fuel.

To set-up a first margin assessment, a three-step process was implemented:

1. Calculation of powers to failure for the Cr_2O_3-doped fuel with its preliminary PCI technological limit.

2. Determination of power margins: comparison of powers to failure (step1) to Class 2 powers for the plant considered with its fuel management and operation mode.
3. Comparison between these margins (step2) and those obtained with standard UO_2 fuel.

This study carried out for two European PWRs plants concludes on a margin difference always positive for the Cr_2O_3-doped fuel with respect to UO_2 fuel. Depending on the configuration, i.e. initial conditioning state and Class 2 event, the margin difference ranges between ~30 to 85W/cm.

The extra margins obtained with the Cr_2O_3-doped fuel give rooms to enhanced plant manoeuvrability conditions. This can be tailored with case-by-case analyses depending on the degree of flexibility needed to operate more efficiently and economically NPPs. Flexibility options include frequency control (power changes are limited to a few %), load follow (power drops at more than 25% nominal power (NP) during a short period of time), limited power modulation (power decreases to as low as 75% NP) or Extended Reduced Power Operation (ERPO) to between ~20-90% NP for several hours or days.
For example, the extra power margin of 85W/cm with the Cr_2O_3-doped fuel translates in a significant increase in the number of power modulation, i.e. ~ 80 or the ERPO duration, i.e. 40 days at 50% NP.

3.2 Wear resistance

Continuous fuel improvements were implemented within the last decade to mitigate fretting wear which remains one of the major mechanisms of fuel failures for LWRs [7], [8]. Here, we distinguished:

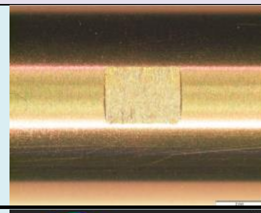
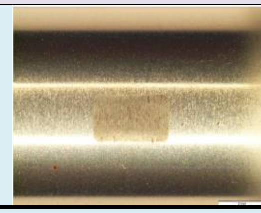
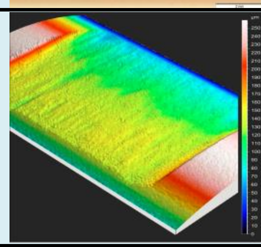
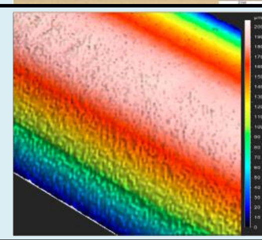
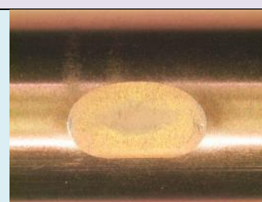
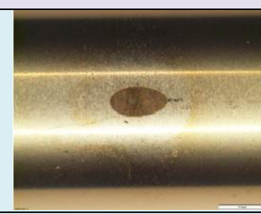
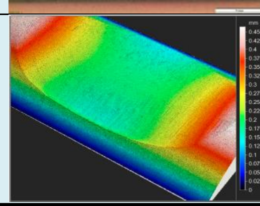
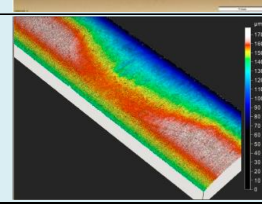
- Grid to rod fretting issues. They are due to premature loss of spring force, or to rod/assembly vibrations induced by turbulence and flow heterogeneities. Fuel rod wear is also observed for some plants in specific baffle locations where stainless steel rods are used in fuel assemblies to mitigate the phenomenon at the cost of a loss of fissile material and thus of power production.
- Debris fretting issues. Loose metallic debris circulating in the coolant can be entrapped in fuel assemblies leading to rapid fretting and penetration of the cladding wall. Failures can appear anywhere in the assemblies depending on the size of the debris.

For both topics, incorporating a harder surface on the rod cladding surface, as such with Cr-coating, can add wear resistance for enhancing the fuel reliability and performance. In this context, Framatome has launched several wear testing campaigns in the AURORE loop located at the Technical Centre of Le Creusot (France). Tests were carried out under a representative PWR coolant environment (pressure, temperature and water chemistry). To differentiate the wear behaviour of the 15µm Cr-coated cladding with respect to the un-coated cladding, the test conditions were intentionally fixed at much harsher conditions than what is encountered in reactor [4].

Different configurations were investigated to assess the cladding wear resistance with components of an AFA 3G grid cell (Alloy 718 spring and dimple), and with an AISI 316 wire brush. The main observations from these parametric tests are the following:

- Under continuous alternative sliding the Cr-coated cladding show enhanced wear behaviour although the friction energy was fairly more important than the one measured with the un-coated cladding. With the Cr-coating, the wear is mainly observed on the spring or the dimple, however, the overall wear (cladding and grid cell components) in volume and in depth is significantly reduced. Looking on the cladding -first confinement barrier- the maximal worn volume is divided by approximately 40 and 80 times for the dimple-clad and spring-clad configurations respectively.
  The table 1 displays some of the results obtained with a focus on the cladding.

- On contact of the wire brush, the Cr-coated tube shows a better wear resistance under alternative sliding and impact-sliding modes. It is also observed that the wear is significant on the wire brush in front of the Cr-coated sample. A precise quantification of the improvement factor brought by the coating is difficult because of problems encountered to have the same loading force or duration for all tests. However, we observed a cladding wear volume lower by a factor of 4.5 with the Cr-coating after 100h testing when the reference case was stopped after 23h. It is assumed that the true gain of the coating is much higher.

		Un-coated cladding	**15µm Cr-coated cladding**
Dimple / cladding tube	Wear depth (µm) / volume (mm^3)	141 / 0.629	12 / 0.015
	Visual appearance		
	3-D view		
Spring / cladding tube	Wear depth (µm) / volume (mm^3)	275 / 2.310	28 / 0.028
	Visual appearance		
	3-D view		

Tab 1: Cladding wear depth and volume in the Aurore tests with grid cell components

These first AURORE parametric test campaigns have enabled to differentiate the wear behaviour between a Cr-coated cladding tube or an un-coated one and its antagonists in a grid cell or with metallic debris. In all cases some significant improvements are shown indicating that only 10µm or so hard Cr layer add wear resistance to the fuel cladding. The use of Cr-coated cladding may therefore significantly reduce the number of defective rods due to grid-to-rod fretting, debris fretting or baffle jetting, thus providing economic benefits for utilities. Fuel failures have detrimental impacts on plant operating activities and costs, and increase workers' exposure. As it is strictly prohibited reloading leaking fuel, additional costs must be considered for identification of the defective components and their repair. Also, there are specific procedures for storage (wet and dry), transport of individual leaking rods removed from assemblies, etc. In all this could result in several hundreds of k€ per failure.

Additional wear test campaigns are on-going to enlarge the demonstration with various Framatome grid cell designs and a wider variety of metallic debris types.

4. Performance in LOCA conditions

To show the benefit of the Framatome E-ATF cladding, studies have been conducted focussing, for example, on the design basis accidental transient considered in France within the current regulatory framework, i.e. the Intermediate Break (IB) LOCA case.

A first study aims, through a unit sensitivity calculation, at illustrating the potential impact of the Cr-coated M5 cladding on an IB LOCA transient, in terms of core thermal-hydraulics and hot rod response, in strongly penalizing conditions where thermal-hydraulic behaviour load leads to rod failure and clad melting with un-coated M5 cladding. A second study aims, through comparative application of an advanced IB LOCA methodology of statistical type, at illustrating impact of the E-ATF cladding on an industrially orientated evaluation of the consequences of the design basis accidental transient..

Both studies are based on the use of CATHARE (Code for Analysis of Thermal-Hydraulics during an Accident of Reactor and safety Evaluation) code. This code is a two-phase thermal-hydraulic simulator in development since 1979 at CEA-Grenoble as part of an agreement between the CEA, EDF, Framatome and the IRSN (Institut de Radioprotection et de Sûreté Nucléaire). The software is based on a two-phase model with six equations (conservation of mass, energy and quantity of movement for each phase). The numerical method used is implicit in 0D and 1D, and semi-implicit in 3D. CATHARE is capable of simulating the physical phenomena that occur during a loss of coolant accident (small and large break LOCA), steam generator tube rupture (SGTR), feed water line break (FWLB), residual heat removal failure (RHR), or steam line break (SLB) [9].

Miscellaneous specific models, present in the base version of the code or developed and validated specially to improve representation of LOCA dominant phenomena are available in the CATHARE code version used. In particular, they concern:

- Clad oxidation, swelling and rupture
- Heat exchange surface reduction in case of clad-to-clad contact
- Flow section blockage in assembly under effect of clad swelling and rupture, and associated flow redistribution
- Fuel relocation at burst elevation following clad rupture
- Heat transfer enhancement following clad ballooning (convective heat-transfer and droplet effects)

Specific masks (adapted and additional code subroutines) were developed to take into account the improved features described in section 2.2 regarding the oxidation and overall thermal-mechanical response of the Cr-coated M5 cladding under accidental conditions, i.e.:

- Improved strength to deformation (reduced creep rate and total elongation at rupture)
- Slowed down oxidation reaction (reduced oxidation kinetics)

4.1 Impact of the Cr-coated M5 cladding on an IB LOCA transient

In order to perform this study, an intermediate break LOCA on a cold leg of a French three-loop (900 MWe) PWR, with subsequent loss of off-site power (LOOP), is considered. The break size is 15.4”.

One specific calculation leading to cladding burst is selected because of its strongly penalizing conditions, with severe consequences regarding cladding temperature, i.e. up to the melting of the reference un-coated cladding. The most significant improvements granted by the Cr-coated

cladding properties are likely to be better highlighted by such a case since this cladding may prevent or delay its own rupture in comparison to reference un-coated cladding.
Results show that burst is not prevented with the Cr-coated cladding. However, the exothermic oxidation reaction is slowed down and the maximum strain is significantly reduced, which means a less penalizing effect of the exchange area reduction due to clad-to-clad contact after burst. As a result, the maximum cladding temperature is significantly lowered than the one reached with a standard M5 cladding, as shown in figure 1.

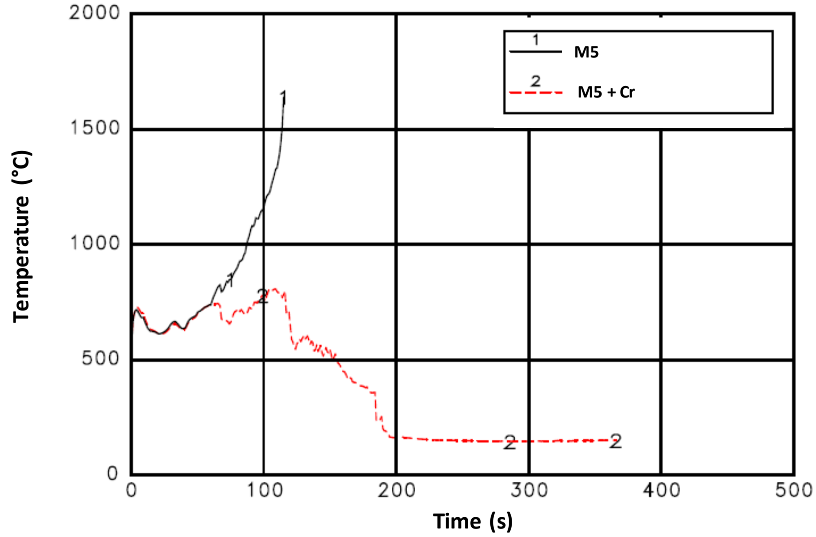


Fig 1: IB LOCA - Base case– Impact of Cr-coating on the hot rod peak cladding temperature

4.2 Impact of Cr-coated M5 cladding on an IB LOCA statistical series

The reference study for this evaluation consists in the application of an advanced Best Estimate Plus Uncertainty (BEPU) methodology to the case of a cold leg IB LOCA on a French three-loop (900 MWe) PWR. The break size is 15.4 inches. The scenario, reactor hypotheses, code and model parameters are intentionally penalized to maximize cladding temperatures and cladding bursts.
The target parameters of the study (safety criteria) are the hot rod Peak Cladding Temperature (PCT) and peak cladding oxidation rate in terms of Equivalent Cladding Reacted (ECR) calculated using the “Baker-Just” (BJ) correlation [10].

The methodology entails the realization of a series of 208 computations with random sampling of influent parameter values according to their probability distribution. According to Wilks’ method [11], the 6th highest PCT (resp. ECR) value obtained provides an estimation of $PCT_{95\text{-}95}$ (resp. $ECR_{95\text{-}95}$) (estimation of quantile 95% of PCT (resp. ECR) probability distribution with a confidence level 95%). The application of the advanced methodology (i.e. the series of 208 calculations) was repeated twice:

- Once for the Cr-coated cladding with all improved features described in section 2.2 regarding the oxidation and overall thermal-mechanical response.
- Once for the Cr-coated cladding will all improved features unless for creep rate, for which original M5 creep has been kept.

The objective of the second Cr-coated cladding application is to distinguish respective effects of reduced creep rate and of total elongation at rupture.

Results for the reference study and for both Cr-coated cladding applications of the methodology are presented in table 2 and figure 2 in terms of hot rod maximum cladding temperature and oxidation rate, and in figure 3 for maximum cladding deformation.

In the Cr-coated cladding series with all improved features, the number of cladding bursts is halved with respect to the un-coated cladding analysis. The maximum cladding deformations are lowered owing to the reduced creep rate and total elongation at rupture characterizing the Cr-coating cladding. Therefore, in case of burst, the heat exchange surface reduction due to clad-to-clad contact is lowered, leading to lower peak clad temperatures with the Cr-coated cladding. The $PCT_{95\text{-}95}$ remains below 850°C for the Cr-coated cladding, whereas it remains at ~1800°C for uncoated M5, which means that clad melting has been reached, causing end of calculation, for 6th highest PCTs of the series, as a result of the intentionally penalized conditions of the study. Finally, the $ECR_{95\text{-}95}$ value is reduced by a factor about 7 with the Cr-coated cladding.
Comparison of Cr-coated cladding series with improved creep law (CL) and with M5 original creep law shows that the improved creep law has a low impact on peak cladding temperatures and on ECR.

Cladding material	**M5**	**E-ATF without CL**	**E-ATF all features**
Nb. of cladding bursts	26	31	15
Hot rod max. cladding temperature (°C)	1800	845	820
ECR (%)	14	2	2

Tab. 2: IB LOCA - Statistical series: Impact of Cr-coated cladding on the hot rod peak cladding temperature and oxidation rate (Wilks' estimation)

The highest peak clad temperatures are obtained for ruptured rods. For the latter, the evolution of clad temperature after burst depends mainly on clad deformation after rupture through effects of heat transfer surface reduction and fuel relocation. The lower burst criterion (which mainly relays on local integrated strain energy) and narrower range of variability for total strain at rupture, which characterize Cr-coated cladding, result in lower deformations after rupture, and are therefore the main contributors to the benefits of E-ATF cladding in case of IB LOCA.

Due to the slower creep velocity law for the Cr-coated cladding, fewer calculations reach burst features before the core cooling conditions are recovered. The number of cladding bursts in the series is therefore strongly reduced with respect to the un-coated cladding analysis.
Nevertheless, for cases where burst will anyway occur because of high power or highly degraded core cooling conditions, the benefits from E-ATF cladding in terms of PCT and maximal ECR will be due to the reduced elongation at rupture (Figure 3).

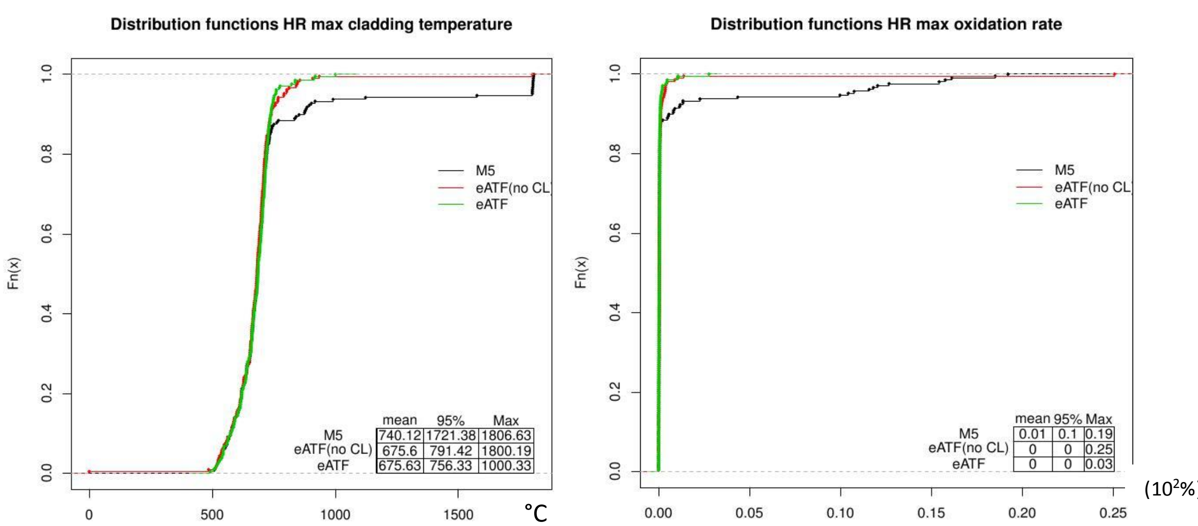


Fig 2: IB LOCA - Statistical series: Impact of Cr-coated cladding on the hot rod peak cladding temperature and oxidation rate

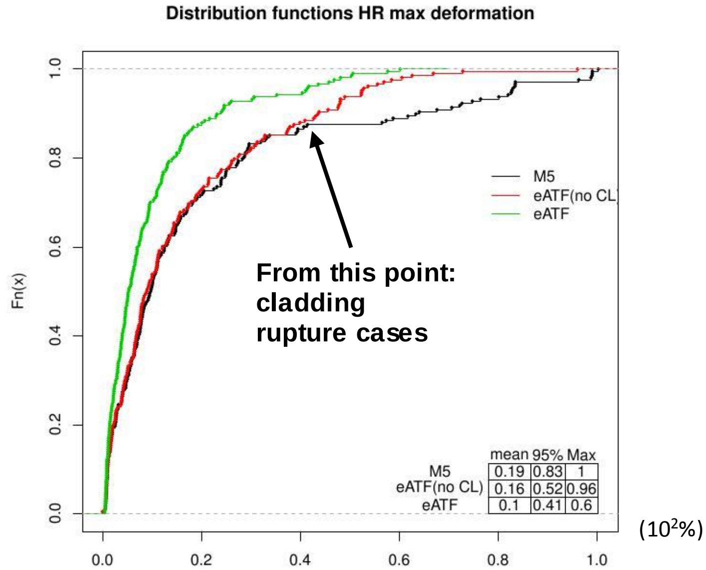
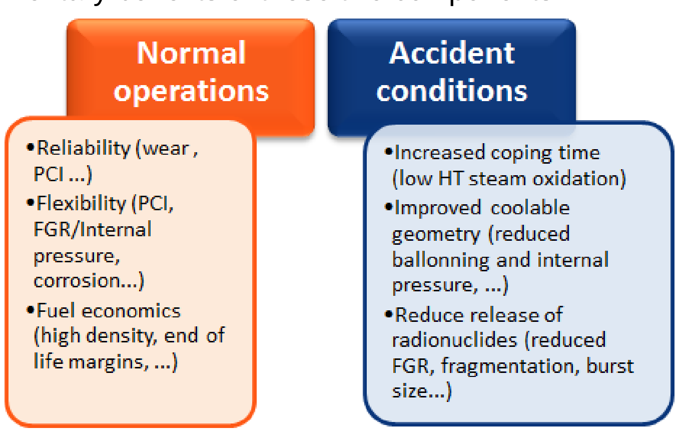


Fig 3: IB LOCA - Statistical series: Impact of Cr-coated cladding on the hot rod deformation

It is worth noting that these assessments constitute a first step and complementary analyses are needed to reinforce the conclusions. The results are highly dependent on the method, regulatory framework, assumptions, and specific analysis conditions. However, we anticipate that benefits will be seen also with other PWR types and with other methods than those considered here.
Future studies will refine the fidelity of the models and evaluate in more detail the potential LOCA accidents. For instance, studies will include updated fuel properties for the chromia-doped pellets, large break LOCA analyses, and US-based methods. Additionally, studies can be performed to demonstrate potential changes to the plant and fuel cycle design which could utilize the increased margin. Also, while the current concepts show limited benefit to severe accidents with no water, beyond design basis accidents can demonstrate the benefits achievable combining the design features with various equipment (such as FLEX) and flow rates.

5. Conclusions

The Cr-coated M5 cladding coupled with the Cr_2O_3-doped UO_2 pellets constitutes a robust and promising near term E-ATF fuel rod solution. Experimental results acquired so far highlight significant and complementary benefits of these two components:



The value assessment studies done to date show important improvements in fuel performance providing economic benefits for utilities and safety margins:

- For normal operations, the enhanced protection against PCI of Cr_2O_3-doped UO_2 pellets translates into power margins allowing upgrading LWRs manoeuvrability with the implementation of modulations of power (up to 80 more per cycle) or longer operation at low power (up to 40 days at 50%PN).
  On the other hand, Cr-coating adds wear resistance to the cladding enabling to significantly reduce the number of defective rods due to fretting phenomena or baffle jetting.
- For LOCA-accident performance, the Cr-coated M5 cladding reduces high temperature metal-water reaction and early tests on un-irradiated cladding have shown reduced balloon and burst size. For high peak cladding temperatures, the reduced oxidation and reduced energy addition from the limited metal water reaction provide more margins in the retention of cladding ductility. The results obtained with an advanced IB LOCA methodology show that the Framatome near-term E-ATF cladding solution benefits significantly from the reduced balloon and burst size. These results are promising for the Large Break (LB) LOCA studies.

In the near time, more analyses will be performed to support these material benefits and more analytical studies exploring normal operational benefits, a wider span of accident scenarios will demonstrate their significance and potential value to the plants.

Acknowledgments
The authors would like to thank the CEA and EDF for the collaborative work within the French Nuclear Tripartite Institute.
Some of the data presented in this article is based upon work supported by the U.S. Department of Energy under Award Number DE-NE0008220 with Framatome Inc.

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