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From observation to understanding:
Approach to analysis of wear mechanisms,
Case of RCCAs and CRDM latch arms

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Abstract

Component wear can affect the ability of a component to fulfil its required function. For a designer or user, it is reasonable to expect possible wear occurrence as soon as parts are in relative motion. It is less obvious to extend this possibility to motions with small or very small amplitudes and loads. However, it has to be admitted that such cases exist. It then becomes imperative to determine the wear mechanisms so that the lifetime of the components and the optimum date of their replacement can be predicted or the degradation can be remedied. For this purpose, standard and widely accepted practice is to carry out simulator tests.

Through examples of wear from nuclear reactor components such as the RCCAs (Rod Cluster Control Assembly) and the CRDM (Control Rod Drive Mechanism) latch arms, an approach for understanding the wear mechanisms and controlling their effects can be undertaken.

Cases of wear have been observed on real-life parts, but the first simulator tests have shown deviations from in-reactor behaviour. Comparative examination of the wear facies of actual parts which have operated in reactor or simulators, both control rods and CRDM latch arms, was the key starting point for a new analytical approach, incorporating the formulation of wear mechanism hypotheses which can account for the observed facies. Expert assessment thus highlighted the importance of the environment by revealing that the wear featured a large component linked to friction-assisted corrosion. By including this tribocorrosion aspect, it became possible to reach understanding of the mechanisms and account for the wear observed in reactor and on simulators.

Further well-controlled simulator tests then made it possible to verify the importance of the tribocorrosion processes in a pressurized water medium. Analysis of the physical-chemical behaviour of the original materials (austenitic stainless steel) also explains why these surface modifications limit or remedy wear-induced degradations, which accounts for the supply of more than 4000 RCCAs whose nitrided rods do not exhibit any quantifiable wear in the treated zones.

Keywords:

Wear, Nuclear reactor, Tribocorrosion

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1 Introduction

As soon as the decision was taken, in the mid-70's, to generalise electricity generation using nuclear power plants, it became evident that the PWR concept had economic advantages over the graphite -gas concept, but above all that nuclear power-generating reactors could fit the electrical current offering to demand. Load follow and frequency control were therefore included very early in the French NPP specifications. As this type of operation could not be provided entirely by controlling the reactor coolant system boron content, the need arose for the RCCAs (Rod Cluster Control Assembly) to participate in reactor control.

As a result, the designers took into account in their development the possibility of RCCA wear and the need to adapt preventive solutions. This is why loose-contact guide tubes and surface treatments (such as ion-nitriding) of the rods were envisaged as early as 1975.

Beyond the simple development of wear remedies and their validation, the key question remains the lifetime of these components. This is why simulation and wear tests, motion models and mechanical strength calculations must go hand in hand.

To put in context the components which will be covered (RCCAs and CRDM latch arms), Figure 1 presents a schematic of a PWR: the CRDMs are in 7, the RCCA guide tubes in 6. Figure 2 presents the continuous guidance system and the guide cards. Figure 3 presents an RCCA and the detailed view of a control rod. Figure 4 presents the CRDM latch arms in open and closed positions on the drive shaft.

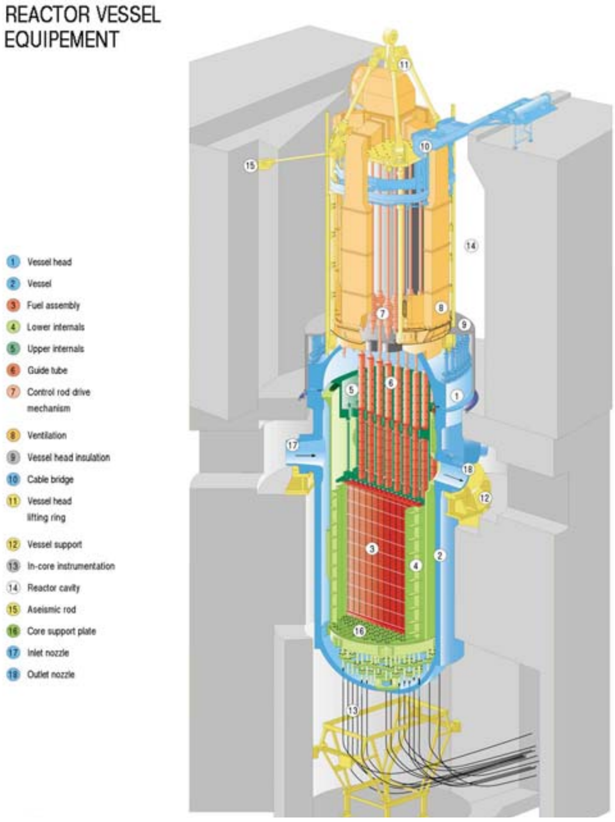

Figure 1: Schematic of a PWR:
3: fuel assembly
7: CRDMs
6: RCCA guide tubes

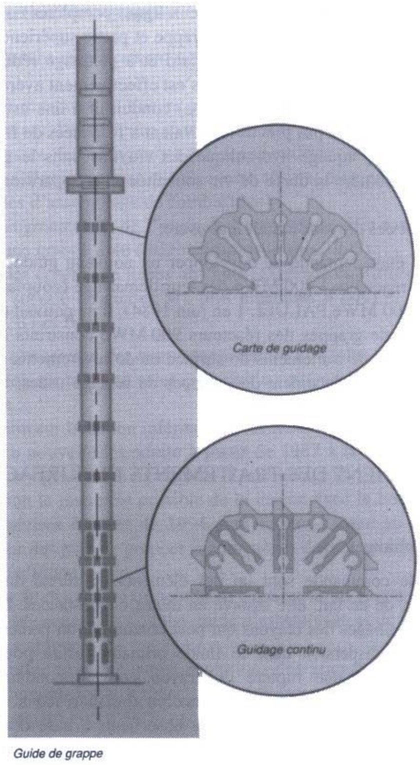

Figure 2: Continuous guidance system and the guide cards

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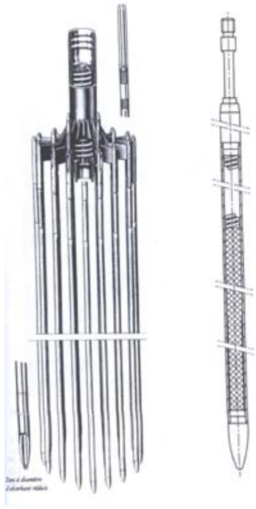

Figure 3 : RCCA and the detailed view of a control rod

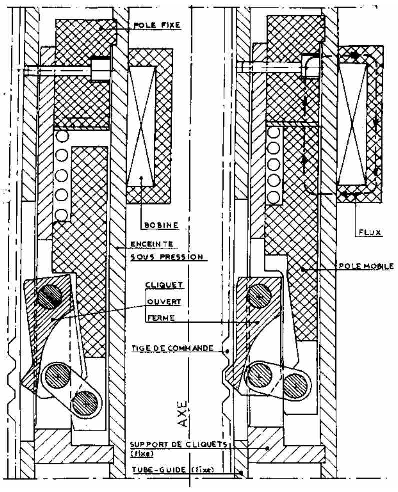

Figure 4 : CRDM latch arms in open and closed positions on the drive shaft

2 Wear remedy validation history

2.1 Premises

To validate the concepts developed, wear tests were run as early as 1978-79 in the SUPERBEC test loop. This comprised a vertical NSSS section containing 4 fuel assemblies, 2 control rod drive mechanisms (CRDM) with their RCCA and guide tube and could operate in pressurized water. Working with real components and operating in the primary environment with real motions, this accelerated test loop was considered as representative and therefore fit to perform the desired validations. These tests validated the benefits of loose-contact continuous guidance systems to limit the wear of the control rods or of coating the rods for example with a chromium carbide coating sprayed with a detonation gun (LC1C).

Subsequently, further wear tests were run on the FROTTEAU simulator at the CEA. Also operating in pressurized water, it simulated contact between a control rod and the continuous guideway over a length of ~85 mm. The tests run between 1985 and 1988 demonstrated the adequacy of the surface coatings and treatments for remedying sliding wear and among them, the superiority of the ion nitriding treatment [1]. Figure 5 presents these results for coated or uncoated AISI 304 steel claddings, rubbing against an AISI 304 steel guide.

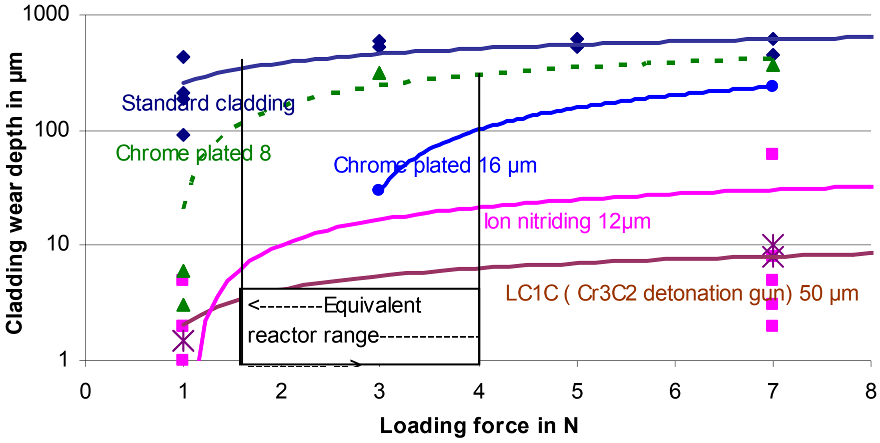

Figure 5: Wear depth for a 15 km test versus hard contact force (FROTTEAU simulator 320°C, 150 bars, 2.5Hz) for different claddings (Stainless steel, ion nitrided, chrome plated and LC1C coated)

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The actual restraining forces and those to be deployed in the FROTTEAU tests had been previously calculated from the geometry of the components and the corresponding hydraulic flows.

However, in 1983 in the US then in 1986 in France, RCCA wear was evidenced in the area of the guide cards, mainly on the shutdown RCCAs (non-treated or coated) which underwent only a small number of steps. This new form of wear, initially called "impact fretting wear", seemed to challenge the estimation of the control rod degradation modes which had led to only longitudinal fretting wear being considered. The wear remedy development therefore moved in four new directions:

- develop a simulator which will enable the motion of the RCCAs to be measured so as to validate the calculations and the parameters of the wear simulators
- validate through vibration wear tests that the ion nitriding treatment also combated this form of wear
- develop a hydraulic solution for this wear mode by increasing rod restraint
- develop a means of monitoring the wear condition of the RCCAs in the reactor.

This is why Framatome ANP's MAGALY loop was built to study, in cold water, the displacements of the rods of an RCCA under the effect of different hydraulic flows. It deploys an actual RCCA and guide tube, together with the top end of a fuel assembly [2]. The measurements provided evidence as early as 1992, that some rods vibrated in the guide cards in a motion composed of a slow rocking superimposed by a higher-frequency vibration.

Vibration wear tests in pressurized water were conducted at the CEA in the VIBREAU I simulator. The applied test conditions were those which gave significant wear on an untreated steel cladding during testing. Applied to nitrided tubes, these conditions confirmed that the strength of the nitrided tube was complete. On the other hand, it became apparent that the wear partner made of AISI 304 steel saw its wear grow by a large factor. This consideration, transposed very hastily to real-world conditions, always left room for doubt about the real strength of the guide cards when facing nitrided, or even coated RCCAs (1997-98). In fact, it appears that these tests could not be judged representative since they also led to significant ovalization of the claddings, which has never been observed during the numerous in-reactor RCCA inspections.

To mitigate the lack of representativity of the VIBREAU simulator, EDF and the CEA developed other installations such as VIBRATEAU et VIVREAU III, then equipped themselves with instrumented AECL machines. For its part, Framatome ANP at this time developed and operated a series of AURORE simulators (with orbital motion of pure sliding, pure impact or sliding impact), of which the latest generation can monitor at any time the dynamics of the motions, the impact and contact forces and measure the friction coefficient and the total wear of the partners.

Framatome ANP also developed a similar installation, also instrumented for forces and displacements, enabling representation of rod contact in the continuous guideway in longitudinal motion (FANI).

2.2 Expert assessments of standard worn RCCAs

Rapid wear of standard RCCAs (RCCAs not wear-treated) observed at the first RCCA inspection after 3 cycles and leading to rod perforation, has led EDF to perform hot lab assessment of the worn control rods facing the cards [3]. The wear traces appear very smooth, free of any oxide layer (compared with the adjacent zones) and without strain hardening marks. The cup-shaped facies points to the wear in the area of the cards not being due to peening (by impact) or to polishing (by friction) of the surface, but it could be linked to a corrosion wear mode. Figure 6 shows an example of the wear facies encountered.

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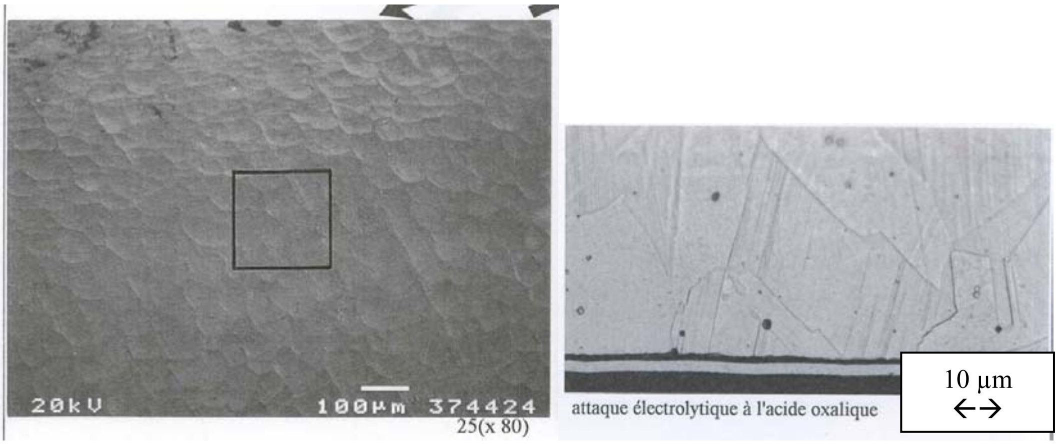

Figure 6 : Surface appearance and cross-section (with nickel coating) of a worn control rod zone

At this stage, it appeared essential, in a logical approach to understanding wear phenomena, to acknowledge that progress in understanding of wear phenomena must rely more on thorough characterization than on uncertain application of a theory or simply applying computer codes.

3 Case of the CRDM latch arms

3.1 Findings and hypotheses

More recently, the question was raised of wear of the latch arm teeth made of Stellite (cobalt-and carbide-based alloy exhibiting electrochemical characteristics in a primary environment similar to those of the austenitic stainless steels of the RCCAs). The CRDM latch arms seem to wear 4 times more in reactor than in loop. However, the loops used contained true mechanisms in a quite similar pressurized water environment and had cumulated an identical number of movements.

The setting-up of a multidisciplinary, multicompany working group (EDF, Jeumont Industrie and Framatome ANP) enabled the phenomena to be analyzed and hypotheses to be proposed [4]. Figure 7 shows a worn latch arm seen in macroscopic cross-section, at the surface and in microscopic cross-section.

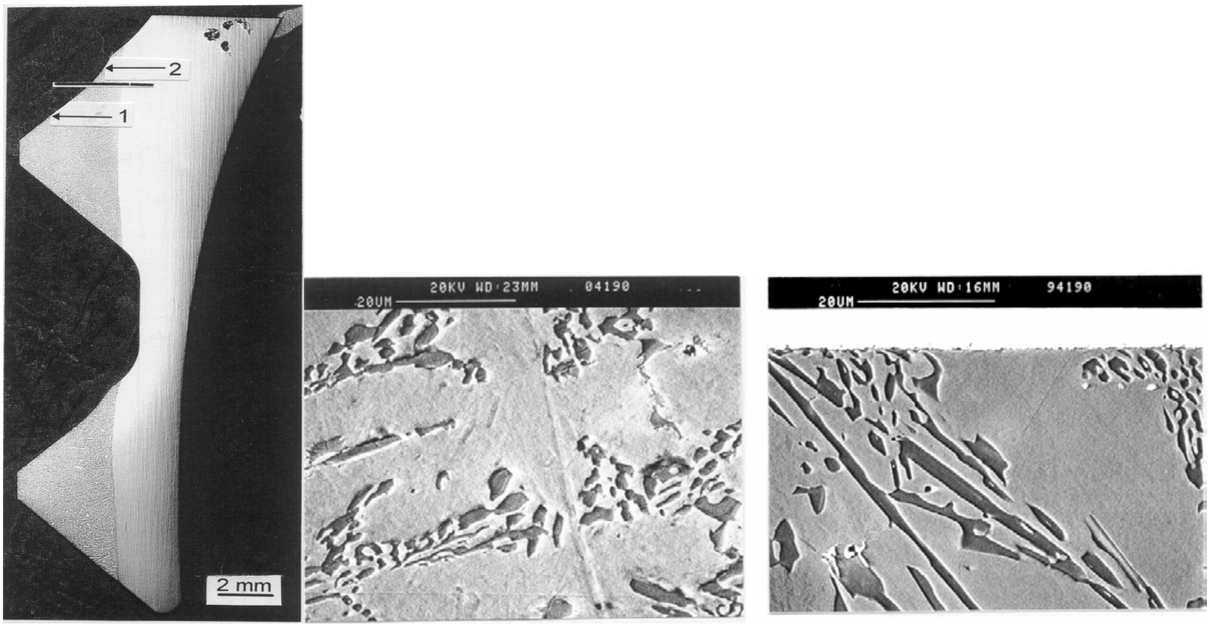

Figure 7 : Macroscopic and metallographic cross-sections and surface view of a latch arm

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The hypothesis put forward to account for the various observations (polished surface, absence of strain-hardening marks …) calls upon a tribocorrosion mechanism : degradation, during friction of the latch arms against the drive shaft, of the passive layer hard-faced with Stellite, then dissolution of the chromium-depleted metal matrix and re-formation of a chromium oxide-based passive layer. At an equivalent number of loadings, the loss of material will increase in proportion to the duration between two movements and will therefore leave the corrosion phenomena (dissolution and passivation) the time to develop. The Ford corrosion model [5] describes the trend of a corrosion current after depassivation :

$i_t = i_0(t/t_0)^{-n}$ in current quantity

(where t is latency time, i_0 and t_0 are constants dependent on the nature and the depassivated surface, n a parameter depending on the corroding medium)

or in corroded mass $m = k\ (t/t_0)1^{-n}$

Considering a realistic value n = 0.7, an average value of the latency times for the loop tests of 0.92 s and for the reactors which have undergone the most 100 s stepping movements gives the factor 4 observed in reality for loop test and site latch arm wear ($100^{0.3} = 3.98$ and $0.92^{0.3} = 0.98$).

3.2 Experimental validation

Tests carried out on Stellite against an alumina ball, initially in H_2SO_4 1N environment (Ecole Centrale de Paris) then in pressurized water (Framatome ANP, AURORE loop) showed that continuous friction indeed led to less Stellite wear than discontinuous friction with latency time. In these various environments, the Stellite wear follows Ford's law with exponent values of this law of ~ 0.8 in cold demineralized water, 0.3 in H_2SO_4 1N and 0.7 in pressurized water. The differences between these coefficients can be attributed to those of the characteristics of the oxide layers and dissolution rates of the metal. It is however remarkable to note that the same law applies, which means that the phenomena can be considered as similar.

However, many questions remain on the actual mechanisms, particularly the degradation of the passive layer during friction.

4 Simulator demonstration of RCCA tribocorrosion phenomena

The incorporation of the tribocorrosion approach, established in the case of the CRDM latch arms and in the case of the RCCAs, has enabled significant advances to be made.

The transposition of one equipment item to another relied upon the fact that the wear affects in both cases a passivatable material and that the wear facies exhibit close similarities.

Figure 8 presents the principle of the AURORE test machine, instrumented for forces and displacements and controlled by the action of electromagnets acting on mild steel parts integral with the tube support.

The possible movements (pure impacts, pure sliding or impact-sliding-detachment) reflect the contact of a rod with a guide card, for example where the point of contact on each of the partners can undergo at each cycle an interaction with the environment.

The application in Framatome ANP's AURORE simulator of the contact pressure parameters and kinematics arising from data analysis of the MAGALY tests reproduced the fast wear modes observed in reactor.

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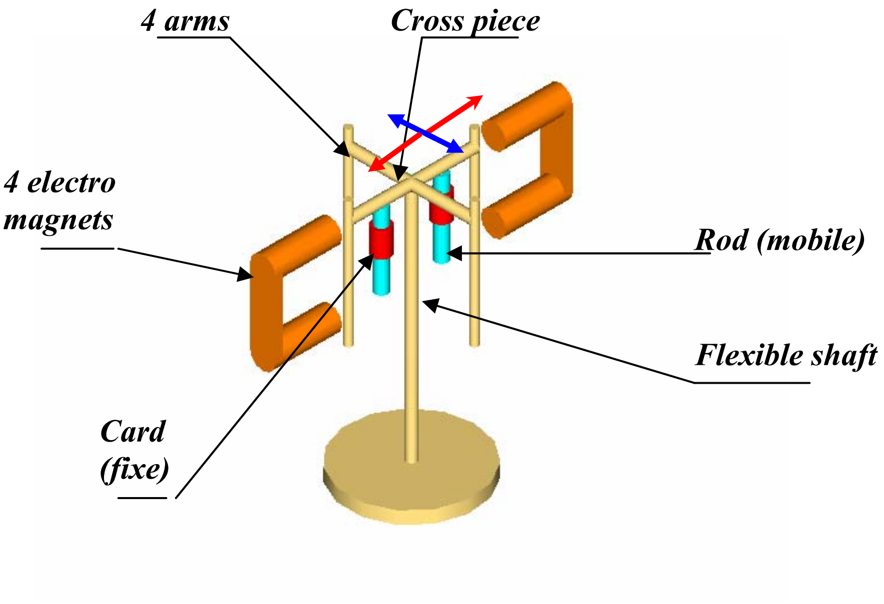

Figure 8 : Principle of the AURORE test machine

The wear facies and kinetics are fully comparable [6] as shown in the facies in figure 9.

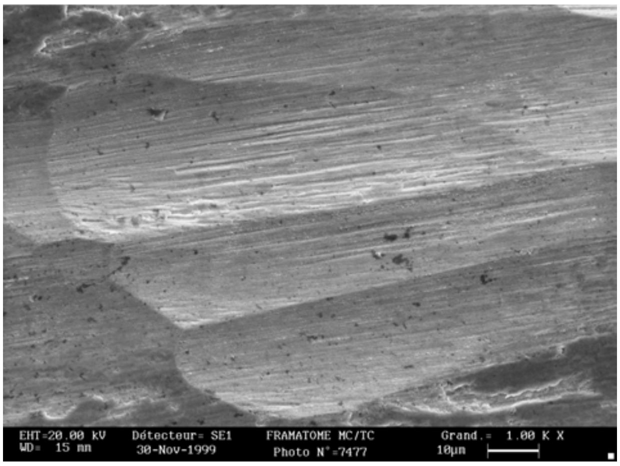

Figure 9 : Wear facies of AISI 304L steel in impact-sliding-detachment wear loading

The evidence is that the impacts do not cause wear, the continuous sliding induces slight wear (but the cup-shaped facies is not encountered), the impact-sliding (-detachment) loadings lead to a wear representative in facies and kinetics. More complete results are presented by D.Kaczorowski [6, 7].

The activation of a wear mode by tribocorrosion during impact-sliding loading in AURORE is clearly highlighted by comparing identical test results in different media: at pH 5 (water with boric acid without lithium) the weight loss is ~ 7 times larger than at pH 7 (water with boric acid and no lithium), without any change in cup-shaped facies.

For a contact between two austenitic stainless steel parts simulating rod - guide card contact, the facies and kinetics are of the same kind for both partners. The following table reports the results observed with non-treated and nitrided tubes.

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Table 1 : AURORE test results PWR medium, 300°C, 154 bar, card in AISI 304 L orbital movement (impact-sliding), loading force 15 N, 10 Hz

Tube	**AISI 304 L**	**AISI 304 L**	**AISI 304 L**	**Nitrided AISI 316 L**
Time in h	**8**	**70**	**150**	**160**
Total wear depth in µm	/	14	47	30
Tube weight loss in mg	1.09	26.55	60.99	0.03
Card weight loss in mg	0.46	5.72	11.41	12.24

For a contact between a nitrided tube and a steel ring, it is clearly observed that the tube wear is null but that of the wear partner remains the same order of magnitude and does not appear modified by a significant factor.

The conclusion is that the wear strength of the nitrided tubes in a tribocorrosion mode is probably not due only to superficial hardening but to the improvement in corrosion resistance of the austenitic matrix. The nitrogen diffusion results in reinforcement of the material non-oxidizability, visible in the rise in equilibrium potential. Admittedly, the superficial zone and that of the grain boundaries can appear as sensitive to localized corrosion, but this is not the reflection of the overall behaviour. This hypothesis is reinforced by the tests presented by Lee [7] on the degradation of the wear strength in salt water of stainless steel nitrided under classical conditions, in other words exhibiting segregation of the nitrogen-rich austenite into chromium nitrides and chromium-depleted ferrite.

Moreover, longitudinal contact wear tests were run in Framatome ANP's FANI loop whose principle is shown in figure 6. A hydraulic jack imparts reciprocating motion to a rod filled with a magnetic mass pressed against the guide by electromagnets. The assembly is immersed in a pressurized water flow. In the sliding motion, it can be considered that the point of contact on the tube can undergo interaction with the environment, whereas it more limited on the guide contact zone.

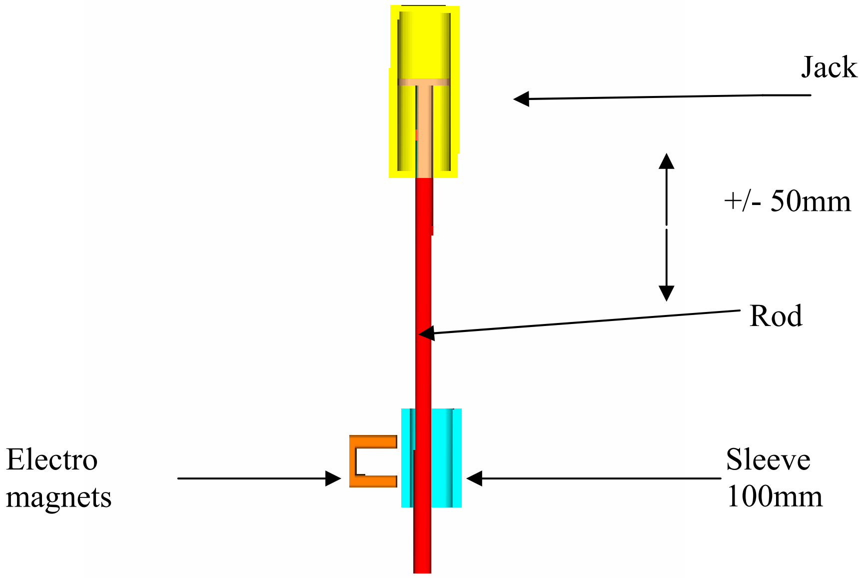

Figure 10 : Operating principle of the FANI simulator

The tests carried out between control rod claddings (nitrided or otherwise) and guide sections (made of steel or Zircaloy) led to the results presented in table 2.

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Table 2 : FANI wear tests, continuous sliding 10 km
285°C, 100 bar, loading force 3N, speed 0.2 m/s

Tube	Guide	Tube wear coefficient ($10^{-12}Pa^{-1}$)	Guide wear coefficient ($10^{-12}Pa^{-1}$)
AISI 304 L	AISI 304 L	1.1	1.3
Nitrided AISI 316 L	AISI 304 L	0.013	0.056
AISI 304 L	Thimble tube (Zircaloy 4)	0.19	3.0
Nitrided AISI 316 L	Thimble tube (Zircaloy 4)	0.044 *	0.3 *

* Length : 5.27 km only

It can be seen that, in this case, the nitriding treatment reduces by a significant factor the wear of each of the two friction partners. This result is distinct from the trend observed in the AURORE tests.

Owing to differences of shape and materials, the tests on the Zircaloy 4 guide thimble and on steel cannot be fully compared. On the other hand, the effect of modifying the tube surface state does not cause any modification liable to disturb the comparisons. The representativity of the facies can only however be fully established after observation of the worn RCCA rod zones in contact with the continuous guideway or in the area of the guide thimbles. However, the likelihood of the motions and restraining force, together with the matching of the nitriding effects on the rod wear, lead to the conclusion that these results are realistic.

5 Hypotheses on the wear mechanisms

The above-presented results tend to validate the importance of the tribocorrosion phenomena in the wear of components made of passivatable metals immersed in the pressurized water of nuclear reactors. However, some questions remain unresolved, such as the origin of the degradation of the passive layers and the different behaviour in impact, sliding or impact-sliding motions. Further, the change in wear strength of the partners during nitriding of one of the components needs to be looked at more closely (status quo or improvement by a very significant factor?).

Based on the findings for the real worn components and the results obtained from instrumented simulators (normal and tangential forces, motions and speed, electrochemical potential …), some hypotheses on the mechanisms can again be put forward, which will need to be validated by additional tests.

5.1 Degradation of passive layers

It seems unrealistic to consider that a passive layer a few nanometers thick applied to a surface whose roughness is of another order, can be degraded only by a friction-related mechanical effect. As a result, the work on the friction of the ceramics and their impact on the occurrence of electric charges at the surface of the components [8] has led to the hypothesis of formation at the surface of the materials of a network of electric charges. Figure 11, proposed by Nakayama [9], illustrates the effects that can be induced by friction of two parts against each other.

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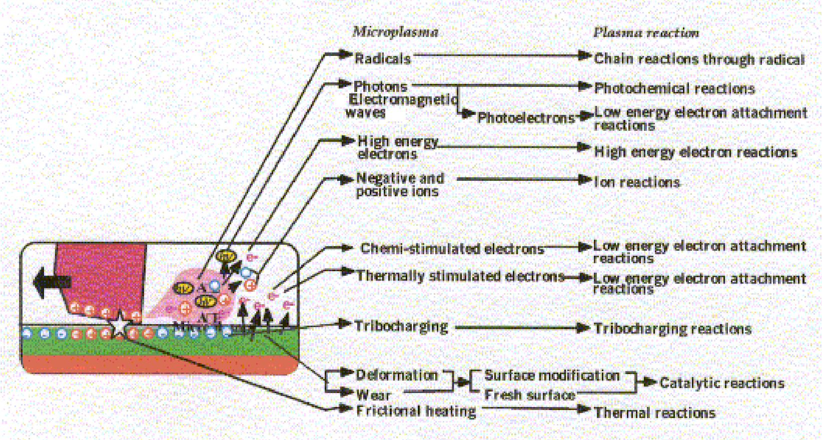

Figure 11 : Triboelectromagnetic phenomena and tribochemistry [9]

Admittedly, the phenomena associated with a microplasma are scarcely likely in liquid medium, but the production of electric charges, their mobility at the conductive surface of a metal or on the contrary their low mobility at the surface of a low-conductivity metal are plausible phenomena. The electrical charges produced by friction are not stable with time. They could return to a stable equilibrium state through mutual destruction (this is facilitated by the friction itself) or in case of detachment of the components through electrochemical reactions dissolving the metal species or reduction of the oxides. The friction tests with potential tracking indeed show that the observed potential is as low as the displacement speed is high (which can also be the sign of a larger depassivated surface) and that the passive layers can disappear even outside the friction mark.

The passive layer degradation (a few tens to a few hundreds of nanometers) could therefore be linked to a phenomenon of destabilization of the oxides, owing to electrochemical reactions induced by the return to equilibrium of friction-induced, low-mobility electric charges on a non-conductive surface.

The polarisation induced at short distance by such charges could also account for the change in the later sensitivity of the worn surfaces.

Beyond an effect linked to depassivation, this hypothesis of charges in metastable equilibrium on rubbing surfaces can account for behavioural differences between sliding motion alone or impact-sliding-detachment. Also, it could explain the behavioural trends during treatment of one of the components, presented in the following paragraphs.

However, it still remains to establish the key factors of the wear phenomenon (pressure, charge, surface, speed, environment, materials…) and to formulate a model of the same type as Archard's law applicable for abrasive wear. Tribocorrosion results were modelled in a law, presented by Mischler [10], linking wear by tribocorrosion with the parameters of rubbed length l, depassivation frequency f, density of charges required to repassivate the surface of the friction mark q, normal force F_n and hardness H in N/mm^2:

$$U = k.l.f.q\,(F_n/H)^{0.5}$$

However, this law does not account for the results of the tests carried out in the context of the wear of the RCCAs and CRDMs. It cannot therefore be considered as universal.

5.2 Differences of wear kinetics between sliding and impact-sliding

The steel/steel contact axis in the AURORE orbital pure sliding tests is renewed on each of the components during the motions. Conversely in the FANI tests, it is partially

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renewed on the tube and not on the guide. As a result, the regeneration of the environment can induce significant differences in repassivation and dissolution of the surfaces laid bare. The electric charges generated by friction could therefore flow better in the continuous contact of the FANI tests than in the discontinuous one of the AURORE tests.

Thus, during discontinuous friction, the mechanical wear effects would be combined with order one tribocorrosion effects (linked to the re-formation of a passive film after its degradation) and the electrochemical effects linked to the return to equilibrium (by dissolving of the metal and repassivation) of the electric charges created by the friction, with reduced mobility on surfaces. It is this second tribocorrosion effect, induced by detachment of the two components, which would explain that the impact-sliding-detachment motions are more wearing than sliding alone. This is what is indeed revealed by AURORE tests in impact-sliding-detachment or in pure orbital sliding, for equivalent sliding lengths and contact forces.

5.3 Behaviour trend of the wear partner during nitriding of one of the components

It was noticed that in a pure sliding test (FANI or AURORE) the nitriding of the tube induced a decrease in the wear of the partner (see table 2). On the other hand in an impact-sliding movement, nitriding does not induce an obvious reduction in the wear of the partner (see table 1). The transposition of these results to reality is not easy, as it also includes other effects such as breaking-in of the surfaces, which can induce an increase of the restraining forces in the continuous guideway.

Lastly, it can be considered that nitriding modifies the density of electric charges created by friction on steel. Electrochemical wear of each of the contact partners will be dependent on the density of electrical charges, their mobility and their neutralisation mode. But nitriding scarcely affects the behaviour of the nitrided tube because it is more corrosion-resistant.

These interpretations are fully consistent with the experience feedback from HARMONI RCCAs: the wear-induced degradation of the rods was drastically reduced without any significant consequences for the wear of the guides, whose effects on drop time trends would have been visible.

6 Discussion on the wear mode analysis approach

Independently of the test results and hypotheses on the wear mechanisms, it is worthwhile considering the approach which leads to obtaining them.

As shown by the above examples of RCCA and CRDM latch arm wear, if the real system cannot be instrumented or all the parameters perfectly known, simulators (representing a system in its entirety) and tribometers (analyzing individual phenomena) are used to approach these phenomena. Two options are then open, which are differentiated by the factors in table 3.

Table 3: Two-approach method for analyzing wear

System	**Simulator** Not instrumentable and global	**Tribometer** Instrumented, Special-purpose
Components	Actual	Cut from real parts
Tests	Expensive and cumbersome	Simplified and less expensive
Expert assessments	Costly and limited	Varied
Loadings	Real (or supposed to be), complex	Known (loadings, frequencies, displacements, …)
Observations	Observed at end of test - Sliding change - Wear	Tracked during test - wear, transfer of material - friction coefficient
Examples (as in RCCAs)	Reactor SUPERBEC, HERMES loops	MAGALY, AURORE, FANI Pin-disk tribometer

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In fact, one of these approaches cannot take precedence over the other. The wear mode investigation calls into play one then the other.

Initially, it is essential to be able to observe worn parts taken from reality or a very similar system; this allows the most likely degradation modes to be selected.

It is then considered essential to search for the exact conditions of the encountered wear mechanisms and to isolate them. To be representative of the effectively activated wear mode, the tests will have to feature similar wear kinetics and facies (including shape and dimensions).

The simulator tests would be much too cumbersome to carry out this "parametric" study and determine realistic wear laws. On the other hand, they are valuable for obtaining wear kinetics and facies (provided they are sure to be representative) and for consolidating the above-mentioned partial conclusions during a full-scale test.

7 Conclusions

The understanding of the wear mechanisms is a multi-faceted approach. The corrosion-related component must now be systematically taken into account, as shown by the analysis of wear phenomena in the PWR environment.

The activation of one or both mechanisms leading to heavy wear depends on the loading range, which means that a test will only be representative if the wear mode is the same as for the real-world case. This necessary but not sufficient condition requires, among other things, that the loadings, environment and wear partners be realistic.

The observation of real heavily worn parts is an important step in identifying the major mechanisms among those it is possible to encounter.

A full-scale simulator is often needed to determine the loadings applied in the contacts, wearing or otherwise.

The input of these wear conditions into dedicated tribometers enables the wear modes to be studied and the laws to be determined. To assess their representativity, the approach is to compare as a minimum the wear kinetics (having reached a judgement on their linearity) and the facies which bear the signature of the wear modes.

It is in fact only at this stage that the wear laws, parametered by the simulator tests and validated by comparison with real conditions, can be input into computer codes. In this way, the lifetime of the components can be extended.

At all events, it should be kept in mind that a wear test does not represent reality: it is designed to represent a mechanism activated for the applied test conditions An attempt is made during the tests to reach the most severe wear mode that can be encountered In reality, this severe wear mode can be blocked or masked by other factors.

For the RCCAs for example, it is well-known that only some rods wear, whereas they are all subjected to similar loadings. A few rods may follow trends such as those revealed by the AURORE tests, but most of them are in more permanent sliding and are therefore represented by the configuration of a FANI type test.

Conclusions on the wear of the guide tubes cannot therefore be drawn from the test results as the latter do not include all the real-world phenomena. However, the excellent experience feedback confirms the sound basis of the nitrided RCCAs.

Beyond the wear of the latch arms or RCCA rods, this approach opens new prospects on the wear tracking of other components, such as the flux thimbles of the in-core instrumentation system. In an even broader perspective, this approach offers new bases for the interpretation of the wear data deriving from experience feedback and the running of accelerated wear tests.

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