18th World Conference on Nondestructive Testing, 16-20 April 2012, Durban, South Africa

Optimization of EDF's NPPs Maintenance due to Flow Accelerated Corrosion and BRT-CICEROTM Improvement by NDT Results Analysis

Stéphane TREVIN, Marie-Pierre MOUTRILLE

Material Mechanisms Testing, General Technical Direction, EDF; Grenoble, France
Phone: +33 476202499, Fax: +33 476202559; e-mail:stephane.trevin@edf.fr, marie-pierre.moutrille@edf.fr

Abstract
Flow accelerated corrosion is very effective for nuclear power plant and fossil power plant. This generalised corrosion can lead to the rupture of pipe and in some dramatic cases killed operators. The influencing parameters are the: pipe isometrics, chromium content of steel, chemical conditioning and operating parameters of the elementary system (temperature, pressure, flow rate, humidity). This degradation is effective between 75 & 300°C on carbon steel and particularly active around 150°C. A software, BRT-CICERO™, is implemented to predict thickness losses and to schedule thickness measurements to prevent leak or rupture and also to manage the maintenance operations.
This paper deals with the maintenance optimization realised at EDF using X-ray fluorescence analysis of pipe components materials and the wall thickness measurement made by UT analysis in correlation with FAC degradation calculation during the outage using BRT-CICERO™. Moreover, the minimum thickness measured on inspected components is used to check the performances of BRT-CICERO™.

Keywords: Flow-Accelerated-Corrosion, X-Ray Fluorescence, UT, minimum thickness, BRT-CICERO™.

1. Introduction

Among the various degradation modes that causes pipe wall thinning in the secondary system of Nuclear Power Plants (Corrosion, Galvanic Corrosion, Environmental Corrosion, Flow Accelerated Corrosion, Cavitation, Droplet impingement, Erosion and Abrasion) FAC is the one that is the more widespread in the installation [1 - 3] and that requires constant efforts to fight. The wall thickness loss due to FAC can effectively occur in any carbon steel piping containing hot water or wet steam and can lead to pipe ruptures with dramatic consequences.
Electricité de France operates 58 Pressurized Water Reactors that were put in service between 1977 and 1997. The degradations and leaks due to FAC that EDF has experienced and the numerous accidents that have been reported abroad, lead EDF to develop a global strategy to control FAC on piping and to prevent any dramatic rupture. This global strategy is based on a National Maintenance Rule which has been written by the corporate engineering level of EDF called "RNM" and applied by every Nuclear Power Plant operator of the EDF fleet. The RNM [9] is mainly based on the use of the FAC-prediction software "BRT-CICERO™".
We proposed to examine the following items in this article :

- The BRT-CICERO™ software and validation.
- The specific non destructive examination used to estimate the best kinetics for susceptible components.
- The performance of BRT-CICERO™ and the consequence on the maintenance strategy compared to other methodology.

.

2. The BRT-CICERO™ software and its validation

2.1. General aspects of flow accelerated corrosion and BRT-CICERO™

Flow Accelerated Corrosion (FAC) is very effective for nuclear and fossil power plant carbon and low alloy steel. Occurring for liquid water or wet steam flow with temperature range between 75 & 300°C it is particularly active around 150°C. Additionally this phenomenon depends on different parameters, not only chemical - as it is a chemical phenomenon - but also on hydrodynamics (flow, isometrics and turbulences), physicals (quality of steam) and thermodynamics (temperature, pressure).

The BRT-CICERO™ software has been developed by EDF since the early 90's and is based on the enhanced Berge's model [2 - 7]. This prediction tool allows to calculate the wall thickness loss in simulated pipes taking into account all influencing parameters like water chemistry, temperature, flow-rates, steam quality (for 2 phase flow lines), oxygen level (more specifically for BWR), operating rates but also the shape, dimensions and pressure drop (through regulating valves) of the individual pipe components. The actual version of the software 3.2.a takes into account the chromium content in the carbon steel and the next one will compute FAC rate with other alloys such as copper and molybdenum. The use of the software allows the operator to establish a list of most affected components based on the calculation of the FAC speed in each individual pipe component. This tool computes the ranking of the pipe components regarding FAC speed, predicted remaining wall thickness or margin calculations.

The wall thickness management is based on the use of the prediction tool BRT-CICERO™ but feedback experience from other power plants in France and worldwide is also taken into account for the final definition of an inspection program. The use of the prediction tool enables the reduction of the inspection volume to approximately 75 to 150 pipe components each second outage. An operator that cannot reduce the inspection volume can also use the software as a ranking tool in order to perform the inspection on the most critical components first.

At EDF the inspection performed on components predicted with a thickness lower or equal to the minimum required thickness is wall thickness measurements according to a grid with ultrasound technique. On each inspected component an alloy measurement is systematically performed also. All inspection data are input into the BRT-CICERO™ data base and taken into account for future FAC calculations. Specific FAC degradations in the weld root areas conducted EDF to validate specific NDE test methods like the ultrasonic method TOFD.

2.2. The BRT-CICERO™ model

The algorithm for kinetics calculation derives from Berge and Saint-Paul model [2, 3, 5] and is modified according to the Sanchez-Caldera model [10, 11] described into the equation (1).

$$V = \frac{\theta \times (Ceq - C\infty) \times F(Alloy)}{\frac{1}{K*} + (1-f) \times (\frac{1}{k} + \frac{\delta}{D})} \qquad (1)$$

Where:
Ceq: solubility of ferrous ion in water in equilibrium with magnetite reduction,

$C\infty$: ferrous ion concentration in bulk water (considering close to 0),
K*: kinetics coefficient of formation of ferrous hydroxide ($Fe + 2H_2O \rightarrow Fe(OH)_2 + H_2$),
f: rate of ferrous ion soluble and transformed in magnetite at Metal-Oxide interface (f is mainly equal to 0.5),
k: mass transfer coefficient, θ: porosity of oxide layer,
δ : oxide thickness, D: diffusion coefficient of ferrous ion in water,
F(Alloy): alloy effect on FAC rate

The model takes into account the whole parameters which have an effect on the intensity of the FAC phenomenon.

The chemistry of water is taken into account through Ceq content of soluble ferrous ion in equilibrium at magnetite/water interface and through $C\infty$ content of soluble ferrous ion concentration in bulk water in circulation. The value of Ceq depends on the hydrogen pressure pH_2 (data not shown), the hot pH and the constants of equilibrium of the various soluble ferro-iron species. Ceq is calculated according to [12] :

$$\mathrm{Ceq} = (\mathrm{pH2})1/3 \,.\, [\mathrm{K1}\ [\mathrm{H+}]2 + \mathrm{K2}[\mathrm{H+}] + \mathrm{K3} + \mathrm{K4}/[\mathrm{H+}]] \qquad (2)$$

where : K1, K2, K3 et K4 are the respective constants of equilibrium of the species Fe2+, Fe(OH)+, $Fe(OH)_2$ et $Fe(OH)_3^-$.

The thermo-hydraulic conditions of each pipe element are taken into account by the coefficient of mass transfer k that is equal to the coefficient of mass transfer of a straight tube of the same diameter k_{ST} multiplied by a geometry factor (Geo) according to the modified Colburn formulation:

$$k = \mathrm{Geo} \times k_{ST} \qquad (3)$$

with k_{ST} determined from the modified Colburn's relation and validation with a test loop called CIROCO.

$$k_{ST} = 0.0193(D/d).(e/d)^{0.2}.Re.Sc^{0.4} \qquad (4)$$

With:
e = roughness in meters (in BRT-CICERO™ this value is set to 4.10^{-5} m).
d = internal diameter (hydraulic diameter) of the component in meters.
Re: Reynolds number. Sc: Schmidt number.

To take into account the shape of the components, a geometry factor is introduced for each component, whose value is dependent on the shape and type of the component. The minimum value of the geometry factor is 1, for straight tubes. Moreover, the hydrodynamic effect of one component on downstream components is taking into account by calculating a decreasing factor along the downstream line.

The pH, hydrogen and temperature effects were checked with the CIROCO loop and all parameters are the results of an optimization between pH calculation [14] and the mixed function of hydrogen pressure versus temperature as described in equilibrium (2). The paper [13] describes the good correlation between hot pH calculation and FAC rate monitored with CICERO loop.

Finally, the effect of chromium and other alloy is well known for many years and is a paramount parameter to reduce the FAC rate [4]. All these parameters allow to propose an empirical function F(Alloy) which modulate the FAC rate according to the alloy contents.

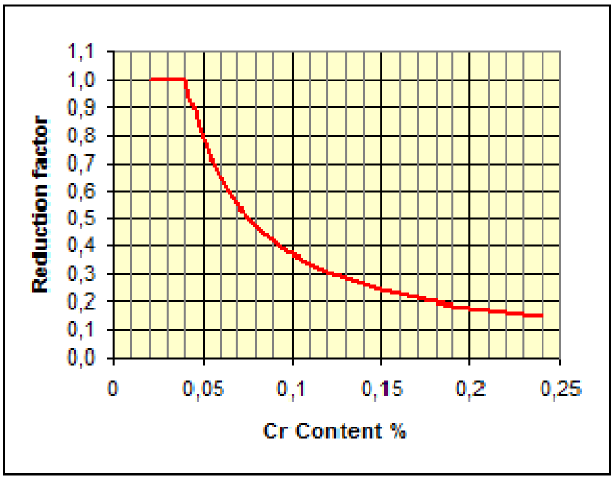


Figure 1. Chromium effect on the relative FAC rate

Chromium effect is shown on figure 1 and indicates that a chromium content lower than 0.04 % has no effect on the FAC rate. For chromium contents higher than 0.04 % the FAC rate decreases linearly in a log scale. For example : with 0.1 % of chromium the component FAC rate is 2.5 times lower than without chromium (or with a chromium content lower than 0.04 %) according to the high mass transfer curve (corresponding to most of NPP's hydraulic conditions).

The Ducreux's relationship describing the steel composition effect on FAC rate is:

$$\frac{FACrate}{FACrate_{max}} = \frac{1}{83.[Cr]^{0.89}.[Cu]^{0.25}.[Mo]^{0.2}} \qquad (5)$$

These material effects are very important in the strategy of component replacement. In order to reduce the FAC degradation, the operators have to consider this effect of chromium and other compounds when a replacement should be done.

3. The non destructive examinations

3.1. Alloy measurement

One of the influencing parameters on the FAC rate of carbon steel is the alloy contents and especially the chromium. The values of chromium, copper and molybdenum contents in low alloy steel vary from 0.00 to 0.30 % (i.e. 0 to 3000 mg/kg) according the grade. The influence on the FAC rate has been demonstrated by the EDF R&D department on the FAC test loop "CIROCO" for chromium values from 0.04 % and up (figure 1). The problem is that the exact Cr content values are not always indicated by the manufacturer. The manufacturer must only guarantee they are lower than the maximum acceptable values (0.25 or 0.30 % depending on the grade for example).

In order to measure accurate chromium content in the components, EDF qualified a

measurement method based on the XRF technique (X-Ray Fluorescence technique). This technique used the emission of characteristic fluorescent X-rays from a material that has been excited by bombarding with high-energy X-rays. The phenomenon is widely used for elemental analysis and chemical analysis, particularly in the investigation of metals composition (commercially called Positive Material Identification – PMI).

EDF used this methodology since 2002 and the technology, the performances and the methods of data processing widely evolved.

- Firstly X MET 3000 TA (from Metorex) has been used during 7 years. This device is based on empirical model for each chemical element which needs to be measured and 2 minutes are necessary for an accurate measurement. Only one component can be measured during signal acquisition.
- Starting 2009, EDF acquired X MET 5100 (from Oxford) based on empirical model and only 1 minute is needed for an accurate However, the calibration of several chemical elements with the level of requirement necessary for the determination of the compositions of unalloyed steels turned out very difficult to realize.
- End of 2009, EDF changed technology and opted for the use of devices based on the fundamental parameters (internal calibration which integrates the effects of matrix). With only one measurement of 30 seconds, all transition metals elements are easily measured by the Niton XL3T 900S.

According to figure 1, the calculated FAC rate appears relatively sensitive to uncertainty of the Cr content measurement. EDF defined the needed accuracy for the chromium content measurements according to the FAC rate calculations made by BRT-CICERO™. These tolerances are the results of an optimisation between the performances of devices and the will to decrease as much as possible the gaps for predictions of remaining time of components before measurement examination.
The required accuracy levels are:

- For Cr contents from 0 to 0.03 % (w/w) the boundary accuracy is ± 30 %
- For Cr contents from 0.03 to 0.077 % the boundary accuracy is ± 15 %
- For Cr contents from 0.077 % the boundary accuracy is ± 10 %

The qualification of the XRF devices used for on site chromium measurements is performed on calibration blocks with certified chromium and other alloy contents. Each element is measured and associated to an uncertainty. A comparison of the performances of devices for chromium measurement is detailed on the figure 2. For each certified value, the uncertainty for the measurement is defined by equation 6.

$$\boldsymbol{\delta} = \sqrt{\boldsymbol{\delta}_{block}^2 + \boldsymbol{\delta}_{device}^2} \qquad (6)$$

With : $\boldsymbol{\delta}_{block}^2$ the variance of the calibration block for considered element.
$\boldsymbol{\delta}_{device}^2$ the variance of 5 consecutive measurements for considered element

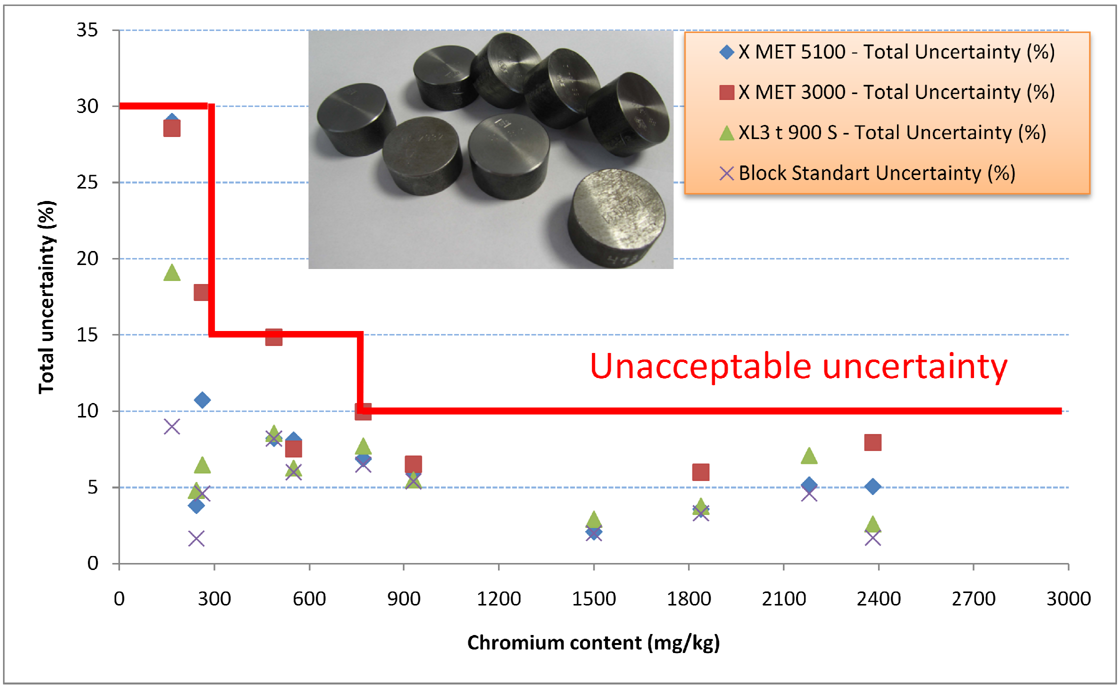


Figure 2. Comparison of uncertainty for chromium measurement for different devices.

It appears that all the devices are in accordance with the expectations but the device Niton is the most successful with the lower uncertainty and the lower time of measurement. And moreover, this device allows measuring all elements without specific calibration such as chromium, copper and molybdenum very effective for FAC resistance but also lead, titanium, zinc, tin... which are the proof that the preparation of surface of on-site components is insufficient before measurement. The surface preparation is very important because the XRF measurement is a surface measurement and any pollution could invalidate it.


Figure 3. Specific device for surface preparation and on-site measurement.

On EDF's fleet many components are measured each year and the new devices help to accelerate the measurements during last years. This measurement is rapid to achieve and with an appropriate procedure provide to operator an accurate value for FAC rate and help them to optimise the maintenance program. Most of the time, only 35 % to 60 % of the components belong to preliminary ranking are examined for thickness measurements after the alloy measurements. By this way, EDF save money and time because alloy measurement is cheaper and faster than thickness measurement.

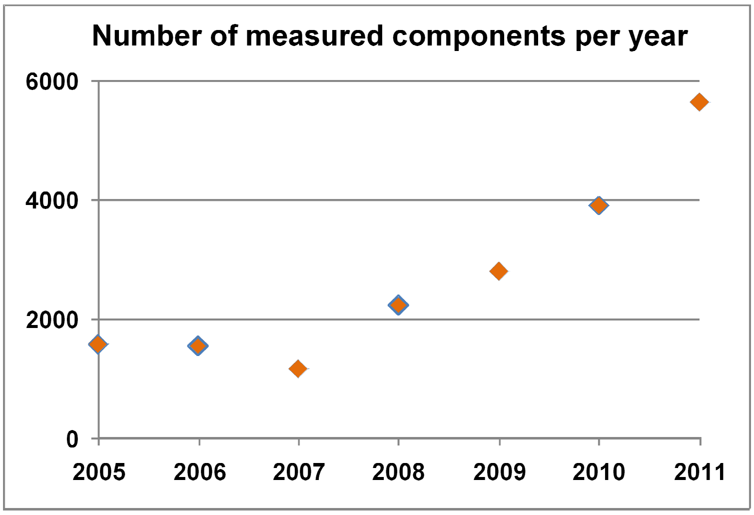


Figure 4. Number of measured components per year.

3.2. Thickness measurement

During inspections on critical elements predicted at design thickness at cycle N+2, the standard procedure of wall thinning loss measurement is performed by standard ultrasound technique. The UT measurements are performed on the elements to be inspected according to a predefined grid (see figure 5 and 6).

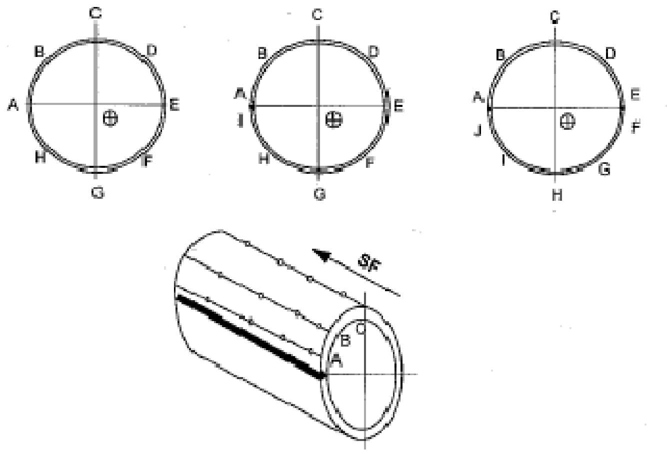
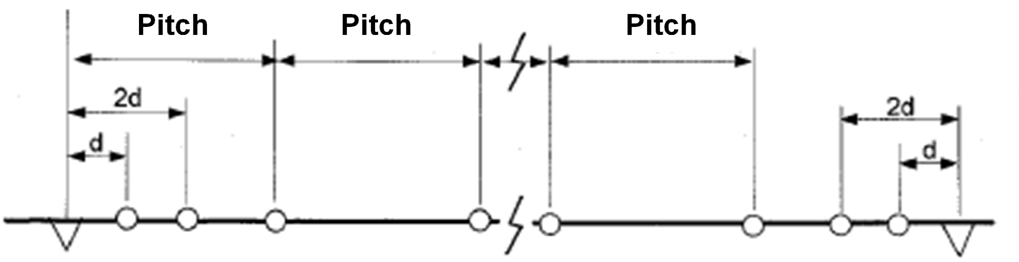


Figure 5. Situation of longitudinal measuring lines



Upstream Weld Fluid Direction Downstream Weld

Figure 6. Situation of measuring points on same longitudinal line

As the forms of the degradation caused by FAC are large areas, the measurements are performed on large mesh grids. The size of the grid depends on the size and form of the elements. For a component without welds, 8 longitudinal lines are defined and the mesh pitch is approximately one third of the component diameter. In the presence of discontinuities or in case of local disturbing areas, the grid mesh can be reduced. In order to assure the repeatability of the measurements, the grid mesh is marked permanently on the components. The surface preparation is performed by grinding and the required surface roughness of 6.3 µm or better (12.5 µm for castings).

Table 1. Values of d and Pitch according to diameter

Diameter	d	2d	Pitch
900 < Ø	50	100	300
360<Ø<900	50	100	Ø/3
300<Ø<360	50	100	100
240 < Ø < 300	40	80	80
180<Ø<240	30	60	60
120<Ø<180	20	40	40
60<Ø<120	20	40	20

Finally, the thickness measurements values are filled in BRT-CICERO™ and used for analysis.

4. Performance of BRT-CICERO™

The performance of the BRT-CICERO™ prediction tool is periodically reviewed to ensure compliance with the French vessel legal and safety requirements. One way to check the performance of BRT-CICERO™ is to compare the components thickness calculated with BRT-CICERO™ with the measured components thickness. At the time being (2010) 14 439 thickness measurements are taken into account and the analysis is still in progress.

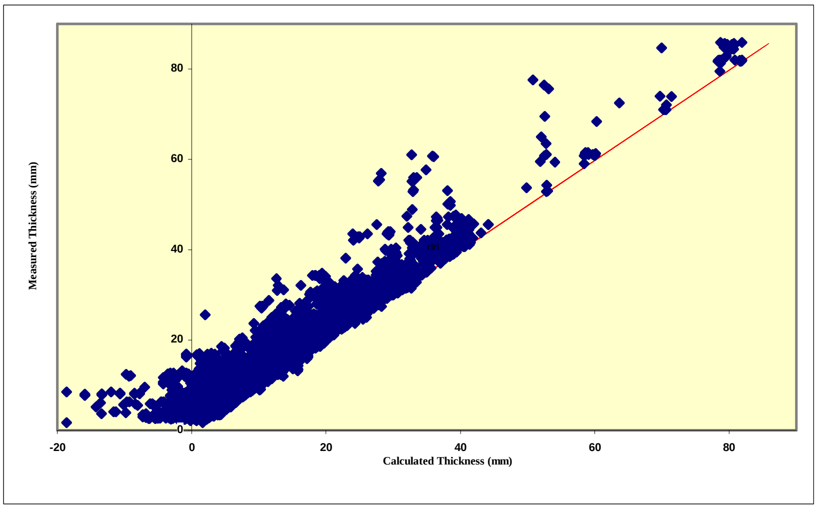


Figure 7. Comparison between minimum measured thickness and calculated thickness for pipe components with BRT-CICERO ™ version 3

After exclusion of the wrong input data that are responsible for artificial non conservative predictions, the curve in figure 7 is drawn. Some points appear to be predicted with a high degree of conservatism: this is generally due to a lack of information on the chromium content or to an initial thickness much higher than specified, which is often the case for thick components (headers, tees, large bore reducers). Some cases can also be due to a too conservative geometry factor.

5. Conclusion and perspectives

As explained in the beginning, FAC is highly depending on alloy and especially chromium content of the component. The effect is well-known and measured values are used by the way of the software called BRT-CICERO™.
EDF use XRF portable device to measure rapidly and easily the alloy contents and this technique allows knowing with a weak uncertainty the content of steel. When values are filled in the software BRT-CICERO™, FAC rate can be recalculate to have the best estimation of the degradation level of components preliminary identify for examination.

The minimum thickness measurement values are also used to validate the model BRT-CICERO™ and especially the geometric factors. The next version BRT-CICERO™ 3.3 will go to take advantage of last analyses of these coefficients.

In the next future, the Laser Induced Breakdown Spectroscopy by plasma induced by laser will be examined for faster and more exhaustive chemical analysis. The welds and casting components will be examined for alloy content. Welds examination made by TofD will be filled in next version of the software (see paper on Welds inspection by ToFD, same meeting by Delacoux, Trevin, Caylar)

References

1. B, Chexal, J, Horowitz, R, Jones, B, Dooley, C, Wood, M, Bouchacourt, F,N, Remy, F, Nordmann, P, Saint Paul, Electric Power Research Institute, Flow-Accelerated Corrosion in Power Plants, TR-106611-R1, 1998.
2. S. TREVIN in Nuclear Corrosion and Science Engineering, Edited by D. FERON Woodhead Publishing Limited, feb. 2012 - part 2, chapter 7, pp 186 – 229.
3. Ph. Berge, J. Ducreux, P. Saint Paul, Water chemistry of Nuclear Reactor Systems 2. Proceedings of the British Nuclear Energy Society, London, p.19, 1981.
4. J. Ducreux, Water chemistry of nuclear reactor systems 3. Proceedings of the British Nuclear Energy Society, p. 227, London 1983.
5. Ph. Berge, F. Khan, EDF International Specialists Meeting on Erosion-Corrosion of Steels in High Temperature Water and Wet Steam, Les Renardières, EDF, France, 1982.
6. M. Bouchacourt, Proceedings of the AIEA Specialists Meeting on Corrosion and Erosion Aspects of the Pressure Boundary Components of Light Water Reactors, Vienna, (1988), IAEA report: IWG-RRPC-88-1, p.19, Vienna 1990.
7. F.N. Remy, Proceedings of the IAEA Specialists Meeting on Corrosion and Erosion Aspects of the Pressure Boundary Components of Light Water Reactors, Vienna, (1988), IAEA report : IWG RRPC-88-1, p. 27, Vienna 1990.

8. W. Kastner, M. Erve, N. Henzel, B. Stellwag, Proceedings of the AIEA Specialists Meeting on Corrosion and Erosion Aspects of the Pressure Boundary Components of Light Water Reactors, Vienna, (1988), IAEA report: IWG-RRPC-88-1, p 49, Vienna 1990.
9. L. Dejoux, Surveillance de la corrosion-érosion des tuyauteries secondaires conventionnelles et de leurs accessoires, EDF report RNM TPAL-AM513-01, April 2009.
10. L. E. Sanchez-Caldera, P, Griffith, E, Rabinowicz, Transaction of the ASME, Vol, 110, p, 180, April 1988.
11. L. E. Sanchez-Caldera – Ph.D Dissertation, Massachusetts Institute of Thechnology, June 1984.
12. F,H, Sweeton, C,F, Baes, Journal of Chemical Thermodynamics, Vol, 2, p, 479, 1970.
13. E.-M. Pavageau, O. de Bouvier, S. Trévin, J.-L. Bretelle, L. Dejoux, 14th International Conference on Environmental Degradation of materials in nuclear Power Systems-Water Reactors, August 23 – 27, 2009.
14. K, Fruzetti, EPRI Final Report, November 2003, TR 1003609.