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Pipe wall thinning management at Electricité de France (EDF)

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Abstract.
Among the various degradation modes that cause 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 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 is mainly based on the use of the FAC-prediction software "BRT-CICERO™" as well as on specific actions for the lines or elements that are not modeled in the software.

KEYWORDS: Flow Accelerated Corrosion, FAC, Degradation mode, Piping, Carbon steel, Maintenance, Prediction software, BRT-CICERO™, Non Destructive Examination, TOFD, Computed Radiography, Chromium.

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) [1], [3], [4], FAC is the one that is the more widespread in the installation [2], [5], [10], [11] 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.

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In the present article following items are developed :

2. The French regulatory requirements on pressure piping,
3. The organization at EDF to manage the risk of pipe wall thinning,
4. The BRT-CICERO™ software and its validation,
5. Small bore piping and low energy lines in BRT-CICERO™,
6. The Quality Assurance requirements,
7. The Non Destructive Examinations (chromium measurement, Digital Radiography, weld root wear detection and dimensioning by TOFD),
8. Consideration of the feedback experience,
9. Conclusion

2. The French regulatory requirements on pressure piping

A new pressure vessel law was issued in France on March 15th 2000 for non nuclear pressurized vessels and piping. The components that are submitted to this law depend on the type of gas they contain (steam / water or other gas), on their design pressure (PS) and volume (or nominal diameter DN for piping). All steam / water piping with PS > 0.5 bar and DN > 100 mm (4 inch) and PS×DN > 3500 bar are submitted to this law.

Basically, the regulator states that the components must be maintained in a good state of work permanently. The operator is responsible for the components security and must have the skills to operate and maintain them.

Regulated piping are submitted to "periodic inspections" "as often as necessary". In practice, the period is based on a criticality analysis that is a function of three parameters : 1) the occurrence of the possible degradation modes (FAC, wall thinning after cavitation but also cracking, fatigue, etc.), 2) the degradation kinetics, and 3) the risks for human beings. The higher is the criticality, the shorter the inspection period must be.

Inside the NPP, a "Recognized Inspection Service" (RIS) has the delegation from the French Administration to ensure the security of the pressurized components. This service is liable for the application of the law, has to prove his capability to carry out his mission in front of the Administration and can impose all type of requirements or actions from the operator to ensure the components security (including the shutdown of the plant).

Each regulated piping must have an Inspection Plan (IP), written by the RIS , that specifies the different actions to be performed and their periodicity. The IP takes into account the different degradation mechanisms that can occur. In addition to periodic inspections, steam / water piping with PS > 0,5 bar and DN > 250 mm (10 inch) and PS×DN > 5000 bar are submitted to periodic qualifications, that consist in a complete internal and external inspection. This periodic qualification must take place every 10-12 years.

3. The organization at EDF to manage the risk of pipe wall thinning

As EDF operates a fleet of standardized Nuclear Power Plants, the maintenance rules are edited by a corporate engineering unit called UNIE (Unité Nationale d'Ingénierie de l'Exploitation). The 58 NPPs have the obligation to apply the national maintenance rules issued by this unit on their equipments.

Since the mid 90's at EDF the pipe wall thinning due to FAC, and the associated maintenance strategy is based on the use of a prediction software developed in house with the cooperation of multiple engineering units. This prediction software is called BRT-CICERO™. After this software enabled the operator to detect a severe damage on an expander downstream of a regulated valve of the unit 2 of Fessenheim in year 2000, the corporate level of EDF decided to make mandatory the use of BRT-CICERO™ for all the 58 NPPs. This decision was called "DP 109". Many position papers were issued afterwards on how to use the software on site, how to model the piping and input the reference data, how to handle the results, when and how to perform the inspections and how to take into account the domestic and international feedback. These papers accompanied the "DP 109" but became too numerous and difficult to master in their totality. Because of this diffuse "guideline", it was therefore decided in 2008 to produce a new single guideline which gives all the prescriptions and recommendations for the surveillance of the conventional secondary piping and valves. This guideline, issued in April 2009, is called the National Maintenance Rule on conventional piping or "RNM" [12].

The RNM tackles all the activities of FAC surveillance on piping, valves and welds. The main principles are the following :

- After having shown the performances of the predictive software BRT-CICERO™ to the regulation body, EDF has obtained a derogation to the March 15th, 2000 pressure vessel law, that enables the operator to inspect for FAC damage only the piping elements indicated by the software (heavy costs of scaffolding and insulation removal are saved this way),
- Each pipe component modeled in BRT-CICERO™ and predicted under the design thickness at the outage N+1 must be either inspected (chromium and thickness measurements) at the outage N or justified by a written analysis submitted to the RIS for approval ; different methods are possible such as using several wall thickness measurements made in the past, etc.,
- Because of the difference in operational conditions it is not possible to establish a justification of non-inspection based on informations from a sister plant,
- Pipe elements located downstream of regulating valves cannot be justified using the above methods and they must be inspected if they are predicted under the design thickness,
- If a pipe component is measured under its design thickness, the component must be either replaced or justified for at most one cycle by a mechanical calculation towards the load of pressure and taking into account the predicted wall thinning during this cycle,
- During a thickness measurement by ultrasonic (UT), all specific pipe components must be meshed entirely (elbows, bends, reducers, tees, etc.),
- The inside wall of double-wall venturis is inspected by televisual inspection,
- For each component inspected by UT, an analysis of the thickness values along the mesh must be done in order to undertake an inspection of the weld in case of a thickness decrease at a mesh extremity (see § 7),
- As the current version of BRT-CICERO™ calculates wear rates on piping elements only and not on welds, and as the degradation of a weld root may not be seen by the analysis of the wall thickness measurement file of the component, especially if the component contains chromium and not the weld, a special inspection program is required for the welds that are assessed to be FAC sensitive (downstream of regulating valves for instance) and with a priority on components whose base metal has a chromium content higher than 0.1 %,
- All the dissimilar welds on the regulated pipe lines must be listed and inspected ; the inspection concerns the carbon steel part of the connection,
- All carbon steel valves on regulated pipe lines must be inspected visually (VT), except those whose shell has already been inspected with no FAC damage after 10 years of operation,
- For the lines susceptible to FAC that are not yet modeled in BRT-CICERO™ (low energy lines, partial time operating lines, small bore piping, etc.), an inspection program must be established that includes the most sensitive areas from an engineering point of view (areas located downstream of reg. valves and diaphragms, tees, series of elbows, etc.).

4. The BRT-CICERO™ software and its validation

The BRT-CICERO™ software has been developed by EDF since the early 90's and is based on the enhanced Berge's model [6], [8], [9], [13], [14]. 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 elements and the chromium content in the carbon steel.

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. The tool allows the ranking of the pipe components regarding FAC speed, predicted remaining wall thickness or margin calculations.

The importance of chromium content of steel in the calculation model [7] allows the software to take into account this very important intrinsic parameter that can explain a high FAC speed in components in conditions of hydraulic flow turbulent but weakly disrupted like straight pipe elements downstream straight pipes. On the EDF fleet several hundred of straight pipes downstream other straight pipes were already predicted with higher FAC rates than the upstream pipe.

The Figure 1 shows an example of a tube downstream a straight tube with a higher **predicted** FAC rate than the upstream tube and a lower minimum **measured** wall thickness.

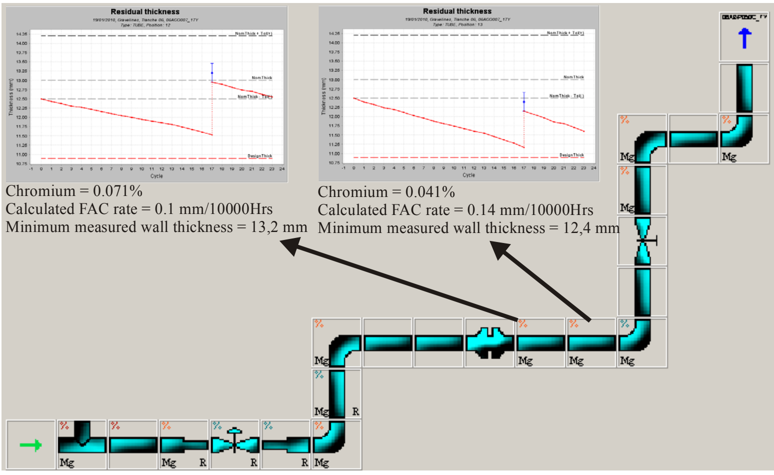


Fig. 1. Tube downstream straight tube

The wall thickness management is based on the use of the prediction tool BRT-CICERO™ but feed back experience from other powerplants 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 can not 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. On each inspected element a chromium 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 or digital radiography.

4.1 The BRT-CICERO™ model

The algorithm for kinetics calculation derives from Berge and Saint-Paul model [6], [8] and is modified according to the Sanchez-Caldera model [13], [14] described into the equation (1).

$$V = \frac{\theta \times (C_{eq} - C_\infty)}{(1/K^* + (1-f) \times (1/k + \delta/D))} \tag{1}$$

Where :

Ceq : solubility of ferrous ion in water in equilibrium with magnetite reduction [14],

C∞ : ferrous ion concentration in bulk water (considering close to 0),

K*: kinetics coefficient of formation of ferrous hydroxyde ($Fe + 2H_2O \rightarrow Fe(OH)_2 + H_2$),

f : rate of ferrous ion soluble and transformed in magnetite at Metal-Oxide interface (f is mainly equal to 0.5 [1]),

k : mass transfer coefficient, θ : porosity of oxide layer,

δ : oxide thickness, D: diffusion coefficient of ferrous ion in water.

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∞ content of soluble ferrous ion concentration in bulk water in circulation. The value of Ceq depends on the hydrogen pressure pH_2, the hot pH and the constants of equilibrium of the various soluble ferro-iron species. Ceq is calculated according to [14] :

$$C_{eq} = (pH_2)^{1/3} \cdot [K_1 [H^+]^2 + K_2[H^+] + K_3 + K_4/[H^+]] \quad (2)$$

where : K_1, K_2, K_3 et K_4 are the respective constants of equilibrium of the species Fe^{2+}, $Fe(OH)^+$, $Fe(OH)_2$ and $Fe(OH)_3^-$.

The thermohydraulic 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 :

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

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

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

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 [17] and the mixed function of hydrogen pressure versus temperature as described in equilibrium (2). The paper [16] describes the good correlation between hot pH calculation and FAC rate monitored with CIROCO loop.

Finally, the effect of chromium is well known for many years and is a paramount parameter to reduce the FAC rate [7]. All these parameters allow to propose a simplified model which is :

$$V = 2k.f(Cr).C_{eq} \quad (5)$$

where f(Cr) is an empirical function including porosity, hydrogen pressure and chromium content effects according to the temperature.

4.2 The BRT-CICERO™ validation

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 (end 2009) 14,439 thickness measurements are taken into account and the analysis is still in progress.

After treatment of abnormal points, the curve in Figure 2 is obtanied. 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.

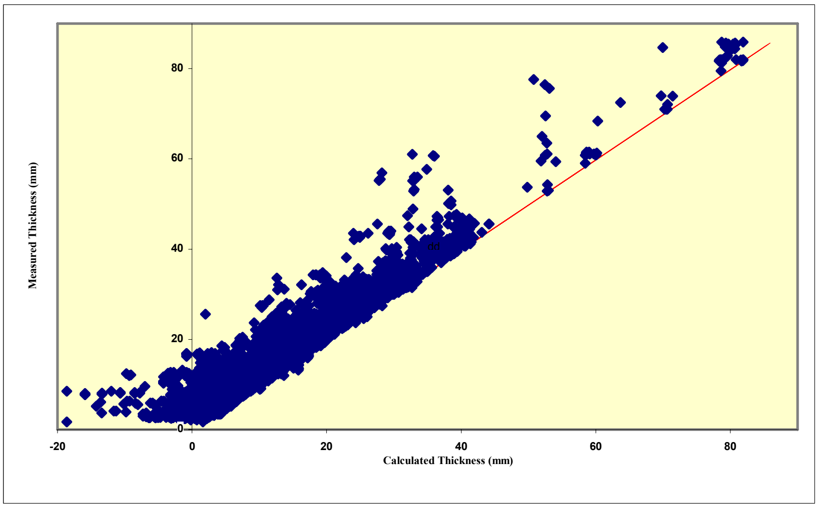


Fig.2. Comparison between measured and calculated thickness for pipe components with BRT-CICERO ™ version 3

5. Small bore piping and low energy lines in BRT-CICERO™

In the mid-90's, when EDF started to use the FAC prediction software BRT-CICERO™, only the main lines were modeled in the plant databases. These main lines are those with the highest energy and therefore with the highest level of risk in case of pipe failure. However, the introduction of small bore and/or low energy lines in BRT-CICERO™ was identified as an important issue of improvement when EDF evaluated its own FAC surveillance strategy after the Mihama accident. Furthermore, a few ruptures on small bore piping were at the origin of production loss, which is another reason for increasing the surveillance.

Therefore a project was launched at EDF to get modeled in the BRT-CICERO™ data bases the complementary lines for the 6 types of reactor : 900 MW (CP0, CP1 and CP2 type), 1300 MW (P4 and P'4 type), and N4 1450 MW. All the lines of the secondary circuit whose operating temperature is greater than 75 °C and whose nominal diameter DN is greater than 32 (1'¼) have been listed. This represents several hundreds of lines for each type of reactor. The second step of the work consists in identifying which among those lines really need to be modeled. Are for instance excluded the lines :

- that have a very low operating rate (for example lines that only operate during the start up and shut down stages, lines to pressure relief valves, by-pass lines to atmosphere, etc.),
- in which the flow rates is very low (equilibrium lines for example),
- in which circulates dry steam (main and live steam lines),
- that have been replaced by stainless steel, etc.

The remaining lines have to be modeled. As they are not main lines (the main lines are already input in BRT-CICERO™), it is sometimes difficult to determine reliable values for their operation parameters (temperature, pressure, flow rate, steam quality, operation rate). When data are missing or are susceptible to uncertainties, conservative assumptions are made in order to set "envelope" values.
After the operational parameters are determined, the geometry of the lines is input in BRT-CICERO™. The precise isometric drawings of each line are needed, in order to get all the required values : pipe length, diameter and thickness, accessories characteristics such as tee angles, bending radius, expander / reducer lengths, orifice diameter of diaphragms, etc. The manufacturing documents must also be used in order to find the steel grades, the manufacturing tolerances and information on valves (especially the pressure drop).

Modeling auxiliary lines of the secondary circuit is a long job whose hardest part is the data research in the documentation and the setting of the most reliable values for the different parameters needed for the FAC calculations. The completion of the BRT-CICERO™ data bases was however completed in end 2009 for the eighteen CP1 900 MW units. Eighty-four new lines totalizing more than 1200 pipe elements have been added per unit, which should greatly improve their maintenance and the storage of NDE results (wall thickness and chromium measurements). The same work for the other sixteen 900 MW units is under progress and should be finished by mid-2010. For the 1300 and 1450 MW units, the work is planned to be completed by the end of 2010.

6. The Quality Assurance requirements

The use of a prediction software for maintenance purposes requires a high level of quality on the data and on the way the software is used. From the quality of the input data depends the quality of the predictions. That's why the RNM requires that 100 % of the input data in the BRT-CICERO™ data bases needed to be verified by each NPP before end 2009. All the chemistry data (amine contents by cycle), the operating parameters of the lines (temperature, pressure, steam quality, flow rates) and the pipe component characteristics (dimensions, diameter, nominal thickness, steel grade, design thickness, etc.) have therefore been verified using the reference sources (chemistry application, design documentation, isometric drawings, etc.). This verification is double-checked by another person, that fills the field "validated by" available for each line in BRT-CICERO™.

The RNM and other statutory documents like the modeling procedure give some rules of use and modeling in the software, on the way to take into account the manufacturing tolerances and the measurement uncertainties for example.

Training sessions on BRT-CICERO™ are organized by a specialized training unit of EDF on a basis of 5 to 6 sessions per year. Only people that have followed this training session with success have the ability to use BRT-CICERO™.

The management of the plant must be strongly involved to have all these verifications and rules applied by the staff. Audits of the plants on the FAC subject are regularly performed by the corporate level.

7. The Non Destructive Examinations

7.1 Chromium measurements

One of the influencing parameters on the FAC rate of carbon steel is the chromium content. The value of the chromium content in low alloy steel varies from 0.00 to 0.30% according to 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 (and [7]). 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 an accurate chromium content in the components, EDF qualified a measurement method based on the XRF technique (X-Ray Fluorescence technique). Because the uncertainty of the Cr content can change the FAC rate, EDF defined the needed accuracy for the chromium content measurements according to the FAC rate calculations made by BRT-CICERO™.

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 contents (see Figure 3).

Fig.3. Calibration blocks used for the qualification

The chromium measurements are made by EDF with annually qualified devices and appropriate procedures. More than 2800 components on the EDF fleet have been measured during the year 2009 for example. Some of the measurements are made by contractors with qualified devices. The use of an XRF measurement device is shown in Figure 4.

Fig. 4. XRF measurement device positioned on a pipe

7.2 Wall thickness measurements by ultrasonic

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. As the form 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 (12,5µm for castings).

7.3 Wall thickness measurements by Digital Radiography

In some cases the use of standard ultrasonic technique can not be applied. For example during operation or in presence of the insulation. In order to dispose other wall thickness measurement methods, EDF validated the use of Digital Radiography (DR). The advantage of this technique is that it can be used on insulated pipe elements even during operation.

Digital Radiography is a non-destructive inspection technique based on the same principles as classic radiography. The difference lies in the detector which in the case of classic radiography is composed of a silver film, and in the case of digital radiography of a photo sensible panel.

The limits of digital radiography for thickness measurements is directly related to the energy of the radiation source being used ('X' ray tubes, sources of Se, Ir or Co).

7.3.1 Validation Methodology

For the validation of the DR technique, a test programme has been drawn up. This programme consisted in measuring the thickness of test tubes and comparing the results obtained with the real values. The determination of the precision of the method is carried out by measurements on various test tubes, depending on the thickness range of use. Supplementary tests on real components were also carried out to check the test parameters on components with realistic defects and the limits of use.

The thickness measurements validated by EDF were carried out using the "Rhythm" software Trade mark of General Electric (see Figure 5) which is composed of a thickness measurement module based on the "wtScope" software developed and validated by the Federal Institute for Materials Research and Testing (BAM) in Germany. The thickness measurement module can be used for all types of detectors such as digitised radiation silver film, photo-sensible image plates and digital detectors.

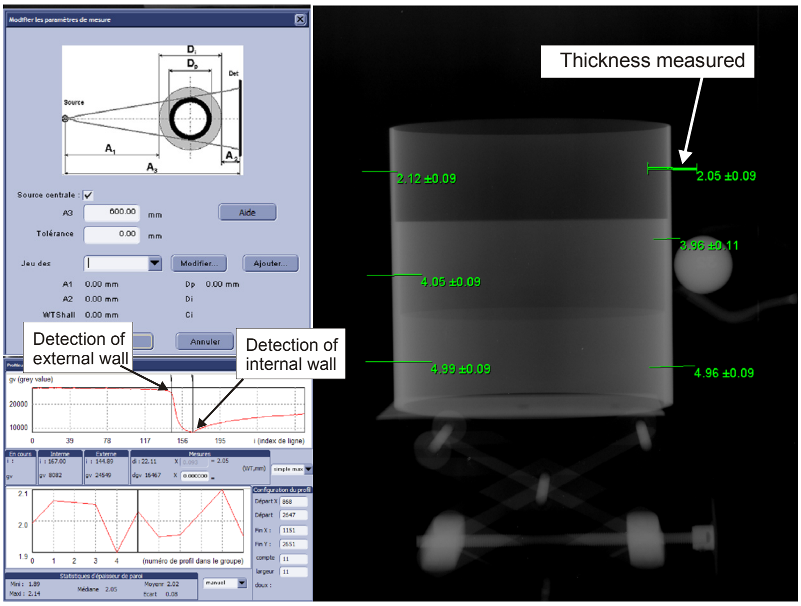
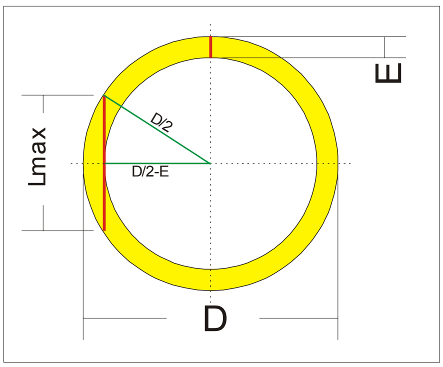


Fig. 5. Wall thickness measurement module of Rhythm DR software

7.3.2 The L-max parameter

The diameter and thickness of the parts to be inspected have an influence on the precision of the thickness measurement and are to be taken into consideration during an inspection. The essential parameter for making the shots is the total length penetrated by the X or γ rays.

This variable, called **L-max** (Figure 6), is determined in the following manner :



$$L\max = 2 \times E\sqrt{\frac{D}{E} - 1}$$

Fig. 6. L-Max

7.3.3 Results of validation tests

The test results show that thickness inspection using the DR technique is possible in the configurations indicated by standard EN 14785.

The essential parameter to be controlled using this technique is the total length of the material penetrated by the X or γ rays. This length "L-max" must be considered as an essential parameter which makes it possible to determine, on the one hand, the feasibility of an inspection with respect to the diameter and thickness of the part to be inspected depending on the source used and, on the other hand, the measurement uncertainty.

Another important variable is the exposure time, which determines the signal/noise ratio. Increasing the exposure times reduces the measurement uncertainty.

The presence of water is an important parameter to be taken into consideration for inspections during operation. The presence of water does not lower the L-Max value itself (water density is lower than that of steel) but the detection of the internal wall can cause difficulties if the L-Max value is close to its limits due to diffuse radiation (radiation scattering). The presence of water will limit the use of DR and was taken into account during the tests.

The resolution of the detector does not have a notable influence on the measurement quality and "fast" detectors are suitable for use for all thickness measurements. The shot configuration has only a minor influence on the measurement uncertainty.

The following table shows the L-Max limiting values on the basis of the precision required and the source used.

Configuration	Measurement accuracy (mm)	Se75 L-Max	Ir192 L-Max	Co60 L-Max
With water	**+/- 0.5**	*****	**75 mm**	**120 mm ***
Without water	**+/- 0.5**	**50 mm**	**95 mm**	**120 mm ***
With water	**+/- 0.7**	*****	**95 mm**	**120 mm ***
Without water	**+/- 0.7**	**55 mm**	**100 mm**	**120 mm ***

*** Maximum limits not yet determined.**

Table 1 L-Max limits for different source types

7.4 The welds inspection

The degradation of welds by FAC and the solutions to control them were identified as important issues when EDF evaluated its own FAC surveillance strategy after the Mihama accident. Different cases of weld root wear occurring in EDF facilities have been analysed. It was established that the form of the degradations are closely linked to the chromium content of the weld deposit material but also to the chromium content of the base metal in the adjacent components. The typical forms of the observed degradations are shown in a simplified manner in the Figure 7.

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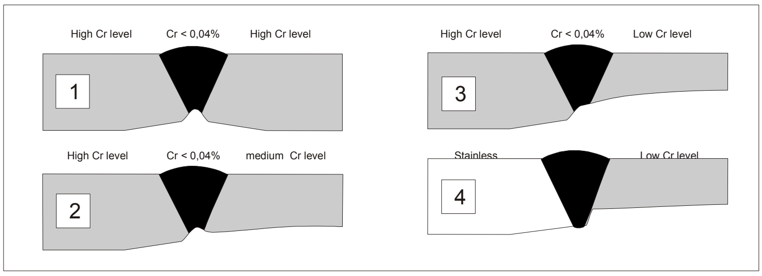

Fig. 7. Simplified forms of weld root wear degradation

Inspections to detect and dimension this type of weld root degradation can be carried out using different non-destructive examination methods including Digital Radiography (DR) or ultrasounds based on the TOFD method. These two methods were tested since 2005 and validated at the end of 2009 by EDF DTG. The use of DR or TOFD depends on the geometry of the components, the configuration on site, and the intervention conditions. The inspection method by TOFD is preferred for weld root wear detection and dimensioning. For wall thickness measurements on small bore piping and piping under insulation, DR can be applied.

7.4.1 Weld root wear detection and dimensioning by TOFD

The NDE technique referred to as Time Of Flight Diffraction (TOFD) is based on the principle of diffracted ultrasound waves. TOFD uses longitudinal waves (LW), the principle of this technique is illustrated in the Figure 8.

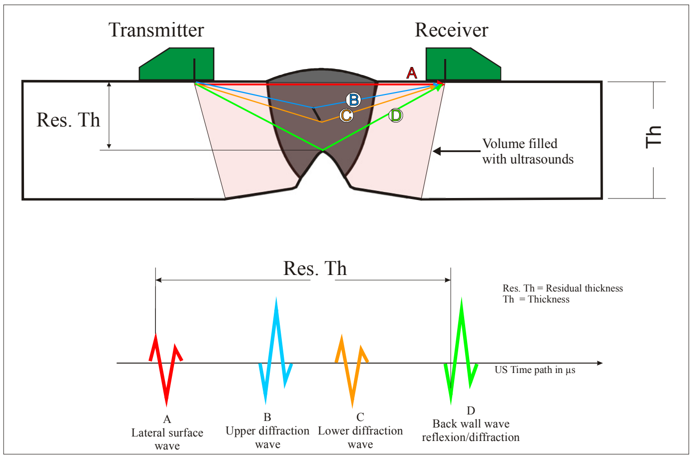

Fig. 8. Principle of TOFD

The couple of transducers (transmitter and receiver) "fills-in" the volume to be tested with ultrasound waves. Among the transmitted ultrasound waves we can identify : the lateral surface wave (A), passing just under the surface from the transmitter towards the receiver taking the shortest path (straight line), the diffraction waves (B and C) generated by the upper and lower ends of a defect, and at the opposite side the reflection (or diffraction) wave D.

The TOFD method makes it possible to dimension defects with a high accuracy because the technique is capable of "measuring" their height and length. Sizing is carried out directly on the high frequency signals.

TOFD is an ultrasound technique and is therefore sensitive to the metallurgical structure of the welds. Accordingly, the technique is not appropriate for the testing of austenitic steel welds.

Another advantage of this technique is that various complex geometrical shapes of components can be inspected. In this case additional analyses or simulations are necessary (welds near expanders for instance) and the accuracy is reduced a little.

7.4.2 Validation Methodology

The use of the TOFD technique was validated through a test programme that consisted in measuring the remaining ligament on test blocks with artificial defects of known sizes, and comparing the measurements obtained with the real sizes. The precision of the method is determined from tests on these blocks. Supplemental tests on real components with real weld root degradation defects were performed to verify the test parameters on real defects. The tests on the elements with real defects confirmed the results obtained on the test blocks.

The whole test programme confirmed the feasibility of the remaining ligament inspection at the root of the weld and Heat Affected Zone by means of the TOFD technique. The measurement precision depends essentially on the position of the couple of transducers compared to the centre of the defect and the tested thickness. To summarise, and for wall thickness up to 44 mm, the applicable accuracy to the remaining ligament measurement at the weld root is indicated in the following table.

Recommended configurations:

Thickness (mm)	Frequency Recommended MHz (CEN/EN Standard)	Recommended beam angle α (CEN/EN Standard)	PCS : Distance between transducers (mm)	Total uncertainty. (mm)	Covered zone (mm) with 3 scans
4 to 7.5	10 - 15	60° - 70°	32	± 0.20	28
7.5 to 13.5	10 - 15	60° - 70°	55	± 0.30	50
13.5 to 25	5 - 10	60°	70	± 0.35	50
25 to 44	3 - 5	60°	100	± 0.45	80

Table 2 Recommended configuration for the TOFD inspection

8. Consideration of the feedback experience

The operational feedback and its treatment is considered by EDF as an important way to improve the FAC surveillance strategy, especially on lines that are not yet modeled in the prediction software BRT-CICERO™. That's why the RNM guideline requires that significant events like leaks or measurements below the minimum acceptable thickness must be formally reported to the corporate level and to the other NPPs of EDF.

International feedback events are analyzed by the EDF corporate level and can lead to special actions on the EDF NPPs, such as the evaluation of the conservatism of BRT-CICERO™ on tubes behind diaphragms after the Mihama accident.

Each year, EDF also organizes a feedback meeting that gathers all the EDF NPPs specialists, in order to share the national and international feedback and to address different issues on the software, the outages management, the inspection volumes, the chromium measurements, the NDE techniques, etc.

9. Conclusion

Flow Accelerated Corrosion occurred and will continue to occur in most of the 441 Nuclear Power Plants that are in operation worldwide. As all these plants are ageing (221 units are in operation for more than 20 years and 81 over 30 years), it becomes more and more important for the operators to manage this degradation mode in order to prevent accidents or leakages that can lead to personal injuries or unscheduled shutdowns.

The use of prediction tools like BRT-CICERO™ can help the operator to identify the most critical components and so to schedule the inspection and maintenance activities in a most efficient manner. International collaboration in the field of FAC is also very important so we can learn from each other and take into account the lessons learned. The international conference on Flow Accelerated Corrosion organized by EDF next May in Lyon France (www.fac2010.net) is one of the actions to improve the overall knowledge on FAC.

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