Prediction of Hernia Formation or Cracking of Boiler Water Tubes due to Corrosion

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Abstract

This work is part of the preventive maintenance of steam power plant equipment and installations. In boiler water pipes, hernia formation, cracking and perforation are recurrent and occur when the thermal power plant is operating at full capacity. This damage is largely due to corrosion and thinning of the tube wall. When corrosion progresses, the thinning of the tubes progresses simultaneously. From a certain value of the wall thickness, under the effect of water/steam pressure, the tubes deform and burst. In such a situation, it is important to predict approximately when these damages will occur, so that appropriate maintenance measures can be undertaken. For this, we seek to determine the corrosion rate and stresses in the tubes due to water/steam pressure, with a view to finding the maximum time limit not to exceed when replacing the tubes. Among the various methods for determining corrosion rate, it is the method based on weight measurement that has attracted our attention. Tube coupons were taken from a corroded boiler tube and from a new tube of the same characteristics, thus avoiding a study over a very long period, since corrosion takes several years to produce its mechanical effects. Knowing the difference in weight between a coupon of the new tube and that of the corroded tube, and the time of exposure of the tubes until damage, it became easy to determine the corrosion rate. From the corrosion rate and the calculation of stresses in the corroded tube, the maximum time limit to be exceeded for replacing tubes was determined, that is a maximum operating

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period of 10 years. The tubes must be replaced, in preventive maintenance, before the end of this time limit to prevent the aforementioned damage.

Keywords: Corrosion rate, stress, tube, boiler, operating time limit

Introduction

Hernia formation, cracking and perforation are major problems in the operation of steam thermal power plants. This damage results from a combined action of mechanical stress and an electrochemical reaction between the metal and the corrosive medium. This damage is often unpredictable and forces the operator to stop the production of electrical energy, in order to carry out the appropriate maintenance actions resulting in the cut of the damaged tubes and their replacement. The shutdown of electricity production thus caused inconvenience in businesses and other users: lack of air conditioning and damage to products kept cold, shutdown or decrease in production in businesses, late delivery and penalty for shortage of unproductive products, etc.

According to the writings of Baroux (2014), Bensabra (2016) and Chattopadhyay, (1995), it is noted that the deterioration of the tubes is largely due to metal corrosion. Corrosion is a relevant problem caused by boiler water. It is due to low pH, dissolved oxygen or carbon dioxide. It also results from the roughness of the metal surface or even the nature of the metal directly attacked. Other factors such as specific acid and chemical (corrosive) conditions, mechanical stress, fatigue, speeds and operating severity can have a significant influence on corrosion rate and produce different forms of attack,

Corrosion can be uniform over a wide area (promoting hernia formation and cracking) or can be much localized (promoting local perforation or pitting). In cases of attack of the metal by uniform corrosion, the effect is the thinning, over time, of the pipe wall, followed consequently by the formation of hernia or cracking under the effect of internal pressure exerted by water or steam.

In the hypothesis that the corrosion of the tubes would be uniform and only due to the interaction between water and metal, the aim is to predict the moments of appearance of damage at the level of the tubes (hernia and cracking). These times being known, preventive maintenance actions can be scheduled for tube replacement. In other words, production shutdowns can be planned, and to prevent inconvenience due to damage to the tubes, the decision may be to replace them at the appropriate time, with notice to users in time of the power cut for maintenance work. This would allow them to make arrangements to plan their activities taking into account the anticipated electricity shortage period.

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In the literature several works such as these of Benguedda (2024), Dinesh (2022), Drastiwati (2017), Duarte-Cordon (2017), Gauri (2014) and Ifeanyi (2023) deal with the damage of boiler tubes and its causes, among which corrosion, but do not lead to a true determination of the time limit for use of the tubes after which these must be replaced in preventive maintenance. This is why one of the important points in this work is to place particular emphasis on determining the operating time limit for boiler tubes.

The objectives

The objectives of this work are at three levels:

Firstly, the aim is to contribute to the reduction of unplanned production shutdowns due to corrosion damage to the tubes. In other words, it is to improve the maintenance efficiency by reducing the failure rate, increasing the boiler reliability and reducing the costs associated.

Secondly, it is important to know when the risk of hernia formation and tube cracking will be highest. For this, it is necessary to determine the stresses in the tube by considering the progressive thinning of the tube wall thickness due to corrosion. The knowledge of this moment makes it possible to trigger preventive maintenance actions, in particular the planning of the replacement of the tubes.

Finally, from an economic point of view, increasing productivity is an ongoing objective that calls for reducing operating and maintenance costs, particularly those related to the maintenance of water-steam system components. Water and steam losses due to damage to the water tubes, associated production shutdowns due to maintenance of the tubes and power cuts generate significant costs that constitute economic losses for the plant.

Achieving these objectives will not only increase the overall performance of the plant, but will reduce the inconvenience to users whenever there is a shutdown of power generation.

Methodology

To carry out this project, the first step is to understand and characterize the evolution of corrosion in the boiler tube wall, through a mathematical model. The aim is to determine the corrosion rate, which corresponds to the rate of thinning of the boiler tube. The method used to determine the corrosion rate is based on the weight loss per year of an experimental coupon cut from a tube undergoing corrosion. This method involves weighing the sample before and after exposure for a certain time to a corrosive environment. At the end of the exposure time, the specimen is cleaned and weighed. The corrosion rate is obtained by dividing the mass lost by the exposure time.

In a second step, it is essential to determine at the level of the tube the stresses due to the internal pressure of water or steam, taking into account the

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rate of tube thinning and the mechanical properties of the material that constitutes it. Determining the rate of thinning is equivalent to knowing the residual thickness of the tube wall, which decreases as corrosion progresses. As the residual thickness decreases, the stresses in the tube increase to reach or even exceed the yield stress.

By establishing a relationship between the rate of thinning and the stresses in the tube coupon, it becomes easy to determine the theoretical time at which hernias and cracks appear. As a result, it's possible to make judicious decisions in terms of the time required to replace corroded tubes as part of preventive maintenance.

Hypothesis: The rate of tube thinning is determined by considering that the corrosion is extended to the entire inner wall of the tube and evolves homogeneously, at the constant heating temperature.

Results

Uniform corrosion

Although there are several morphologies of corrosion, the one that concerns us in this work is uniform or generalized corrosion. This form of corrosion occurs in the same way on the entire inner surface of the boiler tube wall. The entire inner surface of the metal in contact with the boiler water/steam is attacked identically (Photos 1 below).

Uniform corrosion is the simplest and most classic of all other types of corrosion. It results from the manifestation of several individual electrochemical processes that occur uniformly across the considered surface. Inside the boiler tubes, it usually appears when the alkalinity of the water is low or when the metal is exposed to the oxygen contained in this water during service or downtime.

It results in a steady decrease in the thickness of the pipe wall if the corrosion products are soluble or uniform deposition over the entire surface of the metal if they are not. It progresses at constant speed over the entire surface of the metal exposed to water/steam. This rate of corrosion is therefore expressed by a decrease in the thickness of the metal per unit of time. It can also be expressed in weight loss per unit area and per unit time.

Uniform corrosion can be reduced or prevented by a suitable choice of boiler tube material, cathodic protection or modification of the aqueous medium (adequate treatment of boiler water, its degassing and its conditioning by the addition of anti-corrosion products).

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Photos 1: Examples of uniform corrosion.

Regular decrease of the tube wall.

(1)

(2)

(3)


Deposits of non-soluble corrosion products (sludge).

(4)

(5)

(6)


Sources: (1) Learn quality (2021); (2) Collaton consultancy limited (2020); (3) TLV, (4) Shutterstock (2020), (5) The news (2004), (6) Rasmussen mechanical services, Waldron R. (2022).

Expression of corrosion rate

For the determination of the corrosion rate by the weight loss method, this consists in cutting a specimen in section from a cylindrical tube of metal, cleaning it and to proceeding to its initial weighing (mass $\mathbf{m_1}$).

Then, a corrosive test fluid is maintained inside the tube section for a predefined exposure time (**Δt).** At the end of this period, the section is emptied of the fluid, thoroughly cleaned of corrosion products, and then weighed again (mass $\mathbf{m_2}$).

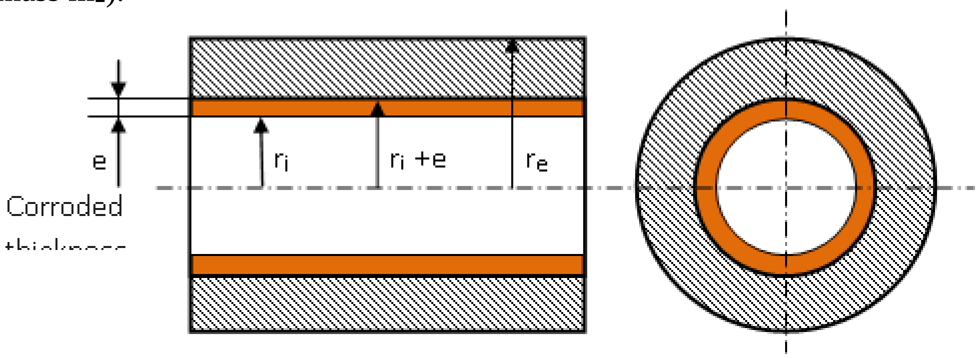

Figure 1: Test tube section in progressive uniform corrosion phase

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The lost mass due to corrosion is obtained by the difference between the initial mass (**m_1**) and the mass of the corroded metal (**m_2**).

$$\Delta m = m_1 - m_2$$

Through this formula, the corrosion rate is the result of dividing the lost mass (Δm) by the exposure time (Δt). It is defined as the loss of mass per unit time or the decrease in thickness per unit time. In practice, corrosion rate calculation is carried out for an annual time Δ**t** of exposure of the metal to corrosive fluid, in order to obtain a significant lost thickness. It is therefore expressed in grams lost per year (g/year), which can be converted into millimeters per year (mm/year) corresponding to the wall thickness lost per year or the thinning rate.

Thus, as the lost mass is Δm during a period Δ**t**, the corrosion rate designated by **V**c is expressed by the relationships:

$$V_c = \frac{Se\rho}{\Delta t} = \frac{\Delta m}{\Delta t} \quad \text{(mass lost per year)}$$

Or:

$$V_c = \frac{e}{\Delta t} = \frac{\Delta m}{\rho S \Delta t} \quad \text{(thickness lost per year)}$$

With the characteristics of the tube:

r_i : inner radius of the tube wall ;
r_e : outer radius of the tube wall ;
S : surface area of the sample in contact with the fluid (in cm^2) ;
e : total thickness lost (mm) ;
ρ : density of the metal (in g/cm^3) ;
E : Young's modulus ;
Δt : duration of exposure (in years) ;
Δm : mass loss over the exposure time (in g) ;
Vc : corrosion rate, in mass or thickness lost per year (g/year or mm/year).

Stresses in a boiler tube under corrosion

Based on the theories on strength of materials developed by Timoshenko (1968), it is a question of determining the stresses due to the steam pressure in the boiler tubes at full operating speed, taking into account the variation of thickness caused by corrosion (thinning of the wall of the tubes). Indeed, as corrosion progresses, the wall becomes thinner and causes the increase of stresses in the boiler tubes. In other words, the rate of corrosion has an influence on the increase of the stresses in the

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boiler tubes, and must be taken into account in the determination of these stresses.

We consider a section of thick boiler tube, represented by Figure 2 below, such that its extreme cross sections are sufficiently far from the extreme sections of the long tube.

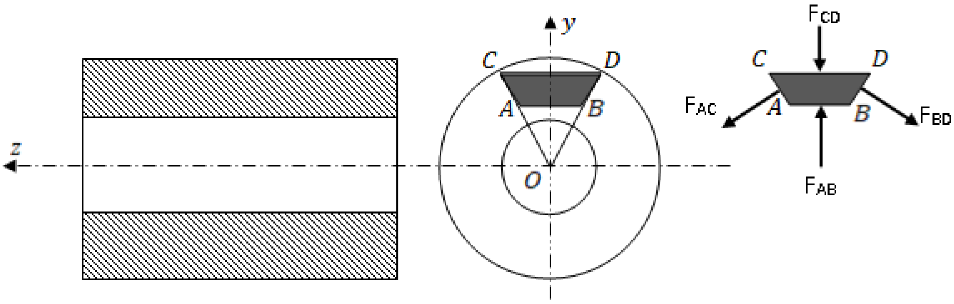

Figure 2: Boiler tube section

Assumptions

- During deformation, the plane sections before deformation remain flat after deformation if they are sufficiently far from the extreme sections of the tube where the axial stresses are zero and where the distribution of the other forms of stresses is complex;
- The fluid temperature is assumed to be constant and symmetrically distributed with respect to the tube axis throughout the duration of the test;
- The deformation is also symmetrical to the tube axis.

Elementary Volume Equilibrium Equation (ABCD)

An elementary tube volume (ABCD) represented by Figure 2 above is considered. We propose to establish the equation relating to the forces exerted on its facets.

Force on the facet (AB)

The radial stress σ_r is uniform at any point of the facet (AB). It is the tensile stress (in the radial direction) known as the external strength per unit area of the material resulting in the stretch of the material. Its basic expression is: σ_r = FABy/ds, where FABy is the strength applied on the area ds of facet (AB). FABy is determined in function of σ_r as follows: $\vec{F}_{ABy} = -\sigma_r ds\,\vec{y} = -2r\sin(d\varphi/2)l_o\sigma_r\,\vec{y} = -2r(d\varphi/2)l_o\sigma_r\vec{y} = -r\sigma_r d\varphi\, l_o\vec{y}$

With $d\varphi$ = angle between lines (AC) and (BD) and $\sin(d\varphi/2) \approx d\varphi/2$ (because infinitely small).

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Force on the facet (CD)

The stress $\sigma_r + \frac{\partial \sigma_r}{\partial r} dr$ is uniform in all point of the facet (CD).

The strength of this facet is expressed as follows: $\vec{F}_{CDy} = \left(\sigma_r + \frac{\partial \sigma_r}{\partial r} dr\right) x\ 2(r + dr)\sin(d\varphi/2) l_o\ \vec{y} = \left(\sigma_r + \frac{\partial \sigma_r}{\partial r} dr\right) x\ 2(r + dr)\ (d\varphi/2)\ l_o\ \vec{y}$ (with : $\sin(d\varphi/2) \approx d\varphi/2$) $= \left(\sigma_r + \frac{\partial \sigma_r}{\partial r} dr\right) x\ 2(r + dr)(d\varphi/2) l_o\ \vec{y} = \left(\sigma_r + \frac{\partial \sigma_r}{\partial r} dr\right) (r + dr) d\varphi\ x\ l_o\ \vec{y} = \left(\sigma_r + \frac{\partial \sigma_r}{\partial r} dr\right) (r + dr) d\varphi\ x\ l_o\ \vec{y} = \left(r\sigma_r + \sigma_r dr + r\frac{\partial \sigma_r}{\partial r} dr + \frac{\partial \sigma_r}{\partial r} dr^2\right) d\varphi\ x\ l_o\ \vec{y} = \left(r\sigma_r + \sigma_r dr + r\frac{\partial \sigma_r}{\partial r} dr\right) d\varphi\ l_o\ \vec{y}$

With $\frac{\partial \sigma_r}{\partial r} dr^2$ negligible, because $dr^2 \approx 0$, infitly small of higher order.

Force on Facet (AC)

The circumferential (or tangential) stress σ_t is expressed in the same manner as σ_r, but with deforming force tangent to a circular line in the cross-section of the material. It acts on a line perpendicular to the longitudinal and the radial stresses. This stress is caused by internal pressure and attempts to separate the pipe wall in the circumferential direction. It is not uniformly distributed at any point of the facet (AC). The one corresponding to a uniform distribution is the mean tangential stress σ_{tm} such as:

$$\sigma_{tm} = \frac{1}{2}\left(\sigma_t + \sigma_t + \frac{\partial \sigma_t}{\partial r} dr\right) = \sigma_t + \frac{\partial \sigma_t}{2\,\partial r} dr$$

Facet strength (AC) is expressed as: $\vec{F}_{ACy} = -\left(\sigma_t + \frac{\partial \sigma_t}{2\,\partial r} dr\right) x\ ds\ x\ \sin(d\varphi/2)\ \vec{y} = -\left(\sigma_t + \frac{\partial \sigma_r}{2\,\partial r} dr\right) x\ dr\ x\ (d\varphi/2)\ l_o\ \vec{y}$ (with : $\sin(d\varphi/2) \approx d\varphi/2$) $= -\frac{1}{2}\left(\sigma_t dr + \frac{\partial \sigma_r}{2\,\partial r} dr^2\right) x\ d\varphi\ x\ l_o\ \vec{y} = -\frac{1}{2}\sigma_t dr\ d\varphi\ l_o\ \vec{y}$ with : $dr^2 \approx 0$

Force on the facet (BD)

The force on the facet (BD) is identical to that on the facet (AC).

$$\vec{F}_{BDy} = -\frac{1}{2}\sigma_t dr\ d\varphi\ l_o\ \vec{y}$$

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Equilibrium equation according to $O\vec{\mathbf{y}}$

The sum of the forces is zero according to $O\vec{\mathbf{y}}$.

$$\sum \overrightarrow{F_y} = \vec{0} - r\sigma_r d\varphi l_o + \left(r\sigma_r + \sigma_r dr + r\frac{\partial \sigma_r}{\partial r}dr\right) d\varphi\ l_o - \sigma_t dr\ d\varphi\ l_o = 0$$

$$-r\sigma_r + r\sigma_r + \sigma_r dr + r\frac{\partial \sigma_r}{\partial r}dr - \sigma_t dr = 0\ \sigma_r - \sigma_t + r\frac{\partial \sigma_r}{\partial r} = 0$$

We have an equation with two unknowns. We need a second equation to determine σ_r and σ_t.

It should be noted that the equilibrium equation following $O\vec{\mathbf{x}}$ is without interest, because one finds an obvious equation of the form: $\sigma_r - \sigma_t = 0$.

Unit deformations of elementary volume (ABCD)

Radial deformation

We consider U = U(r) the radial displacement of the surface (AB) of radius r.

The surface displacement (CD) of radius r + dr is:

$$U + \frac{\partial U}{\partial r}dr$$

The total radial elongation Δl_r of the elementary volume will be:

$$\Delta l_r = U + \frac{\partial U}{\partial r}dr - U = \frac{\partial U}{\partial r}dr$$

It is the elementary volume deformation due to the tensile force in the radial direction. Its general expression is: $\Delta l_r = l_r - l_o$, where l_r is the length of the specimen after deformation and l_o its initial length.

The radial unit elongation ε_r of the elementary volume will be:

$$\varepsilon_r = \frac{\Delta l_r}{dr} = \frac{\frac{\partial U}{\partial r}dr}{dr} = \frac{\partial U}{\partial r}$$

The radial tensile strain (ε_r) is the relative length of deformation exhibited by the elementary volume subjected to a tensile force in the radial direction. In the general form, its expression is: $\varepsilon_r = \Delta l_r / l_o$.

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Tangential deformation

For the surface element (AB) of radius r, before tangential deformation, the arc is:

$$\widehat{AB} = rd\varphi$$

After deformation, the new radius is r + U and the new arc is:

$$\widehat{A'B'} = (r + U)d\varphi$$

The tangential deformation Δl_t is then:

$$\Delta l_t = (r + U)d\varphi - rd\varphi = Ud\varphi$$

The tangential unit elongation ε_t of the elementary volume will be: $\varepsilon_t = \frac{\Delta l_t}{rd\varphi} = \frac{Ud\varphi}{rd\varphi} = \frac{U}{r}c$ (corresponding to deformation in circonferential direction)

Hooke's law on radial and tangential deformations

It gives the unitary deformations ε_r and ε_t as a function of the stresses σ_r and σ_t.

$$\begin{cases} \varepsilon_r = \frac{\sigma_r}{E} - \frac{\upsilon\sigma_t}{E} \\ \varepsilon_t = \frac{\sigma_t}{E} - \frac{\upsilon\sigma_r}{E} \end{cases} \quad \text{(where E is Young's modulus and } \upsilon \text{ is Poisson's ratio)}$$

Young's modulus (E) is a property of the material that tells us how easily it can stretch and deform and is defined as the ratio of tensile stress (σ) to tensile strain (ε).

Poisson's ratio (υ) is the ratio of transverse contraction strain to longitudinal extension strain in the direction of the stretching force.

After solving the system of equations with respect to σ_r and σ_t, we obtain:

$$\begin{cases} \sigma_r = \frac{E}{1 - \upsilon^2}(\varepsilon_r + \upsilon\varepsilon_t) \\ \sigma_t = \frac{E}{1 - \upsilon^2}(\varepsilon_t + \upsilon\varepsilon_r) \end{cases}$$

We replace ε_r and ε_t by their expressions as a function of U to obtain:

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$$\begin{cases} \sigma_r = \frac{E}{1-\upsilon^2}\left(\frac{\partial U}{\partial r} + \upsilon\frac{U}{r}\right) \\ \sigma_t = \frac{E}{1-\upsilon^2}\left(\frac{U}{r} + \upsilon\frac{\partial U}{\partial r}\right) \end{cases}$$

Determination of σ_r and σ_t

We determine U by replacing σ_r and σ_t by their expressions (Hooke's law) in the previous equilibrium equation to obtain:

$$\frac{E}{1-\upsilon^2}\left(\frac{U}{r} + \upsilon\frac{\partial U}{\partial r}\right) - \frac{E}{1-\upsilon^2}\left(\frac{\partial U}{\partial r} + \upsilon\frac{U}{r}\right) - r\frac{\partial}{\partial r}\left[\frac{E}{1-\upsilon^2}\left(\frac{\partial U}{\partial r} + \upsilon\frac{U}{r}\right)\right] = 0$$

$$\frac{U}{r} + \upsilon\frac{\partial U}{\partial r} - \frac{\partial U}{\partial r} - \upsilon\frac{U}{r} - r\frac{\partial}{\partial r}\left(\frac{\partial U}{\partial r} + \upsilon\frac{U}{r}\right) = 0$$

$$\frac{U}{r} + \upsilon\frac{\partial U}{\partial r} - \frac{\partial U}{\partial r} - \upsilon\frac{U}{r} - r\left[\frac{\partial}{\partial r}\left(\frac{\partial U}{\partial r}\right) + \frac{\upsilon}{r}\frac{\partial U}{\partial r} - \upsilon\frac{U}{r^2}\right] = 0$$

$$\frac{U}{r} + \upsilon\frac{\partial U}{\partial r} - \frac{\partial U}{\partial r} - \upsilon\frac{U}{r} - r\frac{\partial^2 U}{\partial r^2} - \upsilon\frac{\partial U}{\partial r} + \upsilon\frac{U}{r} = 0$$

$$\frac{U}{r} - \frac{\partial U}{\partial r} - r\frac{\partial^2 U}{\partial r^2} = 0$$

Dividing this equation by r gives a homogeneous second-order differential equation with non-constant Euler coefficients:

$$\frac{\partial^2 U}{\partial r^2} + \frac{\partial U}{r\,\partial r} - \frac{U}{r^2} = 0$$

Solving the differential equation

To solve this equation of variable r, we make a change of variable in order to make the coefficients constant by assuming that:

$$r = e^{\alpha} \text{ (where } \alpha \text{ is the new variable) } \partial r = e^{\alpha}\,\partial\alpha, \text{ so } \frac{\partial r}{\partial \alpha} = e^{\alpha}$$

$$\frac{\partial U}{\partial r} = \frac{\partial U}{\partial \alpha} \text{ x } \frac{\partial \alpha}{\partial r} = \frac{\partial U}{\partial \alpha} / \frac{\partial r}{\partial \alpha} = \frac{\partial U}{\partial \alpha}/e^{\alpha} = \frac{\partial U}{e^{\alpha}\,\partial\alpha}$$

$$\frac{\partial^2 U}{\partial r^2} = \frac{\partial}{\partial r}\left(\frac{\partial U}{\partial r}\right) = \frac{\partial}{\partial r}\left(\frac{\partial U}{e^{\alpha}\,\partial\alpha}\right) = \frac{\partial}{\partial \alpha}\left(\frac{\partial U}{e^{\alpha}\,\partial\alpha}\right) \text{ x } \frac{\partial \alpha}{\partial r} = \frac{\frac{\partial}{\partial\alpha}\left(\frac{\partial U}{e^{\alpha}\,\partial\alpha}\right)}{\frac{\partial r}{\partial \alpha}}$$

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$$= \frac{\partial}{\partial \alpha}\left(\frac{\partial U}{e^{\alpha}\,\partial \alpha}\right)/e^{\alpha} = [\left(\frac{\partial^2 U}{\partial \alpha^2}e^{\alpha} - \frac{\partial U}{\partial \alpha}e^{\alpha}\right)/e^{2\alpha}]/e^{\alpha} = \left(\frac{\partial^2 U}{\partial \alpha^2} - \frac{\partial U}{\partial \alpha}\right)/e^{2\alpha}$$

$$\frac{\partial^2 U}{\partial r^2} = \left(\frac{\partial^2 U}{\partial \alpha^2} - \frac{\partial U}{\partial \alpha}\right)/e^{2\alpha}$$

By using the expressions of $\frac{\partial U}{\partial r}$ and $\frac{\partial^2 U}{\partial r^2}$ in the differential equation, we obtain:

$$\frac{\left(\frac{\partial^2 U}{\partial \alpha^2} - \frac{\partial U}{\partial \alpha}\right)}{e^{2\alpha}} + \frac{\frac{\partial U}{\partial \alpha}}{e^{2\alpha}} - \frac{U}{e^{2\alpha}} = 0 \text{ or merely } \frac{\partial^2 U}{\partial \alpha^2} - U = 0$$

We have a second-order differential equation with constant coefficients. We are looking for two particular integrals of the form $U = e^{k\alpha}$, where k is a constant to be determined.
We have:

$$U = e^{k\alpha}\ ;\ \frac{\partial U}{\partial \alpha} = me^{k\alpha}\ ;\ \frac{\partial^2 U}{\partial \alpha^2} = m^2 e^{k\alpha}$$

Carrying it into the differential equation with constant coefficients, we obtain:

$$k^2 e^{k\alpha} - e^{k\alpha} = 0, \text{which is reduced to: } k^2 - 1 = 0$$

The solutions are then: $k_1 = 1$ and $k_2 = -1$.

The particular integrals sought are then:

$$U_1 = e^{\alpha} \text{ et } U_2 = e^{-\alpha} = \frac{1}{e^{\alpha}}$$

Returning to the variable r, we obtain:

$$U_1 = r \text{ et } U_2 = \frac{1}{r}$$

The general integral we are looking for is: $U = C_1U_1 + C_2U_2 = C_1 r + \frac{C_2}{r}$ (where C_1 and C_2 are constants to be determined)

The unit deformations ε_r and ε_t are written as a function of r as follows:

$$\begin{cases} \varepsilon_r = \frac{\partial U}{\partial r} = C_1 - \frac{C_2}{r^2} \\ \varepsilon_t = \frac{U}{r} = C_1 + \frac{C_2}{r^2} \end{cases}$$

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Expressions of σ_r and σ_t

Replacing ε_r and ε_t in the expressions of σ_r and σ_t gives:

$$\begin{cases} \sigma_r = \frac{E}{1-\upsilon^2}(C_1 - \frac{C_2}{r^2} + \upsilon C_1 + \frac{\upsilon C_2}{r^2}) \\ \sigma_t = \frac{E}{1-\upsilon^2}(C_1 + \frac{C_2}{r^2} + \upsilon C_1 - \frac{\upsilon C_2}{r^2}) \end{cases}$$

$$\begin{cases} \sigma_r = \frac{E}{1-\upsilon^2}[C_1(1+\upsilon) - \frac{C_2(1-\upsilon)}{r^2}] \\ \sigma_t = \frac{E}{1-\upsilon^2}[C_1(1+\upsilon) + \frac{C_2(1-\upsilon)}{r^2}] \end{cases}$$

The constants C_1 and C_2 are determined by referring to the boundary conditions. Let Pi be the pressure at the inner surface of the tube and Pe the pressure at the outer surface of the tube.

We have:

$$\sigma_{ri} = -P_i \quad \text{(compression)}$$
$$\sigma_{re} = -P_e \quad \text{(compression)}$$

Introducing Pi and Pe into the expression of σ_r, we have:

$$\begin{cases} -P_i = \frac{E}{1-\upsilon^2}[C_1(1+\upsilon) - \frac{C_2(1-\upsilon)}{r_i^2}] \\ -P_e = \frac{E}{1-\upsilon^2}[C_1(1+\upsilon) - \frac{C_2(1-\upsilon)}{r_e^2}] \end{cases}$$

$$\begin{cases} -P_i = \frac{EC_1}{1-\upsilon} - \frac{EC_2}{(1+\upsilon)r_i^2} \\ -P_e = \frac{EC_1}{1-\upsilon} - \frac{EC_2}{(1+\upsilon)r_e^2} \end{cases}$$

$$\begin{cases} P_i = \frac{-EC_1}{1-\upsilon} + \frac{EC_2}{(1+\upsilon)r_i^2} \\ -P_e = \frac{EC_1}{1-\upsilon} - \frac{EC_2}{(1+\upsilon)r_e^2} \end{cases}$$

By adding the two equations, we derive:

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$$P_i - P_e = \frac{EC_2}{(1+\upsilon)}\left(\frac{r_e^2 - r_i^2}{r_e^2 r_i^2}\right) \; E$$

$$C_2 = \frac{(P_i - P_e)(1+\upsilon) r_e^2 r_i^2}{E(r_e^2 - r_i^2)}$$

$$C_1 = \frac{(1+\upsilon)(r_i^2 P_i - r_e^2 P_e)}{E(r_e^2 - r_i^2)}$$

The stresses σ_r and σ_t then take the expressions:

$$\begin{cases} \sigma_r = \dfrac{r_i^2 P_i - r_e^2 P_e}{r_e^2 - r_i^2} - \dfrac{(P_i - P_e) r_e^2 r_i^2}{r^2 (r_e^2 - r_i^2)} \\ \sigma_t = \dfrac{r_i^2 P_i - r_e^2 P_e}{r_e^2 - r_i^2} + \dfrac{(P_i - P_e) r_e^2 r_i^2}{r^2 (r_e^2 - r_i^2)} \end{cases}$$

Expressions of σ_r and σ_t in the case where the external pressure Pe = 0

When the boiler is in operation, the pressure outside the tubes is considered to be negligible compared to the zero steam pressure (Pe ≈ 0). The nullity of Pe translates in terms of equation by:

$$\begin{cases} \sigma_r = \dfrac{r_i^2 P_i}{r_e^2 - r_i^2} - \dfrac{P_i r_e^2 r_i^2}{r^2 (r_e^2 - r_i^2)} \\ \sigma_t = \dfrac{r_i^2 P_i}{r_e^2 - r_i^2} + \dfrac{P_i r_e^2 r_i^2}{r^2 (r_e^2 - r_i^2)} \end{cases}$$

$$\begin{cases} \sigma_r = \dfrac{r_i^2 P_i}{r_e^2 - r_i^2}\left(1 - \dfrac{r_e^2}{r^2}\right) \\ \sigma_t = \dfrac{r_i^2 P_i}{r_e^2 - r_i^2}\left(1 + \dfrac{r_e^2}{r^2}\right) \end{cases}$$

In the interval [ri , re] we consider the functions f(r) and g(r) such as:

$$f(r) = 1 - \frac{r_e^2}{r^2} \; \text{ et } \; g(r) = 1 + \frac{r_e^2}{r^2}$$

f(r) ≤ 0 and g(r) > 0 (because r is always less than re), hence σ_r is always a compressive stress, and σ_t is always a tensile stress.

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For r = ri, g(r) is maximum, so:

$$\sigma_t = \sigma_{t\,maxi} = \frac{P_i(r_e^2 + r_i^2)}{r_e^2 - r_i^2} \quad \text{(on the inner surface of the tube)}$$

For r = re, g(r) is minimum, so:

$$\sigma_t = \sigma_{t\,min} = \frac{2P_i r_i^2}{r_e^2 - r_i^2} \quad \text{(on the outer surface of the tube)}$$

Radial deformation of the tube

The expression of the radial strain is known:

$$U(r) = C_1 r + \frac{C_2}{r} = \frac{r(1+\upsilon)(r_i^2 P_i - r_e^2 P_e)}{E(r_e^2 - r_i^2)} + \frac{(1+\upsilon)(P_i - P_e) r_e^2 r_i^2}{rE(r_e^2 - r_i^2)}$$

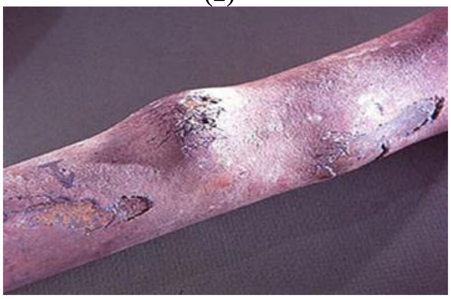
For Pe = 0, the radial displacement of the inner surface of the tube is: $U(r) = \frac{r(1+\upsilon)(r_i^2 P_i - r_e^2 P_e)}{E(r_e^2 - r_i^2)} + \frac{(1+\upsilon)(P_i - P_e) r_e^2 r_i^2}{rE(r_e^2 - r_i^2)} = \frac{r_i P_i}{E}\left(\frac{r_i^2 + r_e^2}{r_e^2 - r_i^2} + \upsilon\right)$

In this case, the radial displacement is outward. This can result in a hernia formation followed by a bursting of the boiler tube (see photos 2 below), if the wall of the tube decreases in thickness due to corrosion, or if the pressure Pi increases beyond the permissible limit value of the material.

Photos 2: Hernia and bursting of tubes due to the combined action of corrosion and pressure.

(1)

(2)



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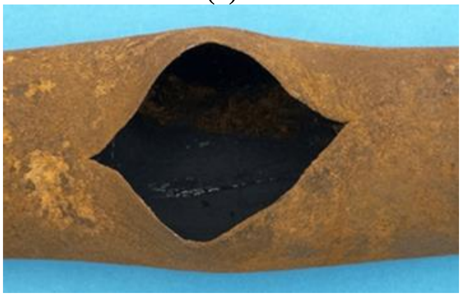
(3)

(4)



Sources : (1) Ait drivex (2017), (2) Veolia water technologies & solutions, (3) Buecker B. & Hughes T. (2020), (4) Yena engineering. (2017).

Maximum shear stress resulting from the combination of σ_r and σ_t

The maximum shear stress is defined by:

$$\tau_{max} = \frac{\sigma_t - \sigma_r}{2} = \left[\frac{P_i(r_i^2 + r_e^2)}{r_e^2 - r_i^2} + \frac{P_i(r_e^2 - r_i^2)}{r_e^2 - r_i^2}\right] = \frac{P_i r_e^2}{r_e^2 - r_i^2}$$

Shear stress is *the component of stress* denoted by τ *and* arises from the shear force T parallel to the specimen cross section S. It tends to cause deformation of a material by slippage along a plane also parallel to the specimen cross section. Its general expression is: τ = T/S.

When corrosion occurs, the thickness of the pipe wall decreases as operation continues over time. Knowledge of the corrosion rate makes it possible to determine when the corroded pipe needs to be replaced (as a preventive measure against possible breakage). Then it becomes essential to calculate the maximum shear stress as a function of the corrosion rate.

Let r_c be the inner radius of the boundary surface between the part of the tube undergoing corrosion and the non-corroded part which we define by:

$$r_c = ri + e = r_i + Vc \times \Delta t$$

With: ri = initial inner radius of the tube at the beginning of operation;
Vc = predefined tube corrosion rate;
Δt = duration of exposure of the tube in a corrosive environment;
e = Vc x Δt = loss of tube thickness due to corrosion during the exposure time Δt (corresponding to the increase in radius ri).

The expression of the maximum shear stress τmax becomes:

$$\tau_{max} = \frac{P_i r_e^2}{r_e^2 - (r_i + V_c \Delta t)^2}$$

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Tube Strength Condition

Let τ_l be the elastic limit stress of the tube at shear. The condition of the tube resistance to fracture is such that:

$$\tau_{max} \leq \tau_l = R_{pg} = R_{eg}/s$$

Where: Rpg = practical elastic limit stress on sliding
Reg = elastic limit stress on sliding
s = safety factor

Moment of Hernia Formation and Cracking (or Explosion)

Deterioration (herniation and then cracking) of the tube will occur when:

$$\tau_{max} > \tau_l = R_{pg}$$

$$\frac{P_i r_e^2}{r_e^2 - (r_i + V_c \Delta t)^2} > \tau_l$$

$$\tau_l[(r_i + V_c \Delta t)^2 - r_e^2] + P_i r_e^2 > 0$$

$$\tau_l(r_i^2 + V_c^2 \Delta t^2 + 2 r_i V_c \Delta t - r_e^2) + P_i r_e^2 > 0$$

Considering that V_c^2 is negligible, the inequality becomes:

$$\tau_l r_i^2 + 2\tau_l r_i V_c \Delta t - \tau_l r_e^2 + P_i r_e^2 > 0$$

$$\Delta t > \frac{\tau_l(r_e^2 - r_i^2) - P_i r_e^2}{2\tau_l r_i V_c} = \frac{R_{pg}(r_e^2 - r_i^2) - P_i r_e^2}{2\tau_l r_i V_c}$$

Period of Operation

The maximum operating time limit Δt_{max} will be such that:

$$\Delta t_{max} = \frac{R_{pg}(r_e^2 - r_i^2) - P_i r_e^2}{2\tau_l r_i V_c}$$

This is the time of hernia formation followed by cracking.

Application to the boiler tubes of a steam thermal power plant (a real case)

The tube sample used was steel with mechanical characteristics defined in the catalog of the Chinese supplier, Superbheater (2021).

Mechanical characteristics for JIS G3462 - STBA12 type steel used:

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Outer diameter = **60.3 mm**, thickness = **3.2 mm**, Re = **206 Mpa** (elastic limit stress).

We deduce from this:
Reg= 0.5Re = 0.5 x 206 = 103 Mpa (elastic resistance to slippage)
s = 1.3
τ_l= Rpg = Reg/s = 103/1.3 = 79 Mpa (practical slip resistance)
Pi = 45 bar
re = 60,3 mm (see figure 1)
ri = 57,1 mm (see figure 1)
Vc (to be determined)
τ_{maxi} (to be determined)
Δtmax (to be determined)

Corrosion rate

The corrosion rate was determined by the method based on the measurement of weight loss mentioned previously (section 3-2). Taking advantage of the downtime for corrective maintenance, a coupon (of length L = 200 mm) of this corroded tube was taken, which put us in an experimental study situation closer to reality. Because reproduce the study in the laboratory, over a long period, under the same conditions as those in a running boiler (pH, alkalinity, conductivity, content of impurities, oxygen concentration, operating temperature, and other characteristics of the water/steam) proved difficult and more expensive. A coupon of the same dimensions was taken from the replacement tube with the same mechanical characteristics as the corroded tube.

Exposure period Δt of the corroded tube to water/steam

The exposure period Δt of the water/steam corroded tube in the boiler was determined by differentiating between its crack date and its commissioning date (known from records).

Δt = (September 16, 2023) – (April 12, 2015) = (8 years + 4 months + 2 weeks) = **8.38 years**.

Lost mass

The corrosion loss mass Δm was determined by differentiating between the mass m_1 of the new replacement tube coupon and the mass m_2 of the corroded tube coupon.
m_1 = 900.7 g (obtained by weighing)
m_2 = 417.8 g (obtained by weighing)
$\Delta m = m_1 - m_2$ = 900.7 - 417.8 **= 482.9 g**

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Corrosion rate in lost mass per year

In the case of a loss of mass m over time t, corrosion rate Vc is expressed by the relation:

$$Vc = \frac{\Delta m}{\Delta t} = \frac{482{,}9}{8{,}38} = \mathbf{57{,}62\ g/an} \quad \text{(mass lost per year)}$$

Corrosion rate in lost thickness per year

The corrosion rate can be expressed in lost thickness per year from the previous results as follows:

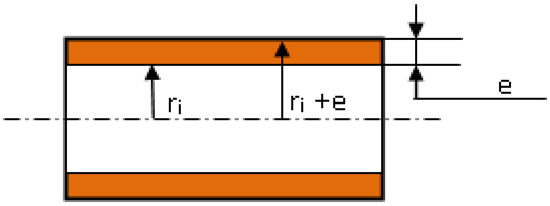

Figure 3: Portion of the corroded tube coupon corresponding to the lost mass

The mass lost m is expressed by the formula:
$\Delta m = \pi\rho L[(r_i + e)^2 - r_i^2] = \pi\rho L(r_i^2 + e^2 + 2er_i - r_i^2) = \pi\rho L(e^2 + 2er_i)$ where e is the total thickness lost during the exposure time of the corroded tube Δt.
$m/\pi\rho L = e^2 + 2er_i$
$e^2 + 2er_i - \Delta m/\pi\rho L = 0$
$e^2 + 2 \times 2.695e - 482.9/3.14 \times 7.85 \times 20 = 0$
$e^2 + 5.39e - 0.98 = 0$
$\Delta = (5.39)^2 + 4 \times 0.98 = 32.97$
$e_1 = (-5.39 + (32.97)^{1/2})/2 = 0{,}176$
$e_2 = (-5.39 - (32.97)^{1/2})/2 = -5.565$ (impossible case)

The corrosion rate Vc in lost thickness per year is given as follows:

$Vc = e_1/\Delta t = 0.176/8.38 =$ **0.021 cm/year** = **0.21 mm/year**

Limited Operating Time

The operating life limit Δtmax corresponding to the beginning of tube damage is calculated from its structural formula in subsection 3-3-5-3:

$\Delta tmax = [79(3.015^2 - 3.015)^2 - 4.5(3.015)^2]/(2 \times 79 \times 2.695 \times 0.021) =$ **11.56 years**

Δtmax = **11 years + 6 months + 3 weeks.**

Shear stress

The shear stress is obtained using the expression developed in subsection 3-3-5:

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Shear stress just before shutdown for corrective maintenance

τ = [4.5 x $(3.015)^2$)] / [$(3.015)^2$ – (2.695 + 0.021 x 8.38)] = **48.26 Mpa** < Rpg = 79 Mpa

Maximum shear stress corresponding to the moment of hernia formation
τmax = [4.5 x $(3.015)^2$)] / [$(3.015)^2$ – (2.695 + 0.021 x 11.56)] = **89.16 Mpa** > Rpg = 79 Mpa

It is noted that the maximum shear stress τmax exceeds the practical elastic limit stress at the slip Rpg, giving rise to the formation of hernia followed by cracking. The calculations show that the practical yield stress at slip Rpg = 79 Mpa corresponds to a duration of operation Δt = 11.09 years ≈ 11years + 1 month. Since the temperature and characteristics of the water in the boiler are not stable, the corrosion rate is not absolutely controllable, despite the provisions of good operating practices. To operate the boiler tubes under conditions of lower risk of deterioration, we recommend an operating life of Δtmax = **10 years**, corresponding to a maximum shear stress τmax = 62.81 Mp **<** Reg. At the end of these 10 years, the tubes should be replaced for preventive maintenance.

Illustration of the evolution of the operating life limit in relation to the corrosion rate

For several successive corrosion rate values, the corresponding values of the operating limit time Δtmax are given in the table below and are represented graphically by Figure 4.

Table: Maximum operating time Δtmax as a function of the corrosion rate

Vc (mm/year)	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1
Δtmax (year)	24,29	12,14	8,09	6,07	4,85	4	3,47	3,03	2,7	2,43

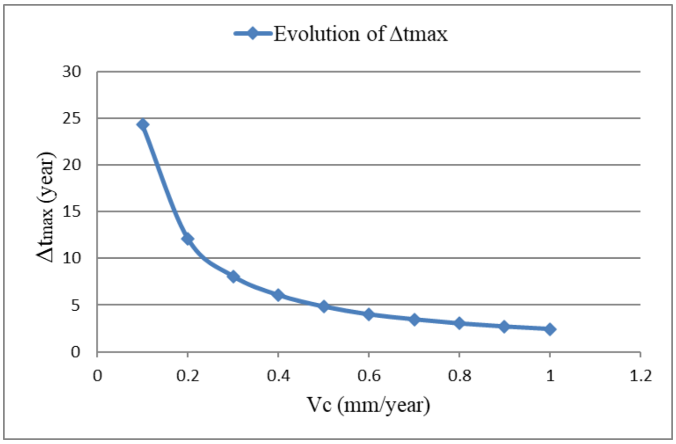

Figure 4: Trend of the evolution of the maximum duration Δtmax

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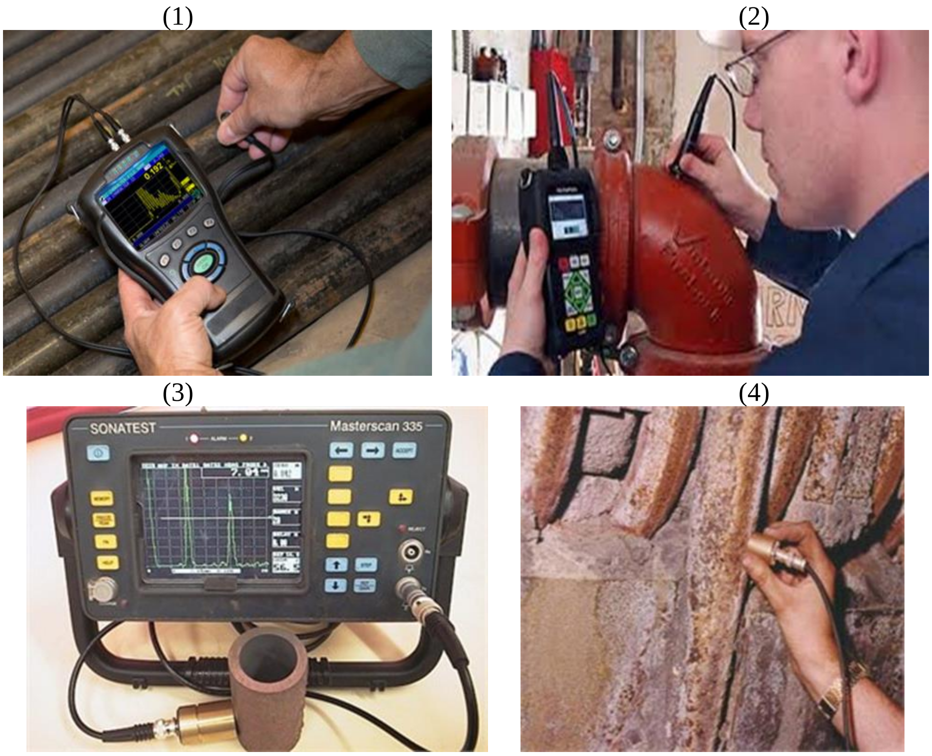
The curve shows that the greater the corrosion rate Vc, the shorter the operating time Δtmax of the tubes before deterioration. It is the responsibility of the maintenance worker to determine the corrosion rate and to associate it with the corresponding Δtmax on the curve. The planning of tube replacement is then made by deciding on a time lower than Δtmax.

For greater accuracy, the curve can be exploited using other (not available to us) practical means to inspect and determine the corrosion rate at regular time intervals from knowledge of the residual thickness. These include:

- Phased array;
- Conventional ultrasound;
- Eddy currents multi-element;
- Time-of-flight diffraction of ultrasound;
- Guided waves;
- Fluorescence and X-ray diffraction;
- Remote visual inspection.

The corrosion rate could be deduced from the value indicated by the measuring device and entered into the expression of Δtmax.

Photos 3: Measurement of the evolution of corrosion.



Sources: (1) Sofranel (2025), (2) Evident, (3) & (4) Kapayeva (2017).

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Other factors responsible for boiler tube bursting

In addition to corrosion, other factors to watch out for can cause boiler tube bursting:

- Poor quality of boiler design, manufacturing, and installation;
- The poor quality of the material used to make the tubes or the has serious defects;
- Early wear of the tubes by combustion products;
- Poor water circulation due to the presence of various objects forgotten in the boiler during maintenance operations;
- The formation of scale in the tubes;
- A severe shortage of water in the boiler causing the local temperature of the tube wall to be too high;
- The concentration of local heat in tubes, due to inadequate adjustment of the burner angle;
- The absence or irregularity of chimney sweeping, causing uneven or irregular heating of the tubes in the combustion chamber.

Conclusion

Articulated around the prediction of boiler tube deterioration in the presence of uniform corrosion this study helps to plan the replacement of boiler tubes in preventive maintenance. As mentioned above, uniform corrosion occurs at the same rate at any point on the surface of the metal in contact with water/steam, resulting in a steady decrease in the thickness of the metal. This results in an increase in the stress in the boiler tubes and their deterioration, with the consequent cessation of the energy supply.

Based on the knowledge of the corrosion rate, which then becomes an important factor, the stress expression in the boiler tubes has been determined. This expression highlights the rapid increase in stresses, as a function of the corrosion rate, and therefore the expected moment of deterioration of the tubes. Indeed, it is interesting to note that calculations of corrosion rate and stresses in tubes make it possible to predict and plan maintenance and replacement actions for boiler tubes. It is not necessary to wait for the elastic limit stresses in the tubes to be reached, but it is necessary to cut and replace these tubes well before any unfortunate incident.

For example, the expressions of corrosion rate, shear stress and tube life shown in a graph were validated for a real case of corroded boiler tube.

The application was conducted using the corrosion weight loss measurement method where tube coupons were taken during a preventive maintenance shutdown, on one hand on a corroded boiler tube, and on the other hand on a new tube of the same characteristics. This application showed

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that the time limit for using the tubes not to be exceeded was approximately 10 years.

In the light of the results, our recommendation was that the tubes should be systematically replaced at the end of their service life, starting from the date of their commissioning. We insist that the operator ensure that the boiler's supply water is of good quality. Indeed, to avoid any corrosion nuisance, it must be vigorously combated by all means. And what we must therefore emphasize is the rigor in the treatment of boiler water, but also the proper setting of the purges. Good boiler water quality will prevent corrosion and its consequences, increase the life of boiler tubes, reduce time losses and maintenance costs and ensure good reliability of the installation.

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Data Availability: All data are included in the content of the paper.

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References:

1. Ait drivex (2017, mars-avril). *Ait drivex, 40 ans d'expérience contre l'encrassement et* la *corrosion acide des chaudières* [photo Ait drivex]. *Bioénergie international* (48) https://www.bioenergie-promotion.fr/50088/bioenergie-international-n48-mars-avril-2017
2. Baroux, B. (2014). *La corrosion des métaux*. Dunod.
3. Benguedda, H. (2024). *Étude de phénomène d'apparition des hernies dans les tubes d'eau des chaudières de la zone 3* [Mémoire de Master, Université de Mostaganem]. DSpace EBIBLIO. http://e-biblio.univ-mosta.dz/handle/123456789/26676
4. Bensabra, H. (2016). *Cours de corrosion et protection des métaux*. [note de cours]. Université de JIJEL. https://fr.scribd.com/document/575990492/cours-sur-Corrosion-et-Protection-des-Metaux
5. Buecker B. & Hughes T. (2020). *Les défis du traitement d'eau de chaudière industrielle.* [Google image online]. *PPCHEM Journal, 22*(6), 252-259. https://journal.ppchem.com/
6. Chattopadhyay, P. (1995). *Boiler operations questions and answers*. Mc Graw-Hill, Inc.
7. Collaton Consultancy Limited (2020, January 12). *General water treatment* [Google image online]. https://www.collatonconsultancy.com/blog/2020/01/12/what-is-corrosion/

 ISSN: 1857-7881 (Print) e - ISSN 1857-7431

8. Dinesh S., & Jose, A. V. V. (2022). Analysis of corrosive degradation and failure of water wall tubes. *Materials Today: Proceedings*, 62(4), 2168-2172. https://doi.org/10.1016/j.matpr.2022.03.359
9. Drastiwati, N. S., Zakiyya, H., Utama, F. Y., & Kurniawan, W. D. (2017, August 24). *Preliminary study of failure analysis on tube material boiler based on pressure aspect*, [Paper presentation]. The 2nd Annual Applied Science and Engineering Conference, Bandung, Indonesia. doi:10.1088/1757-899X/288/1/012110.
10. Duarte-Cordon, C. A., Espejo, E., & Martinez, J. C. (2017, September). Failure analysis of the wall tubes of a water-tube boiler. *Engineering Failure Analysis*, *79*, 704-713.
11. Evident. *45MG pour le contrôle de la corrosion*. [Google image online]. https://ims.evidentscientific.com/fr/products/thickness-gauges/45mg
12. Gauri, M. Z., Sankhala, K., & Dharmendra, K. J. (2014). Remaining life analysis of boiler tubes on behalf of hoop stresses produced during operation of power plant. *Journal of Engineering Research and Applications*. *4*(7), 34-38.
13. Ifeanyi E. K., Inglis, H. M., & Kok, S. (2023). Prediction of the time to failure of boiler tubes flawed with localized erosion. *J. Pressure Vessel Technol*. *145*(2): 021502 (9 pages). https://doi.org/10.1115/1.4056606.
14. Kapayeva S. D., Bergander M. J., Vakhguelt A., & Khairaliyev S. I. (2017, December 31). Remaining life assessment for boiler tubes affected by combined effect of wall thinning and overheating. *Journal of Vibroengineering*. *19*(8). https://www.extrica.com/article/18219. https://doi.org/10.21595/jve.2017.18219
15. Learn Quality (2021, May 8). *Corrosion, featured*. [Google image online]. https://learn-quality.com/what-is-corrosion/
16. Rasmussen Mechanical Services, Waldron R. (2022, April 4). *How boiler feed water affects boiler operations* [Google image online]. https://www.rasmech.com/blog/boiler-feed-water-quality-affect-boiler-operations/#:~:text=Low%2Dquality%20boiler%20feedwater%20contains,are%20in%20your%20raw%20water.
17. Shutterstock (2020, 9 Mars). *Tuyau d'eau bouché, couche de corrosion* [Google image online]. https://www.shutterstock.com/fr/search/metal-corrosion
18. Sofranel (2025). *ECHO 9 Série: Mesure d'épaisseur de corrosion* [Google image online]. https://www.sofranel.com/fr/echo-9-serie
19. Superbheater (2021). *Le premier service de chauffage électrique en Chine*.
https://www.superbheater.com.

 ISSN: 1857-7881 (Print) e - ISSN 1857-7431

21. The news (2004, October 18). *Benefits of ultrasonic testing in determining pipe corrosion.* [Google image online]. https://www.achrnews.com/articles/93529-benefits-of-ultrasonic-testing-in-determining-pipe-corrosion
22. Timoshenko, S. P. (1968). *Résistance des matériaux – tome 1: théorie élémentaire et problèmes* (3ème ed.). Dunod.
23. TLV. *Corrosion dans les conduites de vapeur et de condensât*. [Google image online]. https://www.tlv.com/fr-fr/steam-info/steam-theory/problems/corrosion
24. Veolia water technologies & solutions. *Water handbook - boiler system failures.* [Google image online]. https://www.watertechnologies.com/handbook/chapter-14-boiler-system-failures
25. Yena engineering (2017, Mars-April). *What are the root causes of boiler tube failures?*
[Google image online]. https://yenaengineering.nl/root-causes-of-boiler-tube-failures/