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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 equipment and installations of a steam thermal power plant. At the level of the boiler water tubes, hernia formation, cracking, and perforation are recurrent and appear when the thermal power plant is operating at full speed. This damage is largely due to corrosion and thinning of the pipe 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 the approximate time of occurrence of such damage, in order to undertake the appropriate maintenance deaths. For this, we seek to determine the corrosion rate and stresses in the tubes due to water/steam pressure, in order to find the maximum limit time not to exceed to replace the tubes. Tubes must absolutely be replaced 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.

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 very 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.

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 about increasing the boiler availability rate by reducing the failure rate.

Secondly, from the stress calculations in the tubes, taking into account the progressive thinning of the tubes due to corrosion, it is important to know when the risk of hernia formation or cracking will be higher. 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 pipes, associated production shutdowns due to maintenance of the pipes and power cuts generate significant costs that constitute economic losses for the plant. And improving productivity means limiting all these losses to the bare minimum.

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 objective is to know the rate of corrosion that corresponds to the rate of tube thinning, so as to know at what thickness and when hernia formation and cracking could appear.

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 rate of tube thinning and the mechanical properties of the material that constitutes it.

The determination of the rate of thinning and stresses in the tubes should lead to the prediction of the theoretical moment of appearance of hernias and cracks. This would enable sound preventive maintenance decisions to be made.

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 after).

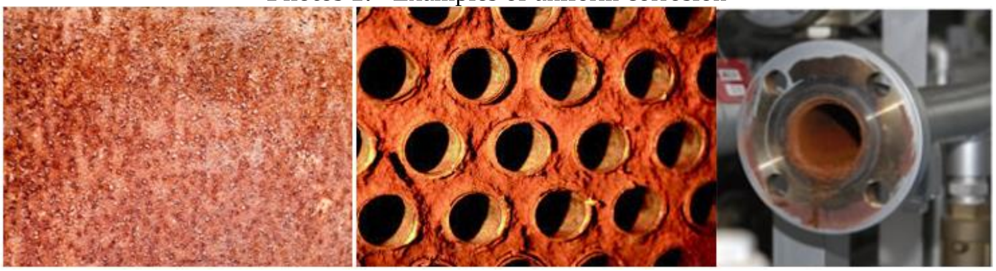
Uniform corrosion is the simplest and most classic of all other types of corrosion. It results from the manifestation of several individual electrochemical processes that occur uniformly across the considered surface. Inside the boiler tubes, it usually appears when the alkalinity of the water is low 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).

Photos 1: Examples of uniform corrosion



a) Regular decrease of the tube wall

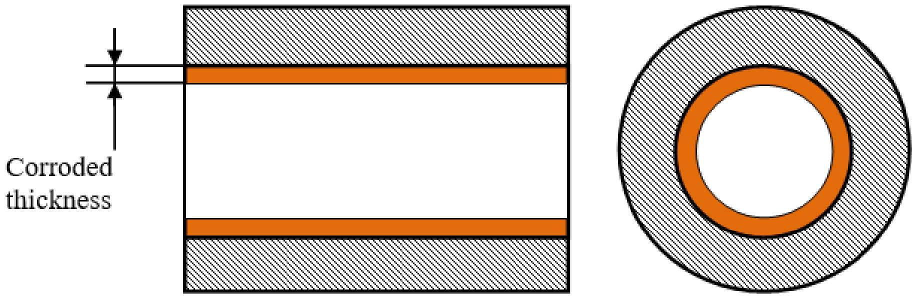
b) Deposits of non-soluble corrosion products (sludge)
Sources: Google images (corrosion of boiler tubes)

Determination of corrosion rate

The determination of the corrosion rate can be done by the weight method which consists in cutting a specimen in section from a cylindrical tube of metal, to clean it and to proceed 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, cleaned of corrosion products, and then weighed again (mass $\mathbf{m_2}$).

Figure 1: Test tube section in progressive uniform corrosion phase



The lost mass due to corrosion is then obtained by the formula:

$$\Delta m = m_1 - m_2 \tag{1}$$

Through this formula, the rate of corrosion can be defined as the decrease in thickness per unit time or the loss of mass per unit area and per unit time. In practice, corrosion rate calculations are carried out for an annual time **t** of exposure of the metal to corrosive fluid, in order to obtain a significant lost thickness. Thus, in the case of a loss of mass Δm during a period **t**, the corrosion rate **V**c (in thickness lost per unit time) is expressed by the relationship:

$$\frac{Se\rho}{\Delta t} = \frac{\Delta m}{\Delta t} \quad \text{(masse perdue par unité de temps)}$$

Corrosion rate:

$$V_c = \frac{e}{\Delta t} = \frac{\Delta m}{\rho S \Delta t} \tag{2}$$

With: S: sample area in contact with fluid (cm2);
e: total thickness lost (mm);
ρ: density of metal (g/cm3);
Exposure time (in years);
m: mass loss over exposure time (in g);
V_{corr}: corrosion rate or thickness lost per year (in mm/year or g/year).

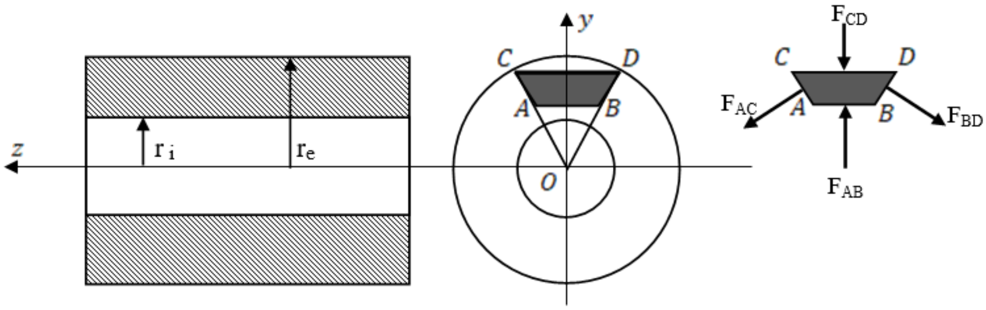
Stresses in a boiler tube under corrosion

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

Characteristic of the boiler tube

A thick boiler tube section, shown in Figure 2 below, is considered to be such that its extreme cross sections are sufficiently distant from the extreme sections of the long tube.

Figure 2: Boiler tube section



Note:

r_i= inner radius of tube wall

r_e= outer radius of tube wall

E = Young's module

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 stressσ_r is uniform at any point of the facet (AB). The expression of strength on this facet is:

$$\vec{F}_{ABy} = -\sigma_r ds\,\vec{y} = -2r\sin(d\varphi/2) l_o \sigma_r\,\vec{y} = -2r(d\varphi/2) l_o \sigma_r \vec{y} \\ = -r\sigma_r d\varphi\, l_o \vec{y}$$

With dφ= angle between lines (AC) and (BD) and sin(dφ/2) dφ/2 (because infinitely small).

Force on the facet (CD) Te 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 in:

$$\vec{F}_{CDy} = \left(\sigma_r + \frac{\partial \sigma_r}{\partial r} dr\right) x\ 2(r + dr)\sin(d\varphi/2) l_o\,\vec{y}$$

$$= \left(\sigma_r + \frac{\partial \sigma_r}{\partial r} dr\right) x\ 2(r + dr)\ (d\varphi/2)\ l_o\,\vec{y} \qquad \text{Avec : } \sin(d\varphi/2) \approx d\varphi/2$$

$$= \left(\sigma_r + \frac{\partial \sigma_r}{\partial r} dr\right) x\ 2(r + dr)(d\varphi/2) l_o\,\vec{y}$$

$$= \left(\sigma_r + \frac{\partial \sigma_r}{\partial r} dr\right) (r + dr) d\varphi\ x\ l_o\,\vec{y}$$

$$= \left(\sigma_r + \frac{\partial \sigma_r}{\partial r} dr\right) (r + dr) d\varphi\ x\ l_o\,\vec{y}$$

$$= \left(r\sigma_r + \sigma_r dr + r\frac{\partial \sigma_r}{\partial r} dr + \frac{\partial \sigma_r}{\partial r} dr^2\right) d\varphi\ x\ l_o\,\vec{y}$$

$$= \left(r\sigma_r + \sigma_r dr + r\frac{\partial \sigma_r}{\partial r} dr\right) d\varphi\ l_o\,\vec{y}$$

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

Force on Facet (AC)

The stress σ_t 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 (CA) is expressed as:

$$\vec{F}_{ACy} = -\left(\sigma_t + \frac{\partial \sigma_t}{2\,\partial r} dr\right) x \; ds \; x \; \sin(d\varphi/2)\, \vec{y}$$

$$= -\left(\sigma_t + \frac{\partial \sigma_r}{2\,\partial r} dr\right) x \; dr \; x \; (d\varphi/2)\, l_o \, \vec{y} \qquad \text{with} : \sin(d\varphi/2) \approx d\varphi/2$$

$$= -\frac{1}{2}\left(\sigma_t dr + \frac{\partial \sigma_r}{2\,\partial r} dr^2\right) x \; d\varphi \; x \; l_o \, \vec{y}$$

$$= -\frac{1}{2}\sigma_t dr \, d\varphi \, l_o \, \vec{y} \qquad \text{with} : dr^2 \approx 0$$

Force on the facet (BD)

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

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

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

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

$$\sum \vec{F_y} = \vec{0}$$

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

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

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

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 $O\vec{x}$ 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 of the elementary volume will be:

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

The radial unit elongation of the elementary volume will be:

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

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 is then:

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

The tangential unit elongation of the elementary volume will be:

$$\varepsilon_t = \frac{\Delta l_t}{rd\varphi} = \frac{Ud\varphi}{rd\varphi} = \frac{U}{r}$$

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.

$$\begin{cases} \varepsilon_r = \dfrac{\sigma_r}{E} - \dfrac{\upsilon\sigma_t}{E} \\ \varepsilon_t = \dfrac{\sigma_t}{E} - \dfrac{\upsilon\sigma_r}{E} \end{cases}$$

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

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

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

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

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:

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

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

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

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

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

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 $U = e^{m\alpha}$, where m is a constant to be determined. We have:

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

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

$$m^2 e^{m\alpha} - e^{m\alpha} = 0, \qquad \text{soit :} \quad m^2 - 1 = 0$$

The solutions are then: $m_1 = 1$ and $m_2 = -1$.

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:

$$U = C_1 U_1 + C_2 U_2 = C_1 r + \frac{C_2}{r}$$

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

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

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 P_i be the pressure at the inner surface of the tube and P_e the pressure at the outer surface of the tube. We have:

$$\sigma_{ri} = -P_i \qquad \text{(compression)}$$

$$\sigma_{re} = -P_e \qquad \text{(compression)}$$

Introducing P_i and P_e 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:

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

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

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

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 $P_e = 0$

When the boiler is in operation, the pressure outside the tubes is considered to be negligible compared to the zero steam pressure ($P_e \approx 0$). 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 $[r_i , r_e]$ we consider the functions f(r) and g(r) such as:

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

$f(r) \leq 0$ and $g(r) > 0$ (because r is always less than r_e), hence σ_r is always a compressive stress, and σ_t is always a tensile stress.

For $r = r_i$, 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 in the next), 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.

Photo 2: Bursting of tubes due to the combined action of corrosion and pressure

Sources : Google images (Boiler tube damage)

Shear stress (maximum resulting from the combination of σ_r and σ_t
The maximum shear stress is defined by:

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

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 tube being corroded defined by:

$$r_c = r_i + V_c \text{ x } t$$

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

The expression of the maximum shear stress τ_{max} becomes:

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

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:

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

R_{pg} = practical elastic limit stress on sliding
R_{eg} = 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:

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

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

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

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

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

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

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

Period of operation

The maximum operating time limit will be such that:

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

Application to the boiler tubes of a steam thermal power plant

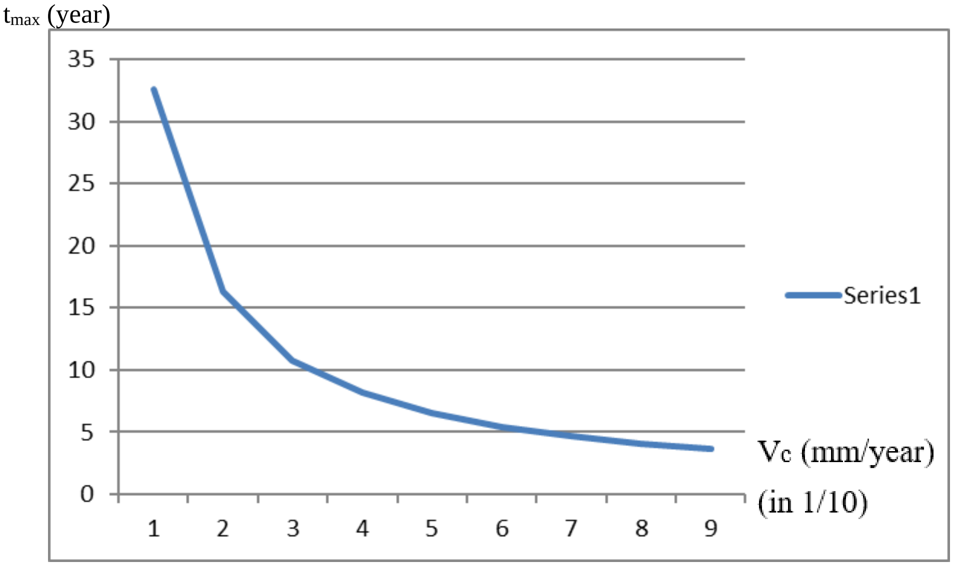
The mechanical characteristics of the tube are manufacturer's data for JIS G3462 - STBA12 type steel, outer diameter = 60.3 mm, thickness = 3.2 mm. Re = 206 Mpa (elastic limit stress). We deduce from this:

R_{eg}= 0.5Re = 0.5 x 206 = 103 Mpa
s = 1.3
τ_l= R_{pg} = R_{eg}/s = 103/1.3 = 79 Mpa
P_i = 45 bar
r_e = 60,3 mm
r_i = 57,1 mm
V_c (see table below)
t_{max} (to be determined)

Table:1 Limited duration tmax as a function of the corrosion rate

Corrosion rate Vc (mm/year)	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9
Limited duration tmax (year)	32,6	16,3	10,8	8,14	6,51	5,43	4,65	4,07	3,62

Figure 3: Trend of the evolution of the maximum duration tmax as a function of the corrosion rate



The curve shows that as the corrosion rate V_c increases, the maximum operating time of the tubes before deterioration decreases. It is up to the maintainer to determine the corrosion rate and to associate it with the corresponding t_{max} on the curve. This is followed by the planning of the tube replacement by deciding on a time lower than t_{max}.

Note:
Other practical methods that can be used to inspect and determine the corrosion rate, at regular time intervals, based on knowledge of the residual thickness, 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 can be deduced from the value indicated by the measuring device and entered into the t_{max} expression.

Photos 3: Measurement of the evolution of corrosion

Source : Google images

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 well before that the tubes must be cut and replaced to avoid any deplorable incidents.

To avoid any inconvenience from corrosion, it must be vigorously combated by all means. What must be rigorously emphasized is the treatment of boiler water. Good boiler water quality will prevent corrosion and its consequences, increase the service life of boiler tubes, reduce time loss and maintenance costs, and ensure good plant reliability.

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