Probability of Failure of Thermal Power Plant Boiler Tubing System Due to Corrosion

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Corrosion is irreversible process of material degradation. Due to detrimental effects exerted on the operating material characteristics, especially in the boiler tube system, it is of one the most important issues in the operation of thermal plants and is considered to be the root cause of many outages. Besides common remaining life assessment methods, it is useful to apply a method of reliability evaluation of the thermal power plant boiler tubes with corrosion damages. Correlation of results obtained by these two methods makes possible to obtain a better knowledge of current tubes material state as well as a more accurate assessment of their behavior during future exploitation. Therefore, an integrated approach of remaining life assessment and reliability evaluation, on the first stage reheater tubes system example, is presented in this paper. Considerations of this kind are very important for the risk-based maintenance programs.

Keywords: *Thermal power plant, corrosion, remaining life assessment, reliability evaluation.*

1. INTRODUCTION

Boiler tubes have limited life and can fail due to various failure mechanisms [1]. Corrosion is the one of the main damage mechanisms in power plants and process industry together with high temperature creep and fly ash erosion, and in boilers corrosion damage is a leading cost in the fossil fuel industry [2]. Corrosion is irreversible process of material degradation and due to detrimental effects exerted on the material characteristics, especially in the boiler tube system, is one of the most important issues in the operation of thermal plants and is considered to be the root cause of many outages.

Reduction of the useful life of boiler tube system due to degradation effects of corrosion and the ever-growing need for a pre-determined availability of a plant unit prompted a number of studies aimed at determining the residual life of boiler tube systems operating under conditions of a particular corrosion mechanism.

However, despite the knowledge of a particular corrosion mechanism, the variety of the corrosion mechanisms operating at different heating surfaces of thermal plant units [3-7] makes the selection of a proper method for determining the residual life a very complex task since the kinetics of the process involved is difficult to determine (function of many variables). This is because the corrosion kinetics is a function of a large number of parameters affecting the quality of working environment and the material corrosion resistance under given operating conditions. On the other hand, even if the means to overcome this problem is available, it is still unclear how to correct and adjust the data obtained from a limited sampling size to represent the state of an entire heating surface.

Until today several techniques are used to monitor corrosion and predict corrosion rates in a boiler. In practice, digital ultrasonic thickness measurement is one of the less complex, low cost and the most usual forms of inspection technologies for generalized or localized corrosion which has been widely accepted [2]. The data collected from ultrasonic UT inspections and service experience is utilised to evaluate the condition of the tubes.

In this paper, a large set of data collected at the first stage of reheater tube system at 350 MW Unit power plant, which was in service for about 60000 hours, is utilised for: statistical analysis of boiler tubes outages and inspection data; and development of a method for estimating remaining life and reliability of reheater tubing system subjected to corrosion deterioration with time.

2. BACKGROUND

It is well known that the reliability assessment of a heating surface is consist of a deterministic, and probabilistic and statistics parts of estimation which are mutually correlated [8,9]. Under the conditions of inner-side corrosion, the reliability of a component is defined by:

(i) initial corrosion resistance of material,
(ii) operating conditions and induced stresses in the tube walls and
(iii) quality of the working environment which influences the corrosion, Fig 1.

Reliability assessment based on the determination of the probability of failure (PoF) is at the same time an extension of the method for evaluating the residual life of any component which is greatly affected by the accuracy of the input data. This method minimizes the

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errors in residual life estimation that would otherwise occur if the data were obtained from a single sample.

The input data, which must describe the metal state, depend on the number and type of the present damage areas, whereas the data that describe the quality of the working environment could not be precisely assessed but rather assumed only. From the accuracy point of view, this requires introduction of certain limitations such as:

- containment of corrosion damage and its kinetics whereby the steam pressure and temperature are the input data from the working environment, while the material strength with corrosion damages is the input data from the material point of view
- selection of an appropriate mechanical model for life assessment as well as other required data
- symbols in your equation have been defined before the equation appears or immediately follows.

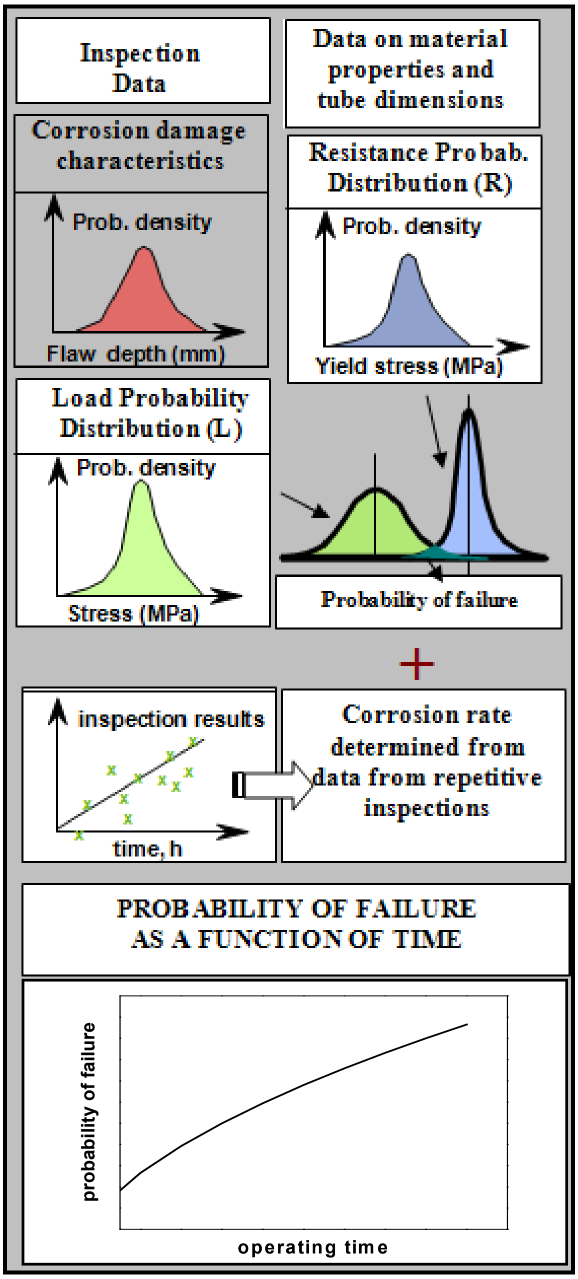


Figure 1. Algoritam for determination of PoF

- determination of parameter of the real distribution density of every input parameters affecting the end results (dispersion of material strength values, wall thickness, etc.)
- information about deviations in strength and dimensions introduced during fabrication of tubes and the lack of information on the density of error dispersion bearing in mind the fact that uncertainty can be reduced by the expert evaluation based on the material behavior under given conditions define the correction factors since the adequate models do not exist.

In this paper the methodology of probability of failure was used for determination of probability of failure of one heating surface with great extent of corrosion damage.

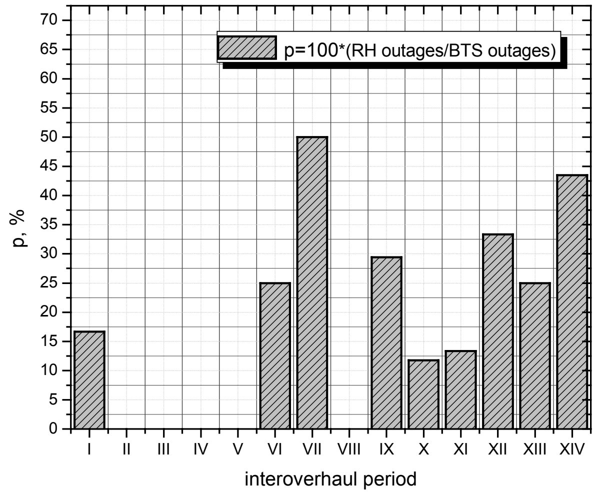


Figure 2. RH outages in comparison to the total number of boiler system (BTS) outages vs. interoverhaul periods

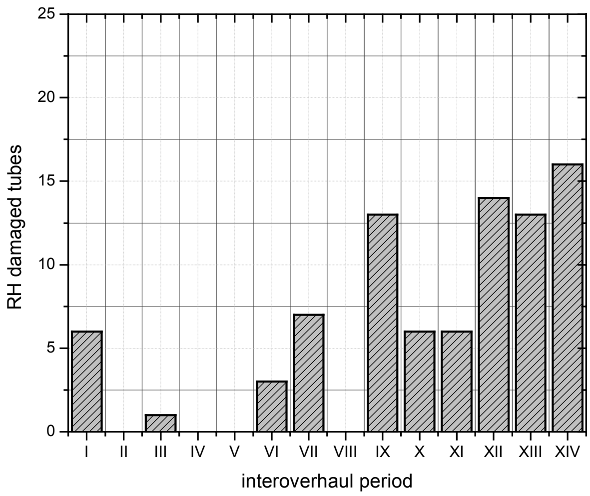


Figure 3. Number of RH damaged tubes vs. interoverhaul periods

The reheater (RH) tubing system was made of two different low carbon low-alloyed steels. Owing to the lowest exploitation parameters ($t_{gas} = 449°C$, $t_{steam} = 344°C$, $p = 45.5$ bar) as compared to the outlet part, the inlet part of the reheater is made from the material with lowest mechanical characteristics. The RH inlet part was made of 15Mo3 steel (DIN -17175/79), whereas the tube dimensions were 60x3.6 mm.

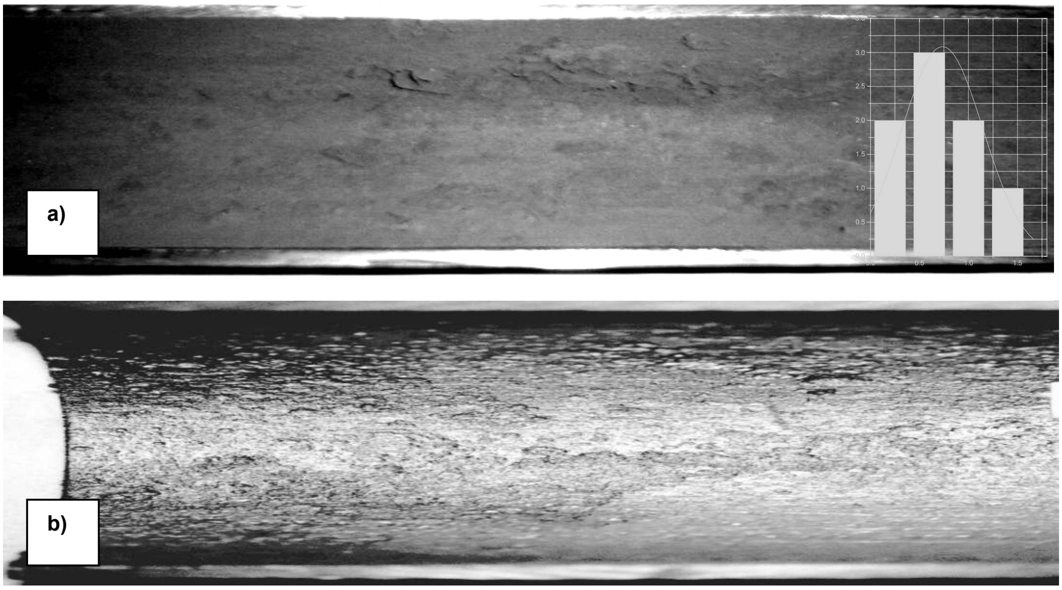


Figure 5. Macro view of corrosion damage at the inner surface with the distribution of pit depths (*d*, mm: mean=0.73450; SD=0.41382). The inner surface before (a) and after removal of the deposit (b)

During exploitation, even from the very beginning, corrosion was responsible for a large number of damages of reheater tube inlet parts. In Figs. 2 and 3 are depicted the quantity of RH outages compared with the whole boiler tubing system outages vs. interoverhaul periods and extend of damage measured by number of damaged tubes. According to outages statistic this heating surface was on the end of usefull life although its design life was at least 100000 h. Based on the previously obtained results and data relating the locations where the failures of tubes occurred, a detailed program for testing of RH inlet zone was developed. This program considered the following:

- NDT control of the first stage RH tube wall thickness, diameter and hardness measurments on a large number of locations, specifically in the zones (critical zones) where failures were previously observed.
- Destructive testings were performed on samples which were cutted out from the most critical zones of RH inlet part – total three tubes of 1.5 m in length.

The samples used in this work were subjected to accurate dimensional control, hardness measurements, tensile strength tests at room and elevated temperatures and chemical analysis of deposits and tube material. In addition, a detailed metallographic analysis of the tubes with corrosion damage was also carried out.

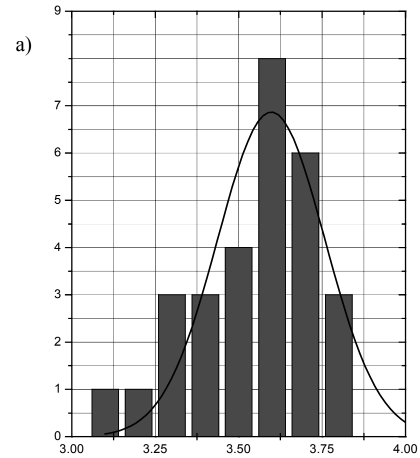
3. NDT TESTING RESULTS

The wall thickness was measured on approximately on 800 locations along the entire length of the first stage RH tubes. In the damaged zones the number of the measuring points was larger and was performed at smaller distance of 200 mm.

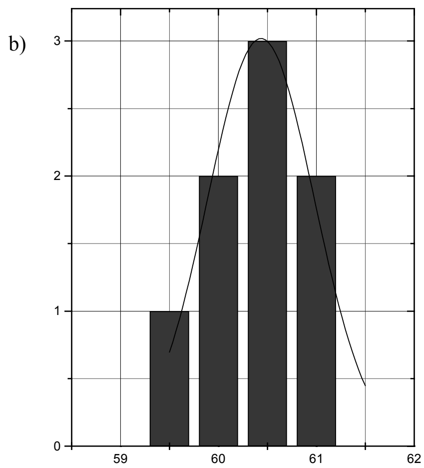
For the undamaged zones, the number of measuring points was determined in accordance with the criteria of scheduled overhauls.

The results, shown in Figs. 4 a) and b), depict normal distribution of inlet RH tube wall thicknesss and diameter.

Using the Poldy method, hardness measurements were made *in-situ* and the results in Vickers units were in the range of 127 – 146 HV30.



mean=3.5224; SD=0.18106 mean=60.43447; SD=0.54548



mean=3.5224; SD=0.18106 mean=60.43447; SD=0.54548

Figure 4. Distribution of inlet RH tube wall thickness [mm] (a) and diameter [mm] (b)

4. DESTRUCTIVE TESTS RESULTS

4.1 Visual investigation

On the inner surface of the tubes, a reddish-brown oxide deposit was observed. The deposit had two characteristic layers: the outer one which was cracked and powdered, and the inner one which was compact and with a good adherence to the base metal.

The oxide deposit was removed by acid solution which revealed many pits and small-elongated cavities of different sizes on the tube inner side, Fig. 5. Figure 5 also depicts distribution of pits found on the examined samples.

Outer tube surfaces were mainly smooth due to a less extensive abrasive action of the gas flow, although the presence of a thin layer of deposit was also observed.

4.2 Dimension measurements of specimens

The results of maximum and minimum tube outer diameter values, as well as the wall and deposit thickness are shown in Table 1.

Table 1: Dimension measurements

Value	Measured values, mm			
	Outer diameter	Wall thickness	Inside scale thickness	Outside deposit thickness
Max	61,2	4,1	0,49 at ∗ position	0,182 at ∗ position
Min	59,7	3,1∗		

4.3 Mechanical properties

The hardness measured on the outer side of the tubes was in the range 131 – 146 HV30, whereas those made in the tube cross-section were in the range 118-126 HV30. The observed difference in the hardness values was associated with the abrasion action of the gas flow as well as manufacturing.

The tensile tests were carried out at room and operating temperatures, Table 2. In the case of specimens prepared from the damaged region, all obtained yield strength values of material were below the value of 285 MPa specified by the DIN – 17175/79 standard.

At operating temperature the minimal yield strength was 146 MPa, which is much below specified 179 MPa according to standard, too.

4.4 Chemical analysis of material and inner-side deposit of tubes

The results of chemical analysis indicated that the composition of the tube material was within the specified values thus confirming that this was 0.3 Mo steel, which corresponds to 15Mo3 type steel (DIN- 17175/79), Table 3.

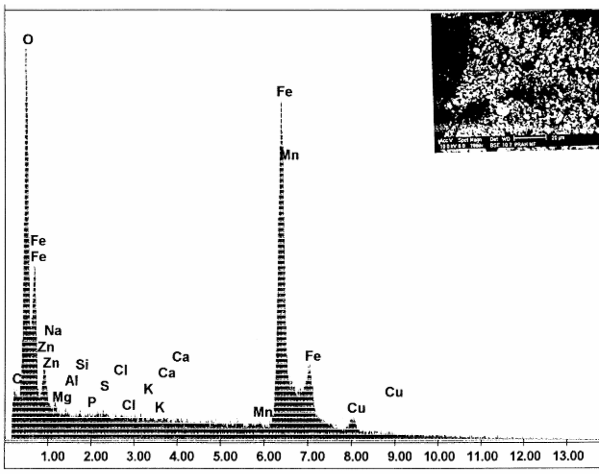


Figure 6. EDAX of RH tube inner-side deposit

Table 2: Tensile properties

Temperature, °C		$R_{0.2}$, MPa	R_m , MPa	A_5 , %
20	free	298	482	28
	defect	251	392	25
300	free	230	396	30
	defect	195	297	28
350	free	215	363	35
	defect	174	281	32
390	free	201	330	35
	defect	149	248	32
DIN 17175		min 285 at 20°C	440-540 at 20°C	min 22 at 20°C
		$R_{0.2}$ at 300 °C – min 206 MPa $R_{0.2}$ at 350 °C – min 186 MPa $R_{0.2}$ at 400 °C – min 177 MPa		

Table 3: Chemical analyses of tube metal

	Chemical composition, wt %					
	C	Si	Mn	Mo	S	P
Sample	0.171	0.267	0.678	0.278	0.021	0.020
DIN – 17175/79	0.12-0.20	0.15-0.37	0.50-0.80	0.25-0.35	max 0.035	max 0.035

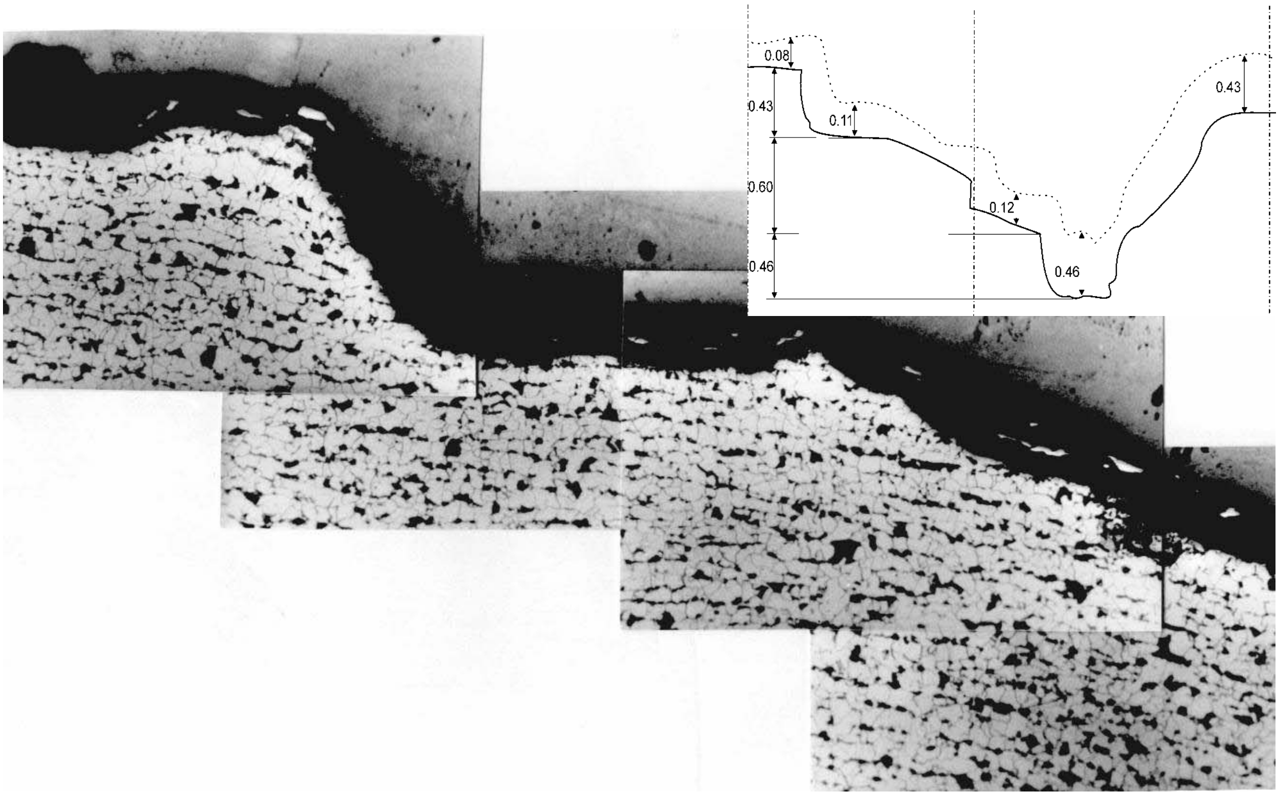


Figure 7. Typical microstructure features of the investigated steel. Inner side. Layered ferrite-pearlite. Corrosion damage. Deposit (100x). The schematic diagram shows the entire profile of corrosion pit.

The results of qualitative and quantitative analyses of deposit on the tube inner side are shown in Fig. 6. These results indicated the presence of iron (Fe) in the form of Fe_2O_3, as well as carbon (C), zinc (Zn) and coper (Cu). In addition to oxide scaling, the presence of Zn and Cu indicated on possible galvanic corrosion.

4.5 Microstructure

The results of metallographic analyses of different locations revealed the similar microstructure features that are a mixture of ferrite and pearlite.

The pearlite content across the tube wall cross section varied from ~ 15 – 16 % in the middle to ~ 9% at the surface layer of the inner side of the tubes.

In addition, it was found that the microstructure was basely in normalized state with the banded features in the vicinity of outer surface.

Significant corrosion damages, seen as scale in Fig. 5, elongated cavities (max 4,3x4,0 mm) and pinholes under scale were present at the surface of the inner side of the tube wall. Removing the oxide layer from the inner side revealed the presence of elongated cavities most likely formed as a result of coalescence of pits.

The corrosion damage seen in Fig. 7 is an indication of steam water corrosion attack which is combined with corrosion during outages. The schematic diagram on Fig. 7 shows the entire profile of corrosion pit.

5. REMAINING LIFE ASSESSMENT AND PROBABILITY OF FAILURE

5.1 Corrosion rate determination

Excluding already removed layers at inside and outside surfaces and taking into account the depth of corrosion crater (~ 0.49 + 0.182 + 1.49) it was found that total metal wall thickness decrease was 1.172 mm.

It is evident that the rate of oxidation was greater at the inner surface. Assuming a parabolic rate of oxidation with time, the thickness of the oxide layer can be expressed as [4]: $\Delta x^2 = K_p t$ where t (h), K_p is rate constant (mm^2/h) and Δx is thickness reduction (mm). Using the present data, it can be obtained that K_p is $2.3{\cdot}10 - 5\ mm^2/h$.

5.2 Remaining life under corrosion condition

The operating stress (σ_W), which changes during exploitation, controls remaining life of tubes exposed to corrosion.

The remaining life is inversely proportional to the tube wall thickness. In addition, thickness reduction caused by oxidation and other corrosion-erosion processes, the presence of elongated cavities and pin holes might act as stress concentrators and thus increase the actual operating stress (σ_{aw}). According to [10], this stress can be expressed as: $\sigma_{aw} = \sigma_{ow} x(1+2y)$ where σ_{ow} is design stress in the tube wall, x is the ratio between designed and measured thickness and y is the ratio between the length and the width of a physical discontinuity (pinholes, cavities, etc.).

The fact that the mechanical properties of the material in the defect region (with pinholes, cavities) are significantly lower than those specified by standards is an indication of the notch sensitivity of the material which, in turn, means that the applicability of stress concentration factor is well acceptable.

By applying the Von Mises criteria based on principal stresses and for the biaxial stress state, actual yield stress can be calculated according to the following relation: $(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2\sigma_o$ [10], where $\sigma_1 = \sigma'_{ay}$, $\sigma_2 = \sigma'_{ay}/2$, $\sigma_3 = 0$ and σ'_{ay} represents actual working stress during yielding $\sigma'_{ay} = 1.15\sigma_o$; in the investigated case σ_o represents the lower value of yield strength at 390°C which is equal to 149 MPa. Estimated actual yield stress under biaxial stress state becomes 171 MPa. Because of the reduction in tube thickness the increase of operating stress must occur.

In this research, the plastic yielding of the material was accepted as the failure criterion [11]. This means that the actual operating stress must not exceed the actual yield stress under a biaxial stress state at 390°C for a safe exploitation of the plant.

Figure 8 shows the variation of the actual operating stress vs. the thickness of the tube wall.

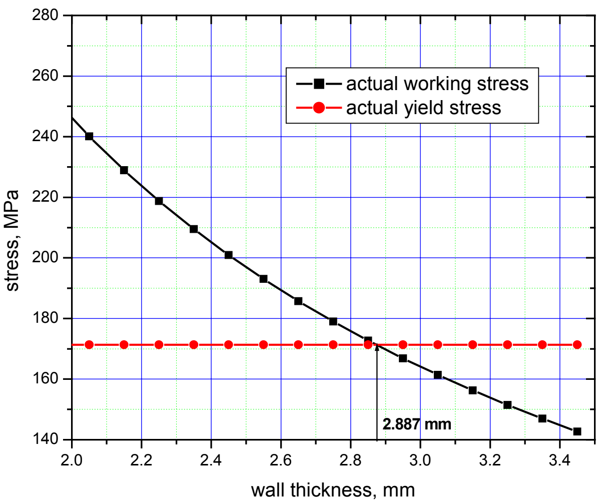


Figure 8. Actual operating stress vs. tube thickness

For example, if we compare the results of actual operating stress represented in the Fig. 8. with the actual yield stress under a biaxial stress state at 390°C, we can obtain the safe limit expressed by wall tube thickness (2.887 mm), Fig. 9. The exploitation of tubes with wall thickness below the value of 2,887 mm is not permissible. Minimal measured wall tube thickness was 3.1 mm, which means that the thickness reserve is $3.1 - 2.887 = 0.213$ mm. results, Considering the corrosion rate constant $K_p = 2.3 \cdot 10^{-5}$ mm^2/h, it can be estimated a residual life as approx. 2000 hours. Therefore, the first stage reheater tubing system has not enough resource for further exploitation.

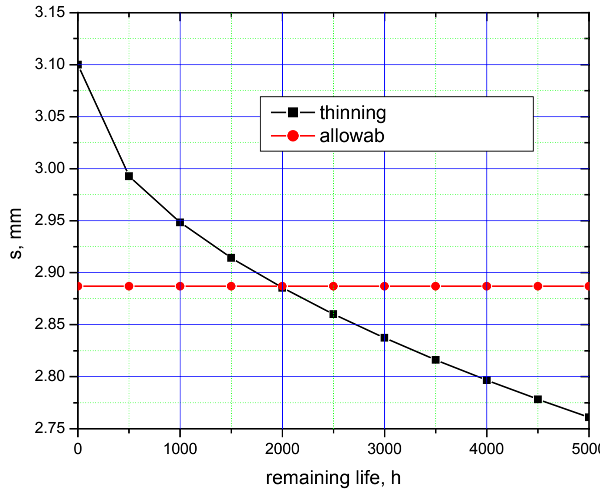


Figure 9. Remaining life of RH tube

5.3 Probability of failure under corrosion condition

For the purpose of probability calculation, it is assumed that obtained corrosion rate will not be changed in the further operation.

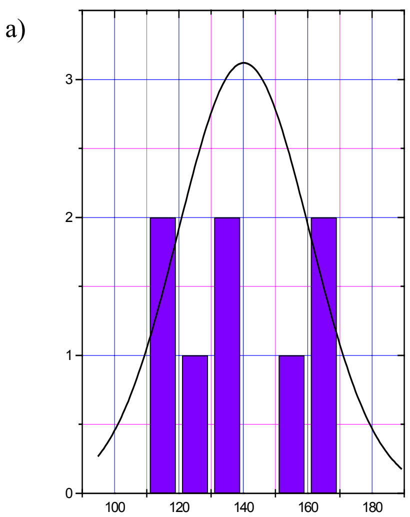
On the other hand, in the case of a tube subjected to internal pressure, the yield stress under the conditions of biaxial stress at operating temperatures is the flow stress and the limiting value defining the probability of fracture appearance. Limit state function (LSF) [8] is expressed as LSF $(\sigma_{aw}) = \sigma'_{ay} - \sigma_{aw}$. LSF is time-dependent variable, and it is a function of the flow size; it becomes positive for safe corrosion defects and negative for failure defects.

If the load and resistance variables are assumed to be random and mutually independent, then the probability of failure (PoF) could be estimated as the probability for which the LSF will have the values of zero or lower.

Figure 10 depicts distribution of operating stress in the tube wall obtained from the measurements of the wall thickness in the corrosion damaged zones and for the stress concentration factor K = 3 as defined by the existing pit profile and flow stress distribution. It is clear that these two diagrams overlap over a very wide range whereby the overlapping area represents the probability that the LSF function takes the values <0.

In fact, this defines the probability for the appearance of fracture.

Assuming corrosion rate to be constant as well as accepting the other premises defined earlier in this work, it is possible to determine the changes in the failure probability with time. This is illustrated in Fig.11.



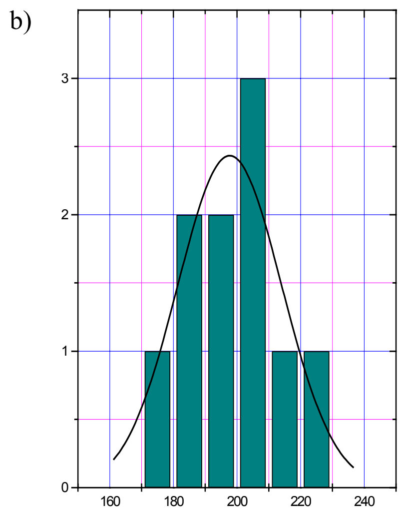


Figure 10. Distribution of: operating stresses in the tube wall in the damaged zones [MPa] (a); distribution of flow stress at operating temperature [MPa] (b)

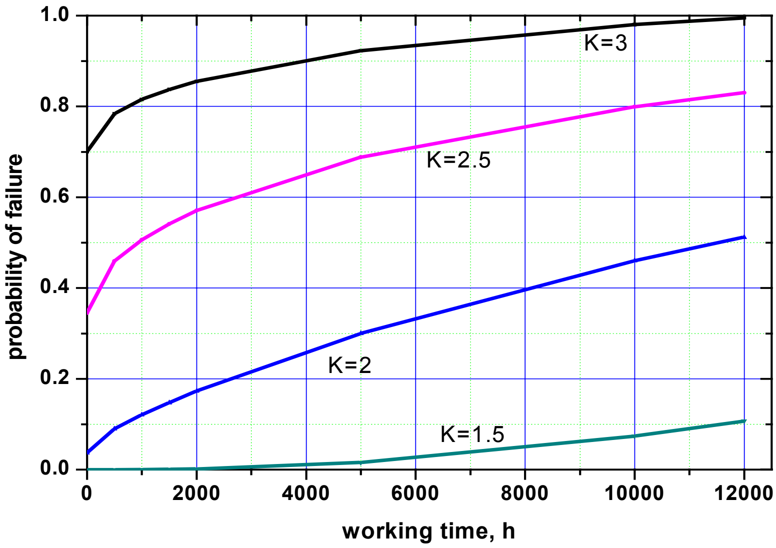


Figure 11. Probability of failure vs. time for specified stress concentration factor K and constant corrosion rate

6. CONCLUSION

The investigated tube was found to be affected by oxygen corrosion on the inner wall tube side. Apart from corrosion pin holes, elongated cavities were also observed.

This kind of damages might act as stress concentrators and thus increase the actual operating stress. By applying the Von Mises criteria based on principal stresses and for the biaxial stress state, actual yield stress was calculated. Also, the plastic yielding of the material was accepted as the failure criterion.

By comparing the results of actual operating stress and the actual yield stress at 390°C, the safe limit for wall tube thickness could be determined. This value of safe limit is used for residual life estimation and in general represent essential data for preventive maintenance.

Determination of PoF reduces the error that is generally introduced in the models dealing with the residual life estimation. From Fig. 11 it is apparent that under the action of high stress concentrations, the time to fracture is very short and in agreement with the life expectancy as determined on the sample using the classical approach.

It should be pointed out, however, that the function PoF is considerably smaller in the case of corrosion damage with low stress concentration, which means that the remaining life of the undamaged zones should be considerably longer than calculated. Therefore, preventive maintenance task should be directed to the endagered zones of RH, and consequently only the replacement of tubes with the significant corrosion damages and local tube wall thining should be carried out. The PoF represents the essential input data for the risk calculation as an integral part of risk-based maintenance programs.

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ВЕРОВАТНОЋА ОТКАЗА ЦЕВИ ЦЕВНОГ СИСТЕМА КОТЛА ТЕРМОЕНЕРГЕТСКИХ ПОСТРОЈЕЊА У УСЛОВИМА ДЕЛОВАЊА КОРОЗИЈЕ

Гордана Бакић, Вера Шијачки Жеравчић, Милош Ђукић, Биљана Анђелић

Корозија представља неповратни процес деградације материјала. Због неповољаног утицаја који има на радне особине материјал, посебно материјала цевног система котла, она представља представља неизоставни део рада термоенергетских постројења и главни узрок многих отказа. Поред уобичајених метода за процену преосталог радног века корисно је применити и методе за процену поузданости котловских цеви термоенергетских постројења које су оштећене корозијом. Корелацијом резултата који се добијају применом ове две различите методе могуће је добити боља сазнња о тренутном стању материјала цеви уз истовремено извођење тачније процене њиховог понашања током даље експлоатације. Стога је у овом раду на примеру цеви улазне зоне пакета накнадног прегрејача приказан интегрални приступ процене преосталог радног века и поузданости. Разматрања ове врсте су веома значајна за приступе у одржавању који су засновани на ризику.