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Combination Non-Destructive Test (NDT) Method for Early Damage Detection and Condition Assessment of Boiler Tubes

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Abstract

Boilers, the most troublesome components of electric power, chemical and processing plants generate high costs in unscheduled shutdowns, repairs and power replacement. Every occurrence of ruptured tubes leads to emergency shutdown of the entire plant. This paper describes the joint international effort to develop faster and more efficient methods for condition assessment and remaining life prediction for boiler tubes. The work was performed under the grant from Kazakhstan Ministry of Education and Science.

The authors have visited a number of coal-fired electric plants throughout Central Asia and found that a combination of wall thinning and overheating were major damage mechanisms contributing to boiler tube failures. The periodic inspection of boiler tubes include ultrasonic measurement of remaining wall thickness and in many cases, it involves cutting tube segments and performing metallurgical analysis for loss of original strength due to overheating. Systematic research was undertaken with the objective to correlate the results of combined non-destructive testing (NDT) with condition assessment of boiler tubes. The evaluation included non-contact wall thickness measurement with EMAT technology plus internal oxide layer measurement with specialized ultrasonics. The first method shows the remaining tube wall thickness, thus allowing to calculate total stress, and the latter one has the potential to indirectly characterize microstructure degradation, which up to now could only be determined by destructive analysis. The existing tube removal criteria are treating each damage mechanism separately while in reality, a combined effect of wall thinning and the "degree of overheating" decides about true condition of a tube. The procedure that utilizes the results of both described NDT methods was developed for improved methodology to assess tube condition and to predict its remaining life.

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Nomenclature

p	pressure inside boiler tube (psi)
d_m	mean tube diameter (m), calculated as: (*outside dia + inside dia)/2*
b	tube wall thickness (in)
b_0	nominal (original) tube wall thickness (in)
t	time (hrs)
t_r	time-to-failure (hrs)
T	temperature (R)
X	thickness of internal oxide scale (mils)
S_u	ultimate strength (psi)

1. Most common boiler tube failure modes.

The objective of the described research was to develop an optimum non-destructive testing (NDT) method or combination of methods that would improve the reliability of coal-fired boilers by reducing down-time related to failure of water-wall tubes. Similar work has been continuing throughout the world for the last 20-30 years, however, the research was always concentrated on low alloys steels, usually Cr-Mo type. Since this project was funded by Kazakhstan Ministry of Education and Science, it had to concentrate on local conditions in Central Asia where low carbon Steel20 is the most widespread tube material in water-wall section (although Cr-Mo steels are used in re-heater and superheater sections). The carbon steel is much cheaper than Cr-Mo steels and in addition, the cost of labour for replacing fossil boiler tubing in Central Asia is considerably lower. It is worth mentioning that India and parts of Southeast Asia use similar boiler water wall and superheater materials to those used in Kazakhstan and that the types of coal used in their power plants has many similarities to Kazakhstan coal. Therefore, it seems that at least some of test and maintenance procedures could be successfully adapted to other Asian locations.

It is well known that the main damage mechanism in Cr-Mo tubes in water-wall section of a boiler include fireside and internal corrosion and erosion causing wall thinning, therefore ultrasonic wall thickness survey is conducted as a preventive maintenance measure. Low Carbon steel, however, brings new requirements as overheating, creep as well as hydrogen embrittlement should be considered as an additional and sometimes major damage mechanisms. It is generally recognized that creep may occur in carbon steels in temperatures over 400-440C, which is well within the range in water-wall boiler tubes [11]. For that reason, any preventive maintenance procedures have to consider overheating as a possible cause of failure. Indeed, during numerous visits by the research team to coal-fired electric plants throughout Kazakhstan, it was found that creep damage was the main reason for tube failures and consequently, the analysis for overheating condition was the main type of preventive maintenance. The usual way was a destructive method, i.e. cutting and removing tube samples from affected section of a boiler and performing metallurgical analysis for evidence of overheating. On the other hand, our team did not find an instance where hydrogen embrittlement would be a major cause of failure.

These initial investigations that included plant visits and literature search had concluded that in order for this research to be useful to plant operators, it has to concentrate on carbon steel as a material of choice for water-wall section of the boiler. The most common reasons for tube failures in Steel20 were: (i) external and internal corrosion and erosion - it is common for combustion products to erode portions of the tube surface or for chemical reactions of molten sulfates, carbonates and oxides with the iron in tube material to locally reduce the tube wall thickness (ii) long-term overheating damage where the material strength gradually decreases with time (iii) short-term overheating, usually occurring during start-up or due to some unexpected occurrences, such as tube blockage, when tube temperature rises suddenly with consequent loss of tensile strength, so that hoop stress from internal pressure causes a violent rupture. It needs to mention at this point that both above types of failure are easy to recognize by a simple observation: while a long-term overheating causes a “thick-lip rupture” with many bulges and cracks visible around, a short-term overheating is connected with “thin-lip rupture” having sharp edges and usually no evidence of other damage around the burst [5]. Samples of actual tube failures are shown in Figure 1.

Figure 1: Most common damage mechanisms observed in boiler water-wall with carbon steel material (Steel20). Surface corrosion and erosion causing wall thinning (*left),* thick-lip burst caused by long-term overheating and creep damage – note multiple longitudinal cracks in the vicinity of a burst (*right).*

2. Wall thinning measurement with EMAT

As boiler ages, corrosion and erosion causes the tube wall to become thinner until it cannot sustain the internal pressure. Weak (thin-walled) tubes should be replaced or repaired long before burst can occur. One common procedure for measuring the water-wall tube thickness is to grind or sandblast the fire side of the water-wall to expose a bare metal and use ultrasonic (UT) to determine the wall thickness. Most often, this is done manually, every 15-20 cm of vertical height, to provide a "map" of wall thickness [1,6]. This approach usually provides highly reliable results but, due to laborious preparation process (sandblasting, need to erect scaffolding) the inspection is costly and takes long time. In addition, the conventional ultrasonic method requires a liquid couplant in order to transmit ultrasound wave into the metal and for that reason it is hard to automate [3].

One of the goals of this research was to improve existing methods of tube evaluation, therefore a feasibility of using EMAT (Electro Magnetic Acoustic Transducer) was investigated for specific conditions, i.e. operating parameters, type of fuel/coal for Central and South Asian coal-fired electric plants. EMAT offers certain advantages over standard UT – no need for tube cleaning and couplant, therefore it brings a potential for significant cost reduction [7]. Further, elimination of repetitive tube cleaning during each shutdown, reduces the rate of corrosion and contributes to boiler life extension. The economic advantages of EMAT are best described by comparing it with standard ultrasonic thickness measurement. Savings are realized by eliminating cleaning and sandblasting, as those operations take on average 2-3 days and are done on a “critical path”, thus directly adding to outage duration. Cutting 3 days of outage time for 500MW boiler saves the utility approx. $1.5Mln (at the power replacement cost of. $40/MWhr [8]. Further, EMAT can be used with robotic crawler, additionally eliminating the need for scaffolding.

EMAT principle is well known and it relies on generating ultrasound wave directly in the metal without a need for a couplant. The EMAT transducer has a strong permanent magnet, usually Neodymium-type and a spiral coil supplied with a current of high frequency (1-2MHz). The current in the coil induces eddy currents on the surface of tested tube and the magnet “pushes” those currents into the tube in the form of elastic wave with ultrasonic velocity, characteristic for a given metal. There are two ways that EMATs can generate elastic energy directly in the boiler water-wall. The first is via the “Lorentz force” mechanism where interaction between an applied magnetic field and induced eddy currents produces an elastic wave. The second is through magnetostriction (MS), where an alternating magnetic field generates an alternating elastic force. While the Lorentz force mechanism has been proven to work well on boiler tubes, but it requires much higher magnetization and systems are heavier and more costly than their magnetostrictive counterparts. The steel surface have low magnetostrictive properties and for that reason, clean tubes cannot generate sufficient EMAT signal for useful inspection. However, when the metal is exposed to conditions commonly encountered in the fire box of coal-fired boilers (temperatures over 400-450C), a tightly bonded scale having a large MS coefficient is formed [2]. EMAT transducers can work with general-purpose ultrasonic instruments with certain modifications, most important being the adequate initial pulse, at least 400V. Figure 2 shows the EMAT principle and how the manual inspection is done on boiler tubes.

EMAT performance in boiler and its comparison to conventional ultrasonics was established by numerous laboratory and field evaluation in USA and UK [8] with the overall conclusion that EMAT provides accurate data.A part of feasibility study for using EMAT to test Steel20 tubes was to determine if external corrosion scale has

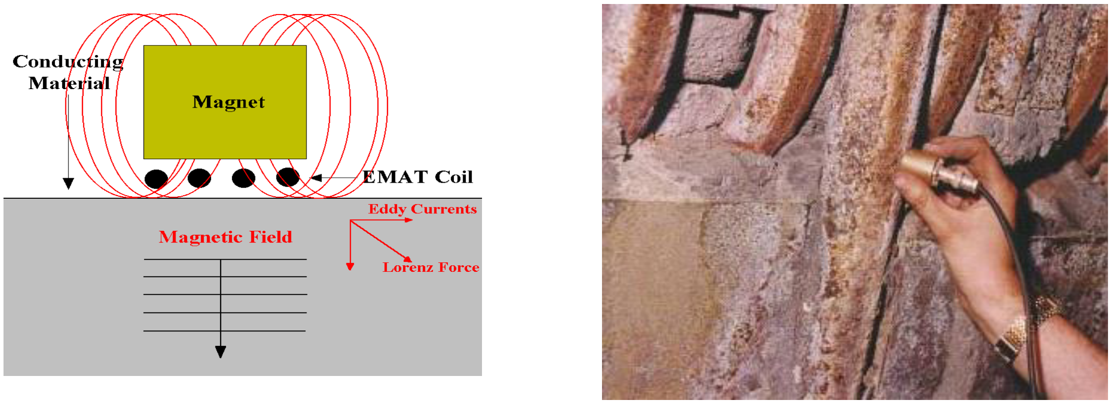
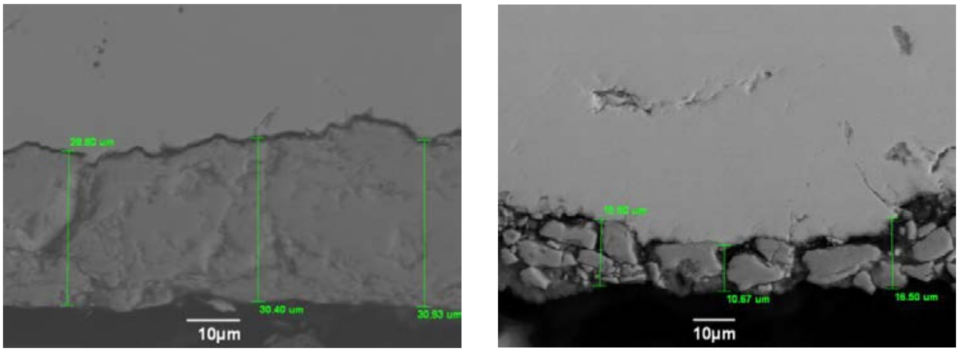


Figure 2: Principle of EMAT (*left*) and the manual EMAT thickness measurement performed on boiler tubes (*right*)

adequate magnetostrictive properties to generate EMAT signal. It is not critical where the scale is located (ID vs. OD) as good indications were obtained with scale on either surface while testing from the outside. More important than location is the chemical composition of the scale, determining its magnetostrictive properties and its adherence to the parent metal [7]. The scale thickness was found not to be that important as authors were able to obtain good EMAT indications through scale ranging from less than few microns to 7mm thick [8]. To determine the chemical composition of the scale and to compare it to boilers in other regions of the world, the spectrometry was performed with further investigation by SEM. Figure 3 shows two microphotographs of external scale with various thicknesses, various degree of adherence to parent tube metal with their corresponding chemical composition.



Sample No.	O (%)	Na	Al	Si	Cl	Fe
1 (*left*)	18.62	4.41	1.54	3.79	0.48	71.16
2 (*right*)	16.11	4.81	1.88	5.08	0.43	70.27

Fig. 3. Microphotographs of two samples with external oxide scale of various thickness with their corresponding chemical analysis. A solid EMAT signal was obtained for the sample on the *left* while the sample on the *right* has produces only a sparse signal. This was most probably due to lack of adherence between the scale and parent metal.

Neither chemical composition nor ferrous oxides contents differed from typical values obtained in other regions of the world. Occasional lack of coupling was most probably caused by non-adherence or loose adherence of the scale to tube material.

The main value of periodic wall thickness measurements with EMAT is the possibility to calculate the actual hoop stress in tubes. Additionally, the thinning rate in (*mm/yr*) can be determined from periodic inspections. The hoop stress is calculated from known strength of materials formula:

$$\sigma_h = \frac{pd_m}{2b} \quad (1)$$

The hoop stress can then be presented as a time function, using thinning rate of $\dot{b}$, determined from periodic EMAT thickness measurements:

$$\sigma_h = \frac{pd_m}{2(b_0 - \dot{b}t)} \quad (2)$$

An exemplary graph of hoop stress for various rates of thinning are shown in Fig. 4 below:

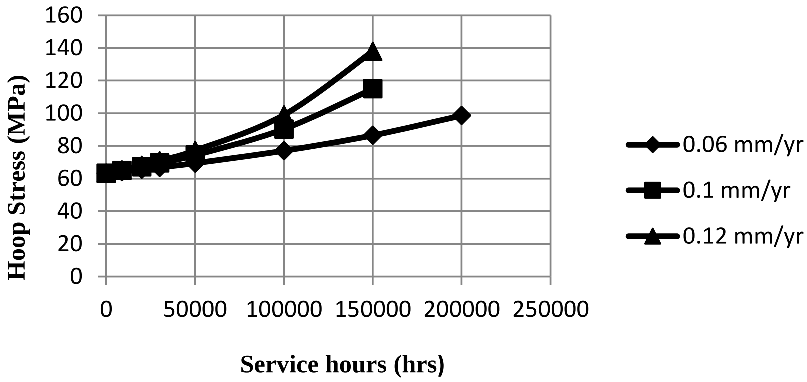


Fig. 4. Hoop stress growth in boiler tubes as a function of thinning rate

3. Detection of overheating condition

Two types of overheating failures in water-wall boiler tubes are usually occurring: a short-term and long-term overheating. There are numerous past publications, handbooks and individual plant maintenance procedures that discuss this issue and in this paper we will concentrate on application of non-destructive test methods and their role in preventive maintenance and remaining life assessment (RLA). The main purpose will be to ascertain that failures will not occur between maintenance intervals.

A tube rupture caused by overheating may occur within few minutes or may take several years. A **long-term overheating** can be usually detected in its early stage by several non-destructive and destructive test methods, while **short-term overheating** can be compared to sudden accidents that will be very hard to predict. On the other hand, the long-term is caused by a combination of long exposure to temperature that can be only slightly above the design temperatures and stress well below the yield point. It is referred to as “creep damage” and characterizes by gradual degradation of metallurgical structure, cracks, bulges, swelling but no detectable changes in wall thickness. The creep prevention should start at the designing stage to correctly select tube material to withstand the metal temperatures. Inside the boiler, the heat is transferred from burning fuel or hot gases by radiation or convection and the outside of tube is very hot – this heat is being transferred to water (in water-wall tubes) or steam (in re-heater and superheater tubes) inside the tubes. The temperature gradient then exists from the outermost to innermost layer of the tube and the "mid-wall temperatures" in carbon steel boiler tubes are designed to be in a range of 370C-420C. Its increase by 100C or even less may already start the process of creep deterioration. At the initial stage, creep can only be detected by destructive metallographic examination under the microscope. It starts with graphitization, i.e. changing iron carbide to graphite at high temperatures. The post-mortem analysis shows thick-lip (low ductility) burst with spheroidized microstructure and creep cavities in the immediate vicinity of a rupture [14].

The electric power industry has been looking for a reliable non-destructive test method to detect creep damage in its early stage [5]. Past research pointed to internal oxide layer as an important marker of overheating condition. The degree to which creep condition had deteriorated metal structure can be indirectly determined by measuring the thickness of internal oxide scale in boiler tubes. Indeed, even very basic calculation of heat transfer would be able to demonstrate that in order to keep the internal tube temperature at saturation temperature, the external tube surface has to be many degrees hotter since the oxide scale has thermal conductivity approx. 15 times less than steel. Thus the mid-wall tube temperature may reach levels high enough for creep damage to initiate. Some sources show so called "transition temperature" from non-creep affected regime to creep affected regime. Such temperature for plain carbon steel is 427C while for 2.25%Cr-1%Mo steel is 510C [4]. The hard, brittle iron oxide, containing magnetite and hematite [9] can be formed on the inside and outside surfaces of steel boiler tubing. This internal oxide layer is very different from much less dense chemical deposits when an incorrect water chemistry is used.

The industry experience had confirmed the importance of periodic internal scale thickness measurements as a tool for evaluating the useful operating life of boiler tubing. In order to determine this thickness in non-destructive way, ultrasonic method proved to be most useful. However, first uses of this diagnostic tool done over a decade ago were cumbersome as they involved recording the amplitude-time (A-Scan) profile. Recently, special transducers and embedded software were developed by few ultrasonic manufacturers that now enables an internal oxide thickness measurement to be made quickly and accurately.

During this research, an attempt was made to develop a correlation between the thickness of internal scale and the "degree of creep damage" for Steel20 samples. While similar correlation has been investigated for Cr-Mo steel, it was never evaluated before for low carbon steel. The initial work was done on three samples taken from boiler: one without any internal scale and two samples with scale of 75 and 140 microns measured by optical microscope. Metallurgical cross sections were prepared at or close to mid-wall location and metallurgical structures were observed by optical microscope. Figure 5 shows the comparison between samples with and without internal oxide at 400X magnification together with appropriate discussions and explanations.

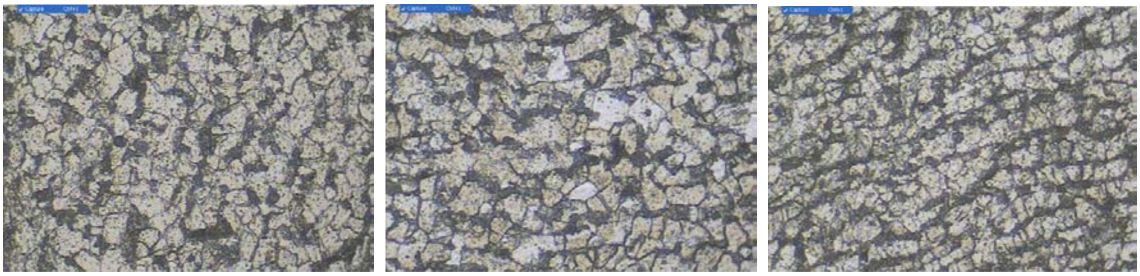


Fig. 5. Metallographical structures for Steel 20. Sample without presence of internal oxide (*left*), with oxide scale 75 micron thick (*center*) and with 140 micron thick (*right*). Ferritic-pearlitic structure observed in all samples with occasional inclusions in ferrite grains. Sample in the *center* differs by enlarged and elongated grains, indicating the initiation of structural degradation. Sample on the *right* has grains elongated with insoluble carbides "bundled" and precipitated on grain boundaries. This is indicative for creep.

4. Combined effect of wall thinning and overheating

The discussion in this paper was intended to demonstrate the value of non-destructive testing in evaluating boiler condition and in providing an important input to Remaining Life Assessment (RLA). The question arises how to treat a combined effect of both overheating and wall thinning, which will determine the way NDT results are utilized. To-date, both results are treated separately, and consequently separate reject criteria exist for overheating and separate for wall thinning. Overheating has been historically evaluated by destructive methods and degradation is then determined by loss of tensile strength, change in hardness and finally by observing metallographic structure under optical microscope. Certain criteria were developed for measurable properties (strength, hardness) but evaluation of structural degradation is still somewhat subjective. Special classification methods exist, such as Toft & Mardsen method [10] that classifies the condition by six (6) stages of spheroidization of carbides: from Stage A – structure not affected by creep to Stage F – structure pre-failure, demonstrating microcracks and cavities with no trace of original pearlitic areas. This method was designed for Cr-Mo steels and there is no prior history of its successful use in carbon steel. Using this method to structures shown in Figure 5 above, the *center* structure is classified as between Stage A and B and the *right* structure is between Stage B and C.

As far as wall thinning, reject criteria are simpler to determine and basic guidelines has been prescribed by ASME Boiler and Pressure Vessel Code. The maximum allowable wall loss for water-cooled tubes (water-wall, economizer) is 30% while for steam-cooled tubes (re-heaters, superheaters) is 15% [12].

Very limited research has been done in the past to consider the effect of combined damage mechanisms on remaining life of boiler tubes. The most comprehensive study to-date has been conducted by EPRI [13] and it recommends first to estimate mean metal temperature to the present time. As shown above, the mean temperature is correlated with the thickness of internal oxide layer and can be estimated from UT measurement of that thickness. Such estimate is done by means of *oxide kinetics models*. For this analysis, the French model [4] was used, originally developed for Cr-Mo steel and therefore it needed to be modified for carbon steel:

$$logX = 0.0002[T(20 + logt)] - K \quad (3)$$

The coefficient K is 7.25 for Cr-Mo steels. Our research has shown that for carbon steel, K should be in the range of (4.5-5.0). This was determined by observation of structural changes and relating them to the temperature rather than by accurate measurements with thermocouples.

Once the mean temperature is determined, the Larson-Miller parameter (LMP) can be calculated [13], which in turn will provide a guidance as to the time to failure at a given stress level.

$$LMP = T(20 + logt_r) \quad (4)$$

The time-to-failure is then estimated from available graphs showing LMP vs. allowable hoop stress in tube wall. The above method, however, does not consider wall thinning and it is obvious that it is easier to overheat and break a thinner tube than a thicker one. Therefore, the improvement to the procedure to predict a remaining tube life that considers a wall thinning is hereby recommended. The proposed sequence is as follows:

1) Determine the mean temperature from thickness of internal oxide scale. As an example, the metal structure as shown in Fig. 5 (*right)* with 140 mils oxide scale was selected. By applying formula (3), the mean temperature was estimated as 470C.
2) Calculate LMP according to formula (4) above by inserting previously determined mean temperature for several different values of time-to-failure hours. In an example shown here, the LMP was calculated for 470C temperature and time-to-failure: 10,000; 50,000; 100,000 and 150,000 hrs. The calculated values of LMP were: 32.1; 33; 33.45 and 33.69 respectively.
3) For each calculated LMP, read the corresponding value of hoop stress–to-failure from graphs available for carbon steel [16], and create the curve: hoop stress (*y*) vs. time-to-failure (*x*). In our example, the graph [13] was reduced to the following formula for a simplicity:

$$logS_u = -0.0867(LMP) + 6.902 \quad (5)$$

and values for LMP were used as shown in Item 2 above. This allowed for creating a graph of a hoop stress as a function of time-to-failure. Further, stress units (psi) were re-calculated to metric system (MPa). The resultant graph is shown in Fig. 6 (*left).*

4) On the same scale, superimpose the graph for hoop stress as a function of time for a thinning rate as determined by periodic EMAT inspection (as in Fig. 4). The estimated remaining tube life can be then determined on the intersection of both curves as shown in Fig. 6 *right* (for 006 mm/yr thinning rate):

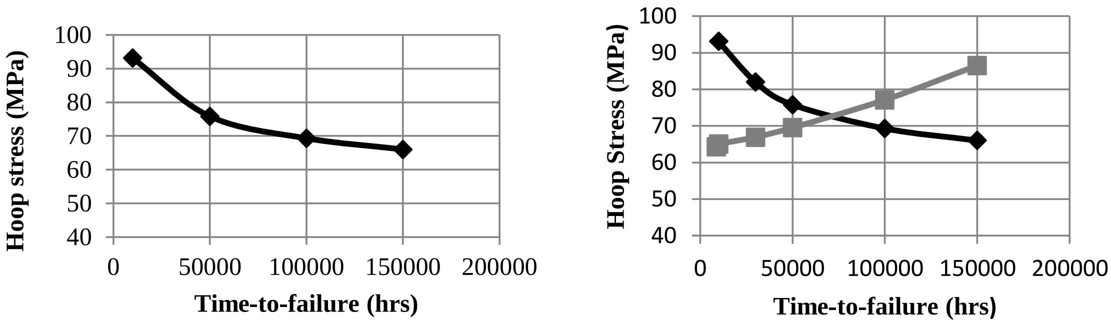


Fig. 6. Hoop stress as a function of time-to-failure for exemplary case of tube overheated to 470C *(left)* and the same curve with superimposed graph of hoop stress as a function of wall thickness at steady thinning rate of 0.06mm/yr (*right*). The tube remaining life is read on intersection of both curves, in example above, approx. 70,000 hrs.

5. Summary and Conclusions

The major objective of this work was to develop a reliable method(s) for non-destructive evaluation of boiler tubes, which would be especially suited for low carbon steel (Steel20), common in Asian power boilers and in many process boilers throughout the world. Tube samples, obtained from visited plants were then subjected to non-destructive and destructive tests. It was concluded that the major damage mechanisms were either wall thinning or overheating damage and a combination of both. Two ultrasonic test procedures were recommended for early detection of both these damage types without necessity of removing tube from the boiler.

EMAT has been proven as an effective method for quick and accurate wall thickness measurement in water-wall boiler tubes without prior cleaning. Further, it is preferred over conventional ultrasonics as it does not require repetitive cleaning and sandblasting, which increase the rate of thinning (corrosion). The chemical analysis had shown that the properties of external scale, specifically its composition and magnetostrictive characteristics are very similar in Central Asia to those experienced in Western countries. Indirect detection of long-term overheating condition and creep by UT measuring of internal oxide layer thickness was found to be fully applicable for low carbon steel. This study had demonstrated that correlation exists between the scale thickness and degree of creep degradation for carbon steel tubes. **The procedure was recommended for determining tube remaining life under combined effect of thinning and overheating.** Future work is needed to obtain a full quantitative correlation for creep damage vs. internal oxide thickness for low carbon steel. This paper is one of the first attempts to develop recommendations for combined treatment of few different types of tube degradation as existing reject/removal criteria treat each damage mechanism separately. NDT methods offer an attractive solution to remaining life assessment in power boilers due to their ability to accurately determine remaining wall thickness and hoop stress in tube and to indirectly detect the degree of creep damage by measurement of internal oxide thickness.

Acknowledgements

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