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Effect of High Temperature on Rear Pass Boiler Tubes in Coal-Fired Power Plant

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Abstract This work presents the investigations on three sample boiler tubes in the rear pass area (low temperature reheater 1 (LTR1)(A210-A1), intermediate temperature superheater (ITS)(A210-C) and economizer tubes)) (A210-C) of a coal-fired power plant in Malaysia, which had been replaced during major overhaul in January 2014 after running for about 11 years. Visual inspections, chemical analysis on deposits, metallurgical examinations and creep analysis on the tubes were carried out. Findings from the investigation were used to determine the tubes condition metallurgically before the removal. The results show that the relatively high temperature at the area pass area did not affect the metallurgical property of the tubes.

Keywords Boiler tubes, Creep failure, Rear pass area, Slag

1. Introduction

Tangentially fired pulverized-coal (PC) boilers are widely used in modern thermal power plants. This is due to the advantages which include having well flame-fulfilled degree in furnace, good flame stability, good adaptability for a wide variety of coal ranks and loads, and low NOx emission [1, 2]. However, there are still shortcomings in the forms of fouling and slagging in the burner zone and upper furnace, heat imbalance and gas temperature deviation in horizontal flue gas pass with the boiler capacity [3-6]. Ash deposition (in the form of slagging and fouling) problems are mostly related to the mineral matter in the coal. These problems in turn, among others, can lead to reduction in heat transfer coefficient from the flue gas to the water inside the wall tubes. As a result, the rear pass area will experience higher temperature compared to the designed value [7]. Another significant result of the reduced heat transfer to the waterwalls is that, the flue gas temperature at the furnace exit will increase to above the ash fusion temperature, resulting the slagging problem worsen in the slope area and on the screen tubes in the convection section of the boiler [8].

These problems have also contributed significantly towards the problems of local overheating (hot spot) and failure of superheater and reheater tubes [5, 6, 9]. Some numerical studies have concluded that the residual swirling flow at furnace exit is the main reason of the deviation [5, 6].

Even though the soot blowing system is designed to resolve the issue, the formation of strongly bonded deposits reduces the effectiveness of the system [10].

French [11] has reported in great detail of creep failure problems of boiler tubes in relation with the morphology of fracture and the changes in microstructure of the tube metals. The existence of creep damaged within the steel microstructure is often signed by creep voids that form at triple points. This process starts with spheroidization stage and then followed by graphitization. As creep deformation continues, voids link to form extensive grain boundary cracks.

2. Operation Facts and Condition of Tubes Replacement Region

2.1. Brief Description of the Boiler

The power plant (3x700 MW) boilers are of sub-critical pressure, single reheat and controlled circulation type [12].

Each boiler is fired with pulverised coal to produce steam for the continuous generation of 700 MW(e). The boilers are designed to fire coals within the bituminous rank.

The combustion circuit consists of a single furnace, with direct tangential firing and balanced draught.

The Firing equipment consists of (i) four elevations, (16) of, remote controlled fuel oil burners equipped with high energy ignitors, used to start-up the boiler and to support combustion of the pulverised coal at low firing rates. The capacity of oil burners is 40% of the Boiler Maximum

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Continuous Rate (BMCR), (ii) seven elevations, (28) of, coal burners located just above or below a fuel oil burner. The capacity of coal burners is 100% BMCR when firing coal within the design range. All the burners are located in the furnace corners (tangential firing).

The PC burners, the oil burners and the air nozzles are arranged in vertical layers. Each PC burner consists of an individual chamber connected to the PC pipe. All the burners and air nozzles can be tilt in the same time to raise and lower the "fire ball" in the furnace, to control the heat absorbed in the walls and in the radiant elements.

The dry saturated steam flows from the drum via the furnace roof tubes, and the rear pass walls to the low temperature superheater (LTS) inlet header for one part of the total flow or directly from the drum to the LTS for the other part. The LTS is a vertical exchanger consisting of 3 elements located at the furnace top against the front, right and left water walls. After crossing the LTS, the steam flows via the interconnecting pipes to the intermediate temperature superheater (ITS). The ITS exchanger is a horizontal exchanger located in the rear pass. The outlet headers of the ITS are linked to the inlet header of the high temperature superheater (HTS). After the outlet header of the HT superheater, steam enters the turbine through the main steam piping. Then its pressure is reduced in the different stages of the HP turbine and is partly returned to the boiler at the temperature and pressure of the last HP stage, through the cold reheat steam piping. The reheat desuperheaters are located on these pipes before reaching the inlet headers of the low temperature reheater (LTR). The steam crosses the LTR and then the high temperature reheater (HTR) and is risen to the required temperature for admission to the MP turbine.

2.2. Tubes Operational Facts

New A210 grade A1 (for LTR and ITS) and A210 grade C tubes (for economizer) were fitted in the boiler unit in July 2003. The tubes' inner radius and wall thickness are detailed in Table 1.

Table 1.

Tube	Normal operating temperature *°C*	Max. temperature *°C*
ITS	425	480
LTR1	452	470
ECONOMIZER	315	330

According to the on-site condition, the furnace rear path temperature of Unit 1 (see Figure 1) has gone-up to 800°C from the normal operating temperature of 680°C. Accordingly, the tube metals of temperature LTR1, ITS and economizer have also increased (see Table 2).

Table 2. Normal operating temperature and maximum temperature for LTR1, ITS and economizer

Tube	Tube's inner radius (mm) *r*	Wall thickness (mm) *t*	Steam operating pressure (MPa) ρ
LTR	31.19	3.81	3.7
ITS	21.41	5.59	17.7
ECONOMIZER	19.58	4.57	19.3

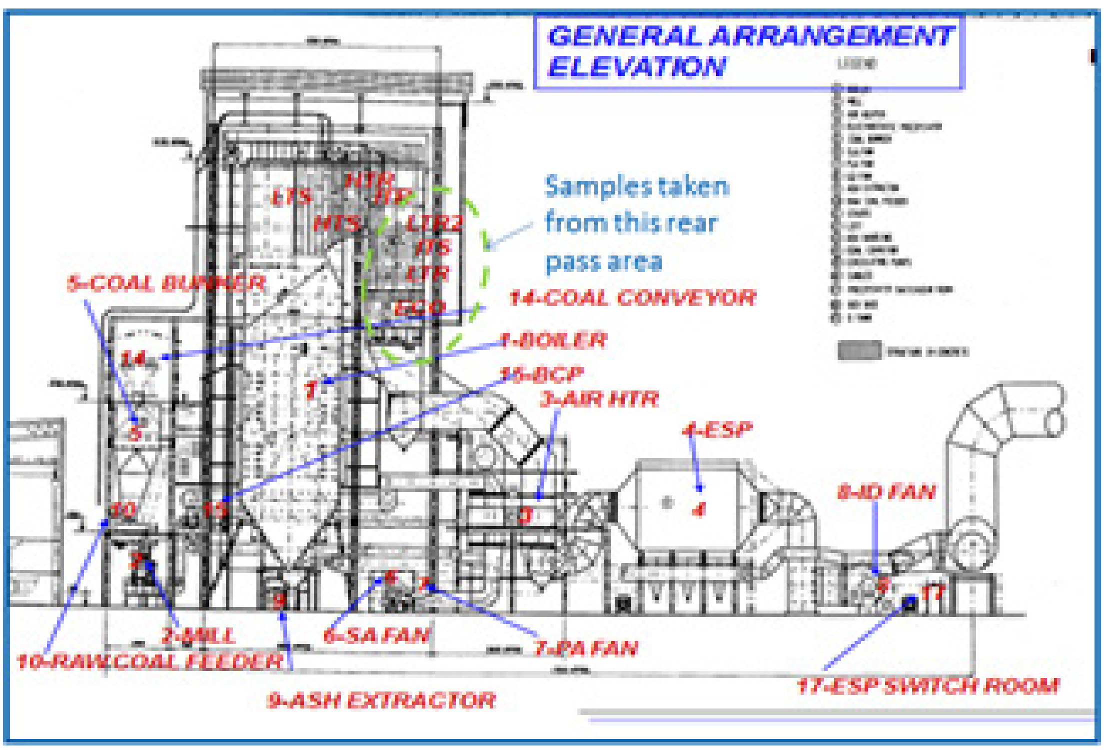


Figure 1. Location where samples were taken

In January 2014, all the LTR1, ITS and economizer tubes of Unit 1 were replaced during major overhaul. Three tube metal samples were taken for metallographic investigation to see the effect of prolonged exposure of those temperatures on these tube metals (see Figure 2).

Figure 2. Tube metal samples

3. Visual Inspection

Visual examination of the as-received (see Figure 2) revealed the following features:

- No abnormal OD or ID deposits or scale were noted.
- No swelling along the length.
- No evidence of active corrosion on either the internal or external tube surfaces.
- No evidence of localized wall thinning along the length.

4. Metallography

4.1. Tube's Microstructure

The microscopic examination of the specimens was also carried-out and the results are shown in Figure 3.

The microstructure of all the 3 tubes shows normal ferrite and pearlite structure except that they are in banded form mostly in longitudinal section. The banding occurs due to the longitudinal inhomogeneity as a result of preferential grouping of ferrite and pearlite in alternate bands aligned in the rolling direction during the sheet/plate hot-rolling operation [13]. The development of ferrite-pearlite banding is mainly due to segregation of alloying elements, during solidification of the ingot from which the product was rolled. Large segregation coefficients during solidification, low diffusion coefficients, large shifts in the A3 temperature and slow cooling from the austenitizing temperature favor the formation of ferrite–pearlite bands [14]. There is no indication of creep (in the form of spheroidization or graphitization) for all the tube samples. The results agree with Figure 4 which suggests that at least 7 years are needed to graphitization to take form in the tubes' microstructure with the operating temperature shown in Table 2.

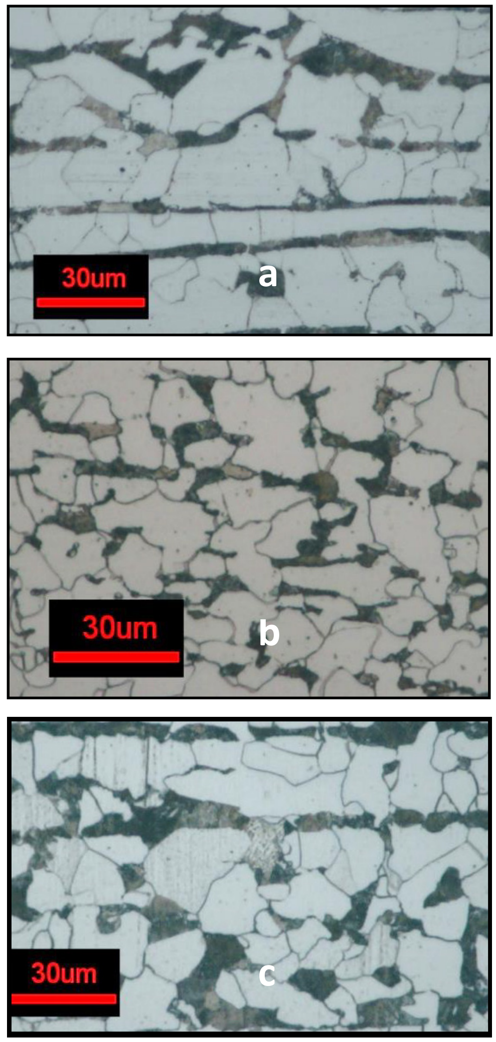


Figure 3. Photomicrograph of (a) ITS, (b) LTR and, (c) economizer

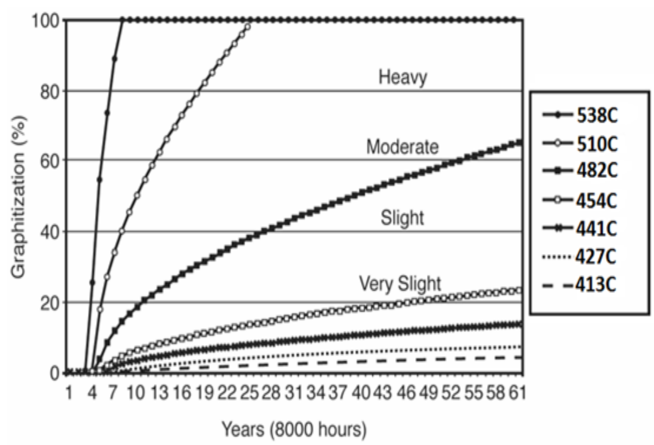
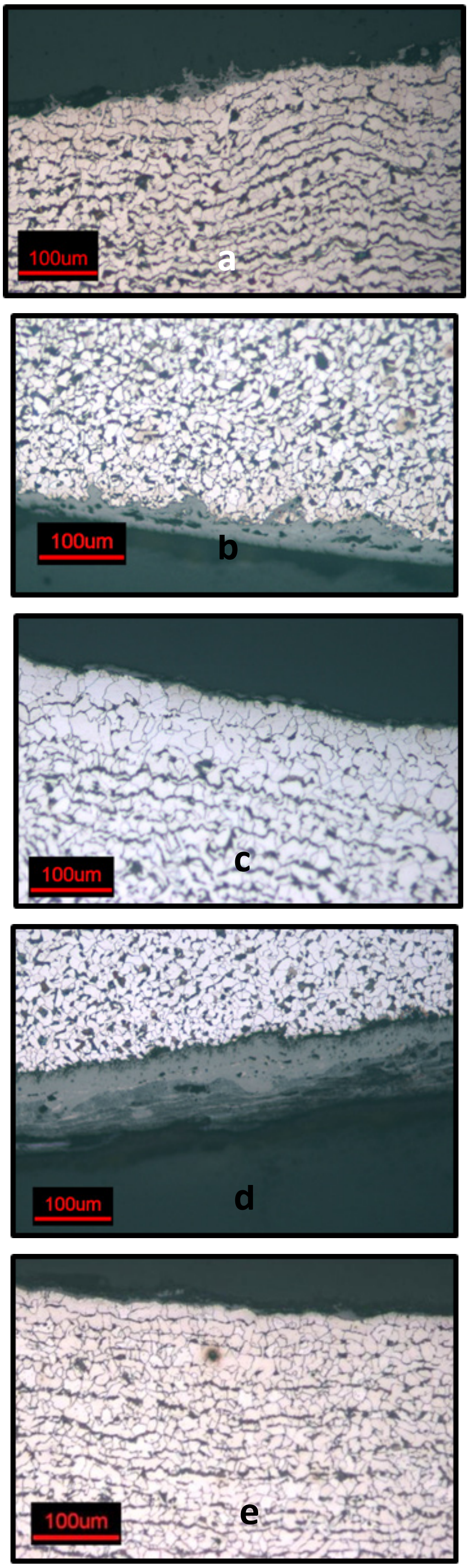


Figure 4. The Relationship between Graphitization, Temperature and Time for carbon steel [15]

4.2. OD (ash deposit) and ID (Oxide) Surface Scales

The OD and ID scales of the three tubes are shown in Figure 5. The thickness of the ID scale of the three tubes is very minimal (i.e. less than 10 µm) whereas for OD scale (ash deposition) for the three tubes is between 20 to 100 μm.



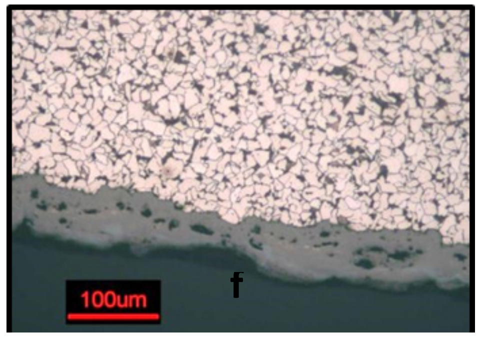


Figure 5. Microstructure of ID (oxide) scale for (a) economizer, (c) ITS and, (e) LTR1 and OD (ash deposits) scale for (b) economizer, (d) ITS and, (f) LTR1

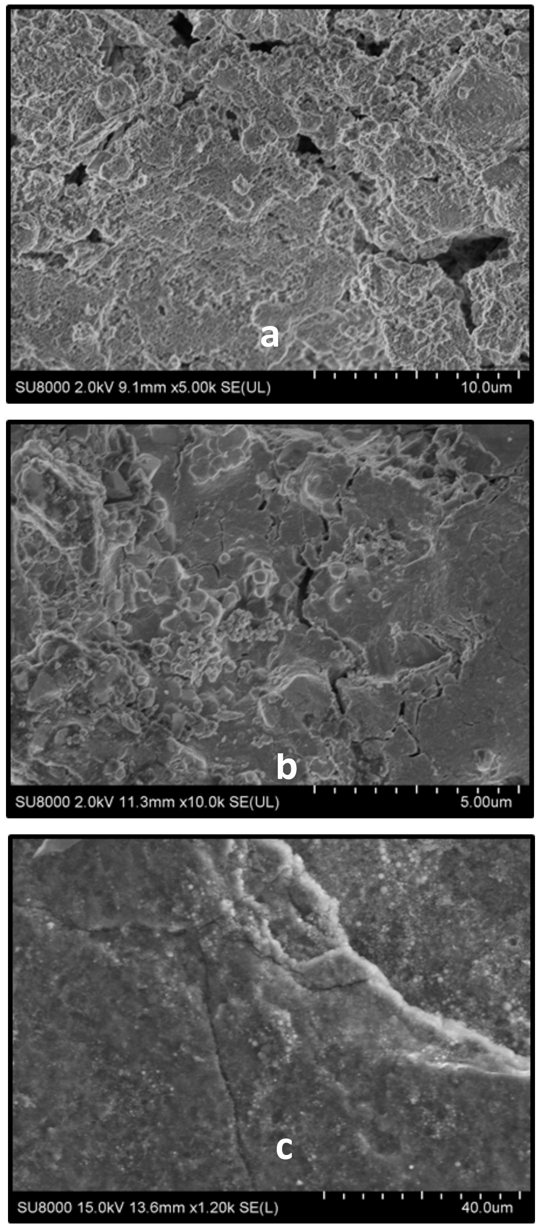


Figure 6. Surface morphology of ash deposit on boiler tubes of (a) economizer, (b) LTR1

Figure 6 shows SEM images of ash deposits collected from (a) economizer, (b) LTR1 and (c) ITS of the boiler. Clearly, the ash deposits on three rear path tubes are porous and brittle. The chemical composition of the ID and OD scales was also determined by using SEM-EDX. The OD scale of all the three tubes were the ash deposition originating from the mineral matter in the coal burnt. Coal mainly composed of C, H and O with some water and traces of inorganic matter [16]. The chemical composition of the outside diameter (OD) scale originated from the mineral matter in the coal used (i.e. ash deposition). Mineral matter is the non-combustible portion of the materials present in coals and forms ash after combustion [16]. Si, Al, Ca and Fe are the major inorganic elements found in coal. The minor inorganic elements include K, Mg, Na, Ti and P. Study has shown that high Fe content in ash as pyrite (FeS_2) promotes boiler slagging by forming low melting point compounds by reacting with alumino-silicates (clays) [8]. Ca can cause severe slagging and fouling during coal combustion. Calcite ($CaCO_3$) is a mineral matter known to be a slag-inducing agent which reduces slag viscosity [17]. Sticky deposit surface will provide a captive surface for impacting ash particles. Calcite decomposes to CaO and CO_2 at 810 to 1100°C.

5. Hardness

Hardness measurement on five selected locations on the internal and external tube surfaces was carried-out and the results are tabulated in Table 3.

Table 3.

Tube	Hardness (virgin) Hv	Hardness (as received), steamside, Hv	Hardness (as received), fireside Hv
Economizer	180 (max)	163 ± 3	163 ± 3
ITS	180 (max)	159 ± 7	159 ± 4
LTR1	146 (max)	158 ± 2	156 ± 2

It can be seen from Table 3 that hardness readings for economizer and ITS remain within the acceptable values. As for LTR1, the as-received (used) tube hardness is just 7% above the maximum hardness of the virgin tube metal. It agrees with the metallographic evidence shown in Figure 3. This is not due to overheating of the tube, followed by quenching process. The metallographic evidence does not support this as no bainite or martensite was observed in the microstructure (see Figure 3).

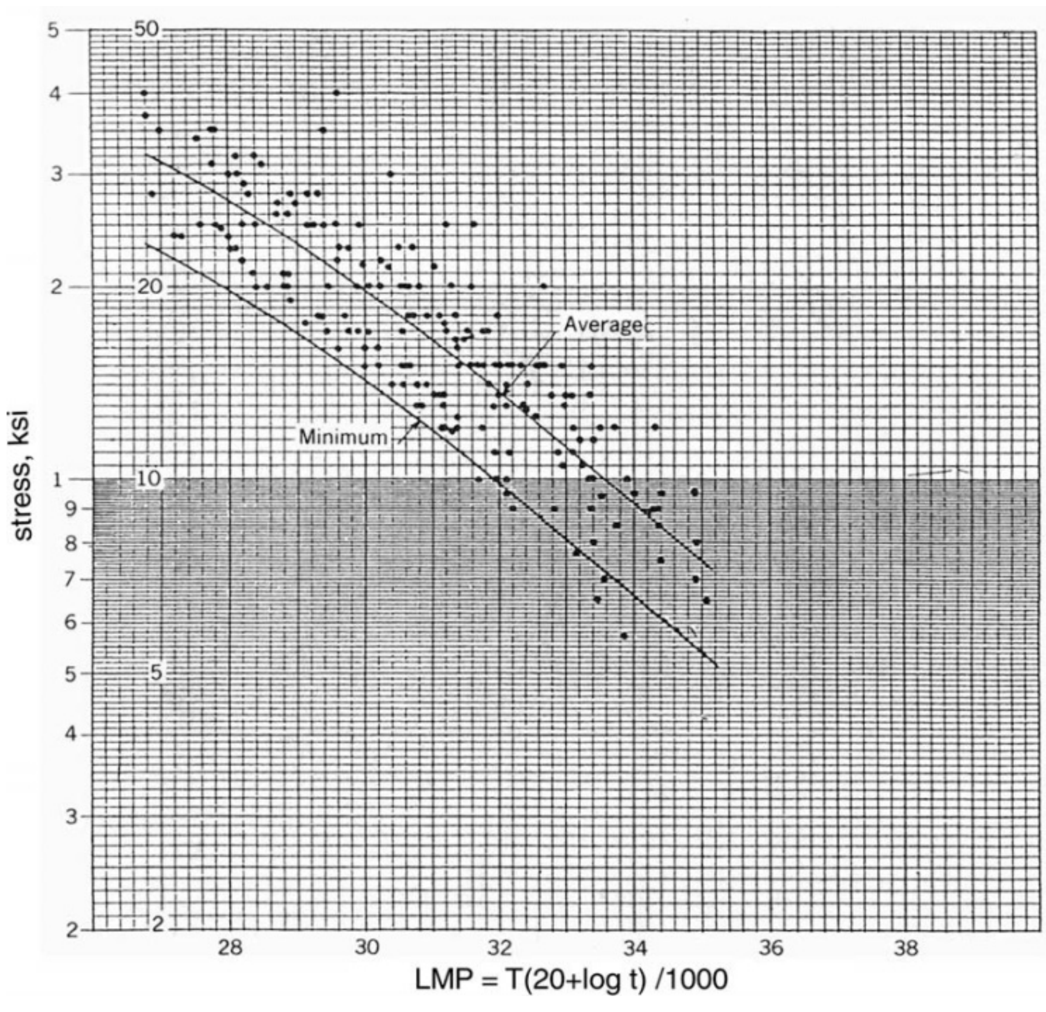


Figure 7. Larsen-Miller parameter with stress variation for rupture of carbon steel pipe and tube (ASTM) [8] (1 ksi = 6.895 MPa)

6. Creep Life Prediction

In order to check possibility of creep problem affecting the removed tubes, calculations of rupture time corresponding to the operational loadings and geometry of the tube need to be carried out. The estimated hoop stress developed in the tube may be determined from [8]:

$$\sigma_h = p[(r + (t/2)/r] \quad (1)$$

where p is operational internal pressure; r and t are inner radius and wall thickness of the tube, respectively.

For the purpose of determining the rupture time of the three tubes, Larsen–Miller parameter (LMP) with stress variation to rupture of carbon steel (ASTM) [8] as shown in Figure 7 is utilized.

The results of the calculation are shown in Table 4. The calculations indicate that the creep damage is not expected to contribute to the failures of these ITS, LTR1 and economizer tubes.

Table 4.

Tube	Hoop stress, MPa	LMP (Average)	Tube metal temperature, °C	Rupture time, hour
Economizer	19.3	32000	330	3.E+09
ITS	17.7	34000	470	3.E+05
LTR1	3.7	36600	460	5.E+07

7. Conclusions

The results show that the high temperature exposure experienced by the economizer, the intermediate temperature superheater and the low temperature reheater tubes did not affect the tubes metallographically as no creep cavities were observed. The strength of the tubes was also maintained as shown by the hardness test results. The experimental results were further supported by the LMP results and the "graphitization, temperature and time for carbon steel" curves.

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