Remaining Life Assessment of Service Exposed Reheater and Superheater Tubes in a Boiler of a Thermal Power Plant

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ABSTRACT

This paper presents the high temperature tensile and the stress rupture properties of 150,000 hours service–exposed superheater and reheater tubes made of 2.25Cr-1 Mo steels in a 120 MW boiler of a thermal power plant. These were used to estimate the remaining life for safety. Experimentally determined yield strength and ultimate tensile strength as well as estimated 10,000 hours – 100000 hours rupture strength as obtained from experimental data in the temperature range of 793 to 853K exhibit a decreasing trend with increasing temperature. Microstructural study did not reveal any significant degradation in terms of creep cavities, cracks, graphitization etc. In general, analysis of tensile and stress rupture data reveal that the service exposed superheater and reheater tubes can remain in service for a length of more than ten years at the operating hoop stress level 40 MPa / 813K, provided no localised damage in the form of cracks or dents has been developed. It is recommended that a similar health check should be carried out after 50,000 hours of service exposure at 813K.

Key words: Service exposed, superheater, reheater, boilers, stress rupture test, tensile properties, residual life.

1. INTRODUCTION

Boiler tubes in power plants have finite life because of prolonged exposure to high temperature, stress and aggressive environment. However, past experience has shown that for a variety of reasons these may have significant remaining life beyond the design specification. This is best estimated by conducting a systematic life assessment exercise during a planned shutdown. In most cases damage accumulation starts from the outer surface. It manifests itself as surface cracks. Therefore careful visual examination and non-destructive tests (e.g. Dye penetration tests, MPI etc.) carried out on the outer surface can give a fair idea about the health of the component. In addition use of ultrasonic flaw detector can also detect nucleation of defects within the material.

Carbon and Cr-Mo steels are extensively used as high temperature components in power plants /1-11/. Even though most of these components have a specific design life of 20 years, many of these have been known to have survived much longer. In view of the increasing cost of setting up a new plant, there is now considerable interest in life extension of the existing units. In order to arrive at a quantitative estimate of the remaining life of such ageing components, it is necessary to have some creep and stress rupture data.

The present work thus incorporates determination of tensile properties in the temperature range of room temperature (298K) to 873K, creep rupture properties in the temperature range of 898K to 973K and microstructural study to assess the condition of the service-exposed reheater and superheater tubes for their continued service.

1.1. Material and history of the service exposed main steam pipes of the boilers:

The material specification with service condition and history of operation of the service exposed superheater and reheater tubes of the boiler are given in Table 1.

1.2 Dimension and visual examination of th service exposed tubes:

The dimensional measurement (see Table 1) carrie out on these tubes did not show any appreciable damag in O.D. (outer diameter). Wall thickness and the cros sections of the service exposed tubes .were found to b of uniform thickness. Dimensions of the outer diamete (OD) were measured at two mutually perpendicula directions along the length of the tube at an interval o 150 mm. The inner surface of the platen superheate outlet tube was dark grey in colour and the thickness o the internal oxide scale was uniform. There was no evidence of any localised attack on the outer and inne surfaces of the tube.

Table 1

Material specification, dimension and service condition of the service exposed tubes

Material	**Platen Superheater Outlet**	**Final Superheater Outlet**	**Reheater Outlet**
Material Specification	BS 3059/622/50 SE	BS 3059/622/50 SE	BS3059/622 S1
Design Steam Pressure at Outlet	151 kg/ cm^2	151 kg/ cm^2	33.044 kg/ cm^2
Operating Steam Pressure Outlet	133.6 kg/ cm^2	133.6 kg/cm^2	28.0 kg/cm^2
Operating Temperature	813 K	813 K	813 K
Design Temperature	823 K	823 K	823 K
Steam flow	3,93,000 kg/hour	3,93,000 kg/hour	361.400 kg/hour
Outer Diameter (OD)	50.8 mm	50.8 mm	50.8 mm
Thickness	10.97 mm	10.97 mm	3.25 mm
Service- Exposed (Running) Hours	150,000hours	150,000 hours	150,000 hours

Table 2

Chemical analysis of the service exposed boiler tubes

Sl. No	**Type of Material**	**Wt % of Elements present**						
		C	**Mn**	**Si**	**S**	**P**	**Cr**	**Mo**
1	Platen Superheater Outlet	0.12	1.14	0.08	0.045	0.03	2.23	0.9
2	Final Superheater Outlet	0.14	0.87	0.14	0.048	0.028	2.31	0.89
3	Reheater Outlet	0.15	0.62	0.21	0.034	0.033	2.49	1.05
4.	BS 3059/622	0.15 max	0.6 max	0.5 max	0.05 max	0.03 max	2.6 max	1.13 max

2. EXPERIMENTAL

Chemical analysis as revealed in Table 2 shows that the materials under the present investigation are basically 2.25Cr-1Mo steels conforming to the grades specified in Table 1.

Optical metallographic examinations (Figs. 1-4) were carried out on the service exposed tubes. The

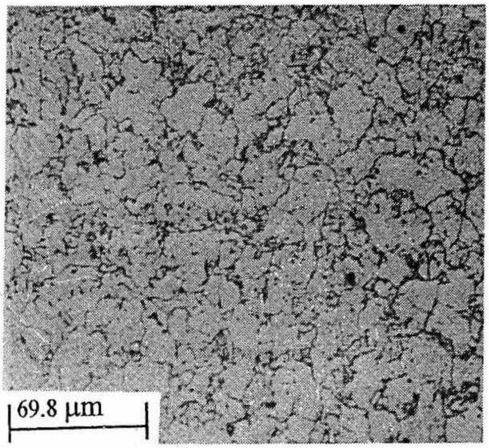

Fig. 1: Optical micrograph of the service exposed reheater outlet tube at X 300 revealed ferritic and bainitic structure with no evidence of creep cavitation damage, oxide scale deposition at inner and outer surface or spheroidization of the tube. The ferrite grains are dispersed with carbides

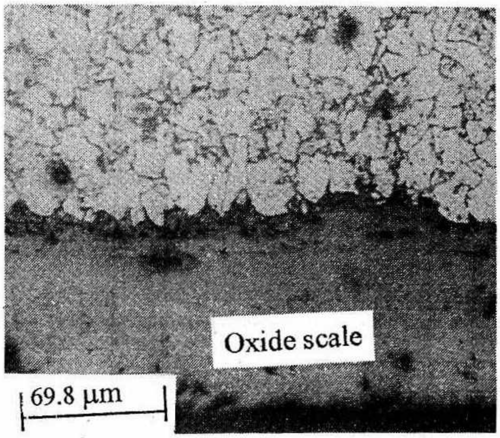

Fig. 2: A typical optical micrograph of service exposed platen superheater outlet tube at X 300 showing a ferritic bainitic structure with no evidence of spheroidization and creep cavitation damage. The ferrite grains are dispersed with carbides. The inner oxide scale deposition was 69.8 microns.

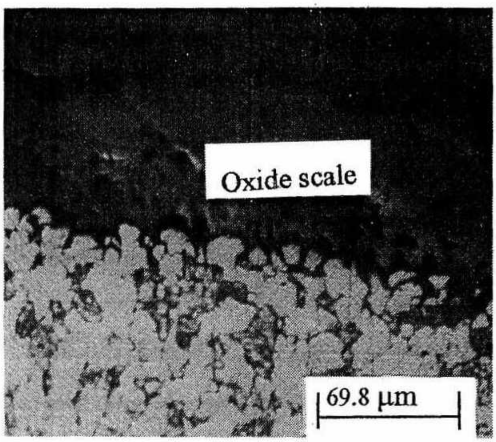

Fig. 3: A typical optical micrograph of service exposed platen superheater outlet tube at X 300 taken in a different region, showing a ferritic bainitic structure with no evidence of spheroidization and creep cavitation damage. The ferrite grains are dispersed with carbides. The inner oxide scale deposition was 69.8 microns.

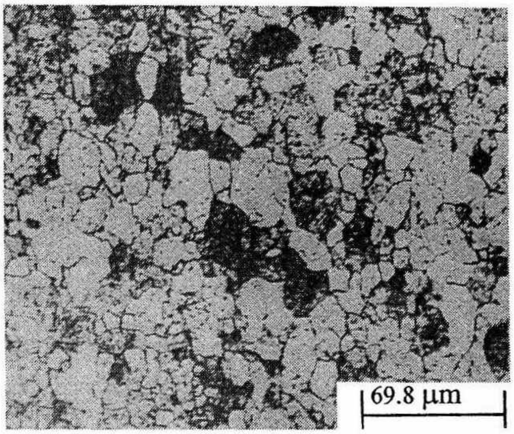

Fig. 4: Optical micrograph of the service exposed final super heater outlet at X 300 revealed ferritic and bainitic structure with no evidence of creep cavitation damage, oxide scale deposition at inner and outer surface or spheroidization of the tube. The ferrite grains are dispersed with carbides

average hardness values (VHN) of these tubes are shown in Table 3.

Tensile tests at room temperature (298 K), 573 K, 673 K, 773 K and 873 K of the service exposed tubes were performed using a digitally controlled 8562 Instron servo-electric testing system, equipped with a 3-zone split furnace with PID control. Standard tensile specimens were made from the service exposed materials as per ASTM E8-79 specification. Tensile tests were carried out on the base metal only from longitudinal direction of the service exposed tub During tensile test, constant test temperature wit ±2°C and a constant displacement rate of ± 0.2 mm/ were maintained. The variation of the Yield Stren (0.2% Proof Stress) and Ultimate Tensile Stren (UTS) with temperature of testing is shown in Figs. & 5b. Fig. 5c shows the variation of % EL (Elongati with test temperature.

Accelerated stress rupture tests using constant lo Mayes creep testing machines were carried out as ASTM 139/83 specification with flat specimens ma from the longitudinal direction of the service-expos tubes. These tests were carried out in the temperatu range of 898-973 K and in the stress range of 38- MPa. The stress levels above the operating stress at ea temperature were selected in such a way as to obta rupture within a reasonable span of time. The ho stress σ_h acting on the service exposed tubes w calculated using the following formula to predict remaining life:

$$\sigma_h = PD/2t \quad ($$

Table 3

Hardness values of the service exposed reheater and superheater tubes

Sl. No	Type of material	Hardness Value (VHN)
1	Platen Superheater Outlet	173
2	Final Superheater Outlet	163
3	Reheater Outlet	176

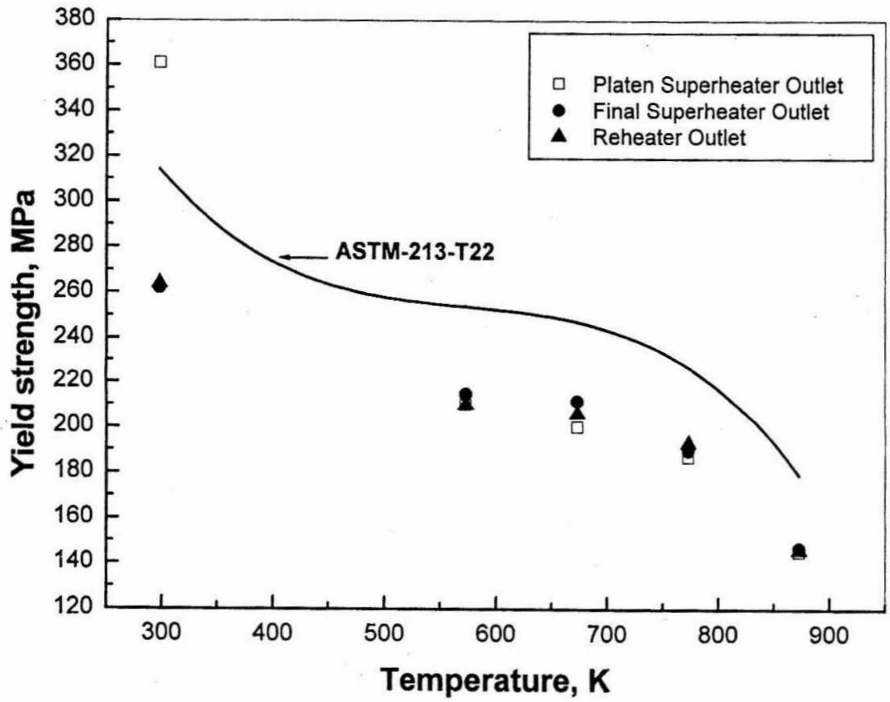

Fig. 5a: Variation of yield strength (0.2% proof stress) with temperature for the service exposed platen superheate final superheater and reheater oulet tubes in a 120 MW boiler of a thermal power plant

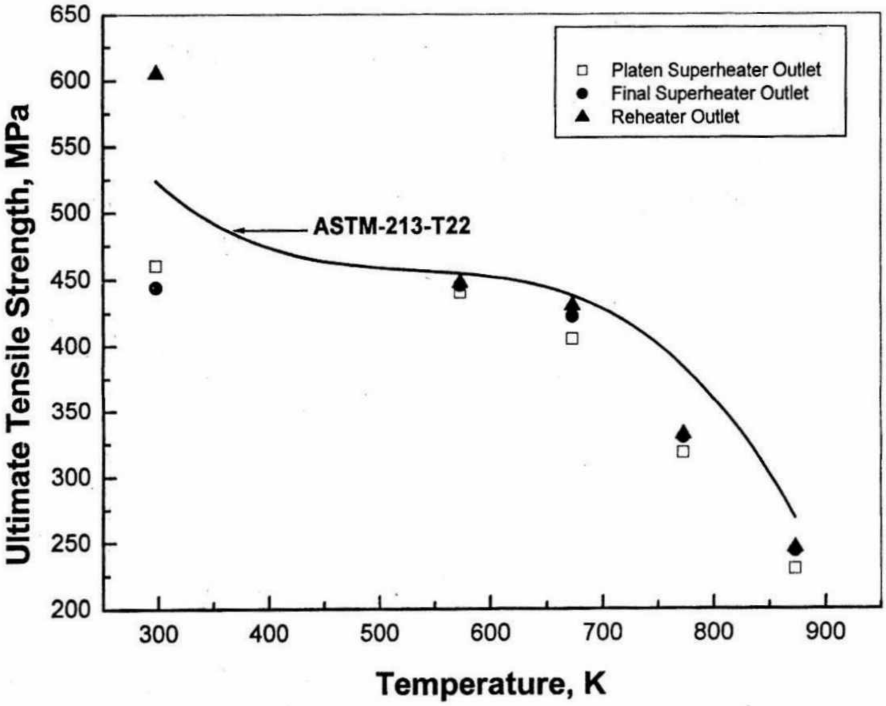

Fig. 5b: Variation of ultimate tensile strength (UTS) with temperature for the service exposed platen superheater, final superheater and reheater oulet tubes in a 120 MW boiler of a thermal power plant

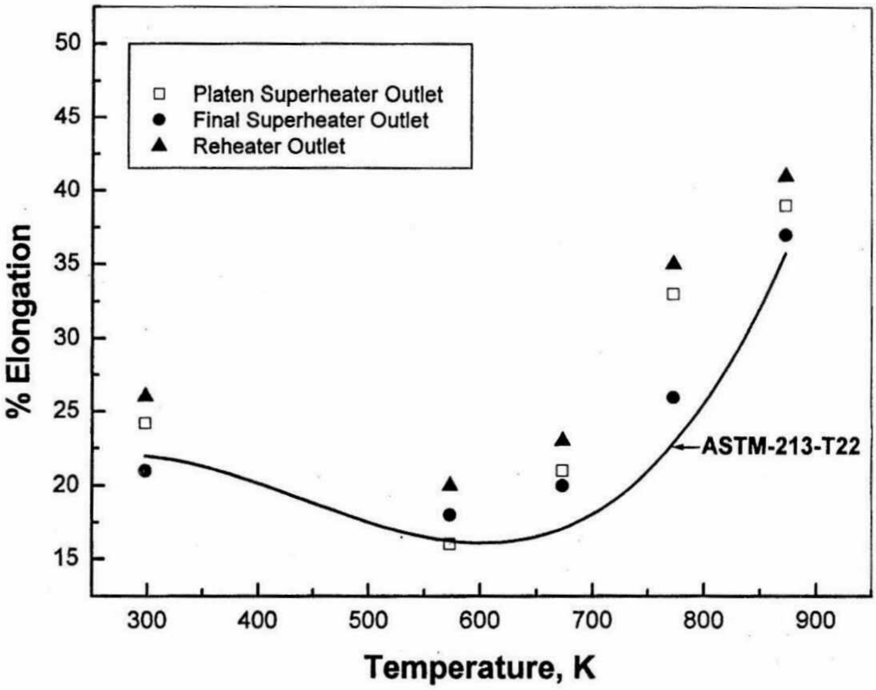

Fig. 5c: Variation of % elongation with temperature for the service exposed platen superheater, final superheater and reheater oulet tubes in a 120 MW boiler of a thermal power plant

where P is the operating pressure in MPa, D is the mean diameter in mm and t is the thickness of the tube in mm. The operating hoop stress thus evaluated is ~ 40 MPa.

The stress rupture data have been plotted in terms of stress vs LMP (Larson Miller Parameter) along with ASME (minimum) data line /12/ for similar grade of steel, for the purpose of comparison (Fig. 6). For the grade of steel under the present investigation /12/, Larson- Miller Parameter $(LMP) = T\,(20 + \log t_r)$

where T = *Absolute Temperature in K*

and t_r = *Rupture time in hours*

The life of the tube in hours was then estimated various temperatures from the LMP value read fro Fig. 6. The variation of temperature versus life in ho of the service exposed tubes is revealed in Fig. Regression analysis of stress rupture data for servi exposed reheater and superheater tubes has been carri

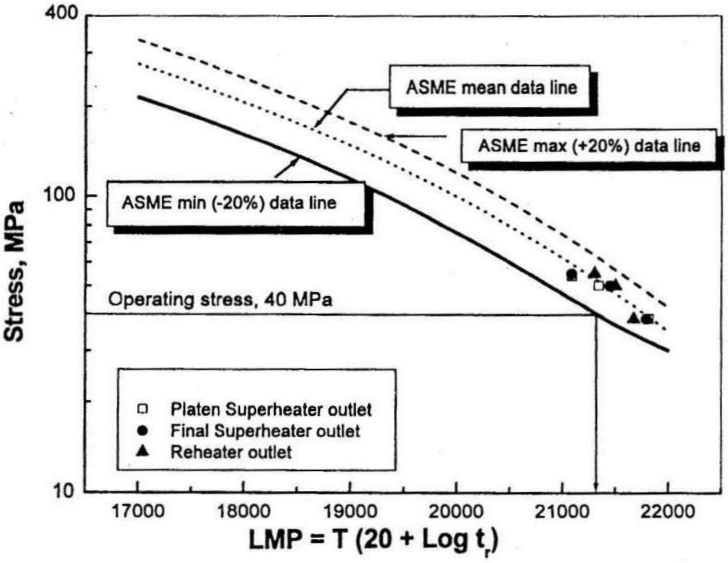

Fig. 6: Plot of stress versus LMP (Larson Miller Parameter) for the service exposed platen superheater outlet, fina superheater outlet and reheater oulet tubes of a 120 MW boiler in a thermal power plant

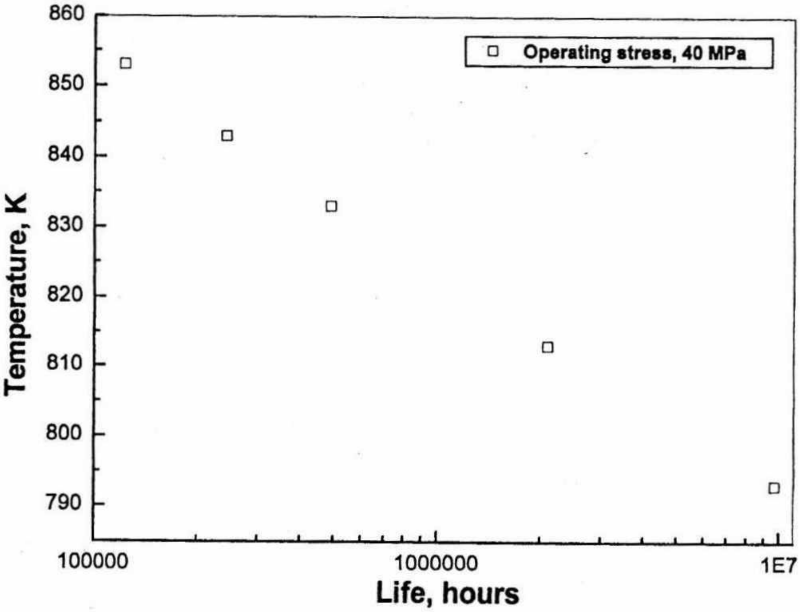

Fig. 7: Plot of temperature versus life of the service exposed platen superheater outlet, reheater outlet and fina superheater outlet tubes of a 120 MW boiler in a thermal power plant

out using a standard software package, in order to evaluate the long term rupture strength of the tubes over a range of temperature presently investigated.

$$\text{Larson- Miller Parameter } (LMP) = T\,(20 + \log t_r) = a_o + a_1(\log S) + a_2\,(\log S)^2 + \ldots\ldots\ldots + a_m\,(\log S)^m \qquad (2)$$

where

S = Rupture strength in MPa

m = Order of polynomial

a_o , a_1 a_2 & a_m are polynomial constants and are shown in Table 4. Table 5 reveals the rupture strength, S, of the service exposed tubes in the temperature range of 793 K to 853 K, for various rupture times and at m=1. The variations of rupture strength with temperature of the service-exposed reheater, platen superheater and superheater outlet tubes are revealed in Fig. 8 and Figs. 9, 10 respectively. It is clear from these figures that the estimated 10000 –100000 hr rupture strengths at various temperatures showed a decreasing

Table 4

Polynomial constants from regression analysis

Type of material	**Order of polynomial**	**Average sum square error**	**a_o**	**a_1**
Platen superheater outlet	M =1, C = 20	0.5376×10^{-2}	0.23631856×10^5	-46.68142
Final superheater outlet	M =1, C = 20	0.11792×10^{-3}	0.23424×10^5	-41.37043
Reheater outlet	M =1, C = 20	0.67626×10^{-2}	0.22533×10^5	-21.746043

Table 5

Estimated rupture strength in MPa

Type of Material	**Temp, K**	**Order of Polynomial**	**Time (t_r) in hrs**		
			t_r =10,000 hrs	**t_r = 30,000 hrs**	**t_r =100,000 hrs**
Reheater outlet coil	793	m=1,C=20	161.0	143.6	124.6
	813	m=1,C=20	138.9	121.1	101.6
	823	m=1,C=20	127.9	109.9	90.1
	833	m=1,C=20	116.9	98.6	78.6
	843	m=1,C=20	105.8	87.3	67.1
	853	m=1,C=20	94.8	76.1	55.6
Final superheater outlet coil	793	m=1,C=20	106.2	97.0	87.0
	813	m=1,C=20	94.6	85.2	74.9
	823	m=1,C=20	88.8	79.3	68.9
	833	m=1,C=20	83.0	73.4	62.8
	843	m=1,C=20	77.2	67.5	56.8
	853	m=1,C=20	71.4	61.5	50.8
Platen superheater outlet coil	793	m=1,C=20	98.5	94.3	81.6
	813	m=1,C=20	88.3	79.9	70.8
	823	m=1,C=20	83.1	74.7	65.5
	833	m=1,C=20	77.8	69.5	60.1
	843	m=1,C=20	72.8	64.2	54.8
	853	m=1,C=20	67.7	59	49.4

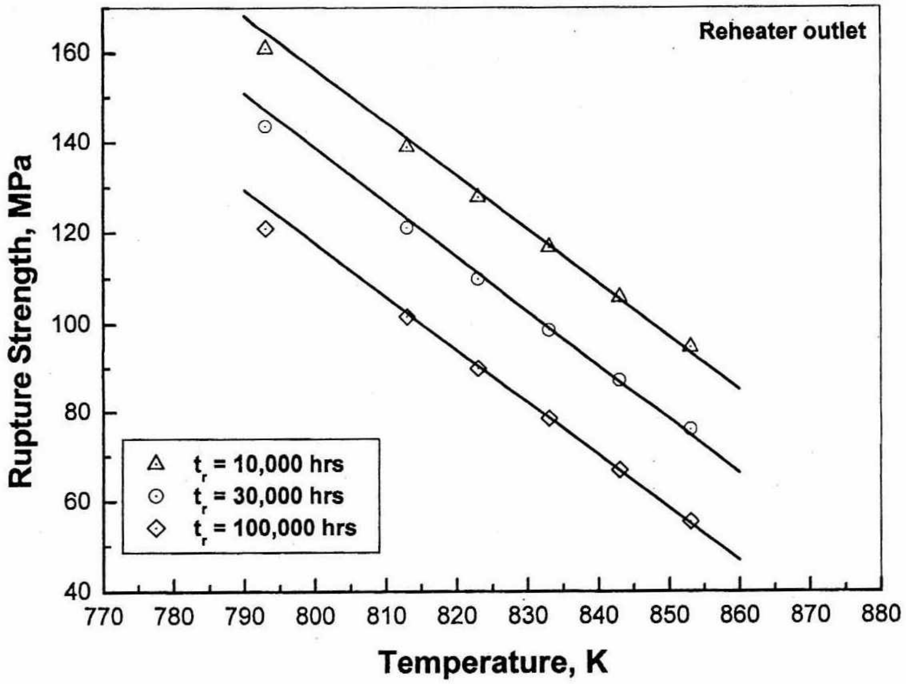

Fig. 8: Plot of rupture strength versus temperature for the service exposed reheater outlet tube

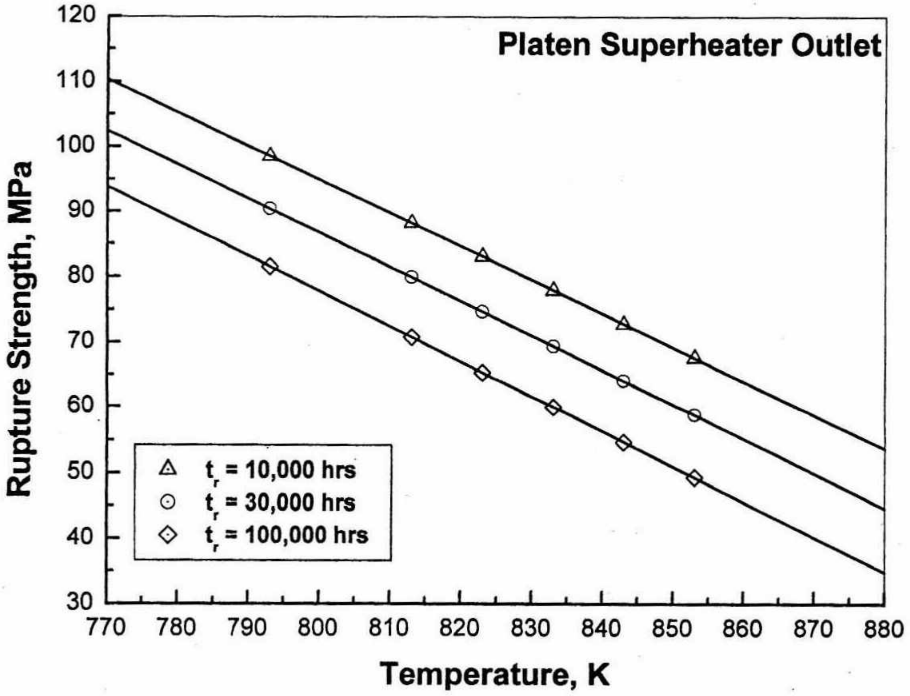

Fig. 9: Plot of rupture strength versus temperature for the service exposed platen superheater outlet tube

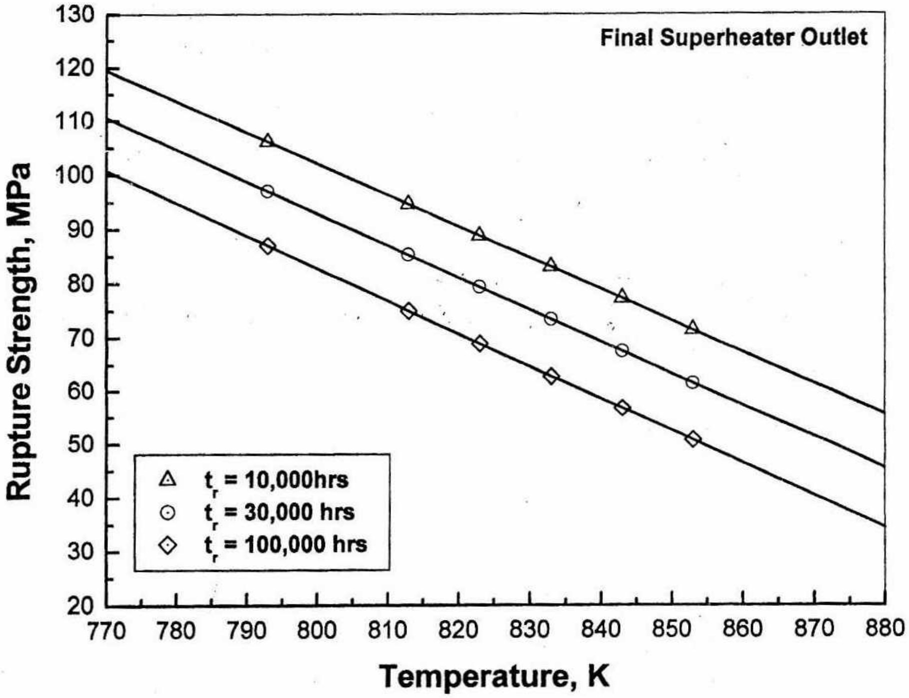

Fig. 10: Plot of rupture strength versus temperature for the service exposed final superheater outlet tube

trend with increasing temperature. This is the general trend observed in service-exposed materials /14-17/.

3. RESULTS AND DISCUSSION

3.1 Visual observation and metallography

Dimensional measurement revealed that there was no change in outer diameter and thickness of the service exposed reheater and superheater outlet tubes. It seems that the tubes have not undergone any appreciable deformation during actual operating conditions. Any evidence of localised damage was not observed on either external or internal surfaces. The hardness level of service exposed tubes revealed (see Table 3) no significant variation in hardness values with exposure lives.

The microstructure of the service exposed reheater, platen superheater and final superheater outlet tubes mainly consisted of ferritic bainitic structure (Figs. 1-4). The ferrite grains are dispersed with carbides. Typical micrographs of service exposed platen superheater outlet tube with an oxide scale of 0.0689mm deposited on the inner surface of the tube are revealed in Figs. .2 and 3. Evidence of graphitization and creep damage in the form of cavitation and decarburisation was not observed in any of the service exposed tubes. Therefore, it is clear that the service exposed reheater, platen superheater and final superheater tubes have had hardly any appreciable degradation from the microstructural point of view.

3.2 Mechanical properties

Room temperature as well as high temperature tensile properties as obtained from experiments are reported in Fig. 5. It is evident from the results that 0.2% proof stress (yield strength) and the UTS (ultimate tensile strength) values for the service exposed tubes showed a decreasing trend with increasing temperature. However, % EL (Elongation) showed an increasing trend with temperature. This is the common trend observed for materials tested at elevated temperature /12-17/. Analysis of tensile data revealed that there is some deterioration in yield stress (0.2 % Proof Stress), ultimate tensile strength (see Figs. 5a & 5b) compared to. ASTM 213-T22 grade of steel due to service exposure, but the %EL (see Fig. 5c) of the service exposed superheater and reheater tubes compared to those of the ASTM 213-T22 grade of steel of similar composition. However, these variations fall within the specified limits for similar grade of steels *viz.* 2.25Cr-1Mo steels, as reported in the literature /12/.

In the absence of discernible cavitation or flaws, stress rupture tests can be selectively used to assess the condition of components. One of the most widely used techniques for life assessment of components involves removal of samples and conducting accelerated tests at temperatures above the service temperature /8/. An estimate of the remaining life is then made by extrapolation of the results to the service temperature. Several uncertainties relating to the validity and application of the technique have been resolved in recent research projects /8/.

In the present investigation, long term rupture strengths were estimated with best fitted curves for third order polynomial. For different orders of the polynomial, the average sum square error (ASSE) was estimated from the following equation:

$$ASSE = \sum (Y_{experimental} - Y_{estimated})^2 / n \quad (3)$$

where n is the number of data points. The first order polynomial was selected for estimation of rupture strength as there was no significant change in the average sum square error for higher orders.

Since microstructural examination did not show any major degradation, it is expected that the mechanical properties will be within expected limits which is also revealed from the experimental data. The inner wall of the super heater tube, which is subjected to the highest temperature, develops a thin oxide layer. This grows with service exposure. If the kinetics of oxide scale growth is known, measurement of oxide scale thickness can give an estimate of the metal wall temperature. This can be used to estimate the remaining life of the tube. The present study shows that the maximum oxide scale thickness is around 0.0698 mm. From the empirical relation available in the literature /18/, the temperature of the metal surface adjacent to the oxide scale can be estimated. Generally, the growth of oxide scale in this grade of steel under the prevailing condition follows parabolic growth rate which is of the form /18/

$$log X = -6.8398 + 2.83 X 10^{-4} (T) (13.62 + log t)$$

where X = *thickness of oxide scale and in mils (1mm* *40 mils), t is the temperature in °R (R= F +460) and* *the time of exposure in hours. In the present case,* *150,000 hrs, X = 0.0698mm = 2.792 mils.* Us published data on oxidation kinetics, the metal temperature was found to be only 760.5 K This unrealistic as it cannot be lower than the temperature steam (813 K). Possibly the tube which was remo has not seen 150,000 hour of service expos Alternately the oxide scale may have spalled and fal at some stage of service. Therefore to estim remaining life it will be more appropriate to use act design temperature which is 853 K.

Short term stress rupture tests were also carried on standard test specimens made from pla superheater outlet, final superheater outlet and rehea outlet coils. The data obtained have been compared the reported data on 2.25Cr1Mo steel in Fig. 6. The l in the figure represents the minimum rupture streng for 2.25 Cr1Mo steels from the literature (the ASM minimum data line). It is clear that all the data above the minimum ASME data line. It is notewor that at low stress levels the stress rupture data do merge with the minimum ASME data line, which is common trend observed in such steels. It is al interesting to note that most of the data seemed to on the ASME mean data line. However, one conclude that all the stress rupture data lie well wit the scatter band of the ASME mean data line (see F 6). Therefore, as far as creep strength is concerned th is no appreciable degradation due to service exposu This is also consistent with the information collec from other destructive and non-destructive te conducted on boiler components.

Fig.7 represents the variation of temperature w rupture time or the life in hours for the service expos platen superheater, final superheater outlet and rehea outlet tubes. It is evident that at 843 K and at 853 K, these service exposed tubes have a remaining life more than 100,000 hours, provided there are no cra dents, microstructural degradation like creep cavitati damage due to micro void coalescence, evidence spheroidization/graphitization, decarburization etc. in the materials due to long term service exposure. However, a similar health check is desirable after 5 years of service exposure.

It is to be noted that the accelerated stress rupture tests were conducted on the specimens containing the oxide scales. Therefore, the life predicted from stress rupture plots using the LMP (Larson Miller Parameter) equation gives the remaining life (t_r) of the service exposed outlet tubes with the oxide scale thickness included. Since the maximum oxide scale deposited was 0.0698 mm only for the platen superheater outlet tube, this would have negligible influence on the remaining life of the service exposed platen superheater outlet tube. This is because this scale was developed over the entire period of 150,000 hours of service under prevailing operating conditions of the plant and the actual average operating metal wall temperature would not exceed the specified operating temperature, i.e. the steam temperature, which is not possible in actual practice.

The hardness values of the service exposed superheater and reheater tubes have been superimposed on the mean data line in the hardness versus LMP plot (see Fig.11), thus enabling us to justify that the temperature of the metal wall adjacent to the oxide scale was not less than the steam temperature. It is clear from Fig. 11 that all data lie on or above the mean data line for 2.25Cr1Mo steels as reported in literature /19,20/. A similar behaviour was also observed from the stress versus LMP plot (Fig. 6), where most of the data lie on the mean data line for 2.25Cr1Mo steel.. Since there was not any appreciable change in the hardness values of such steels even due to prolonged service exposure, the stress rupture data at low stress levels did not merge with that of the ASME minimum data line (see Fig. 6).

Since it is not always possible to give the precise residual life in view of some uncertainties including the over extrapolation, it is also the practice to make use of the following criteria to decide the serviceability (see Fig. 12) of such service exposed components / 11 /:

a) Time margin = $t_f / t_s \geq 3$
b) Stress margin = $\sigma_{creep} / \sigma_s \geq 1.50$

where t_s = service life
t_f = rupture life at service stress (σ_s)
σ_s = service stress
σ_{creep} = stress for rupture corresponding to the service life

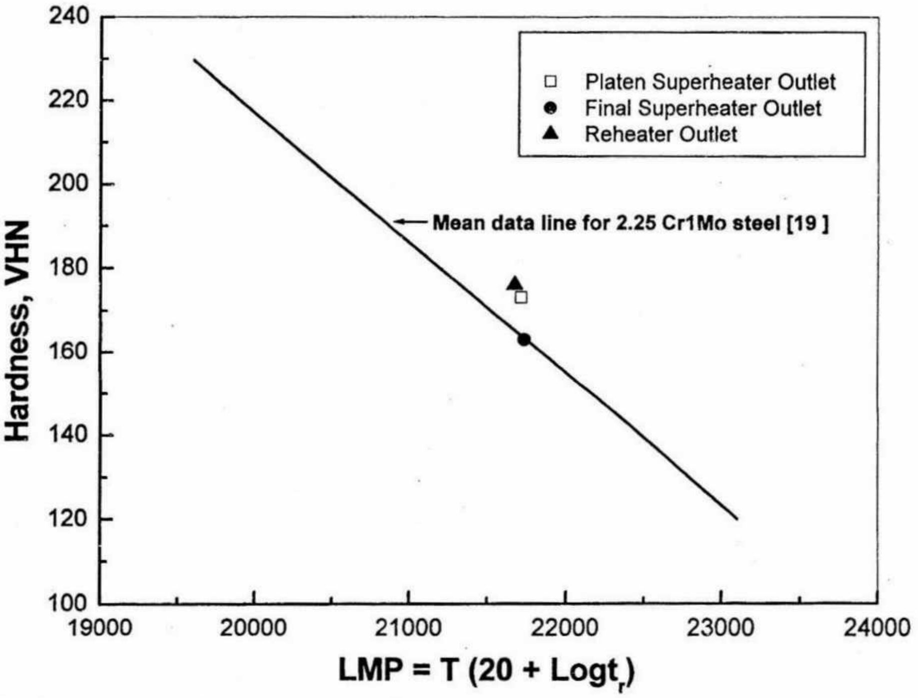

Fig. 11: Plot of hardness versus LMP (Larson Miller Parameter) for the service exposed platen superheater outlet, final superheater outlet and reheater outlet tubes of a 120 MW boiler in a thermal power plant

Table 6

Stress and time margin at 813K

Type of material	Stress margin at operating hoop stress level	Stress margin at design stress level s	Time margin at operating hoop stress levels
Platen superheater outlet	1.65	1.92	14.
Final superheater outlet	1.65	1.92	14.
Reheater outlet	1.95	1.65	14.

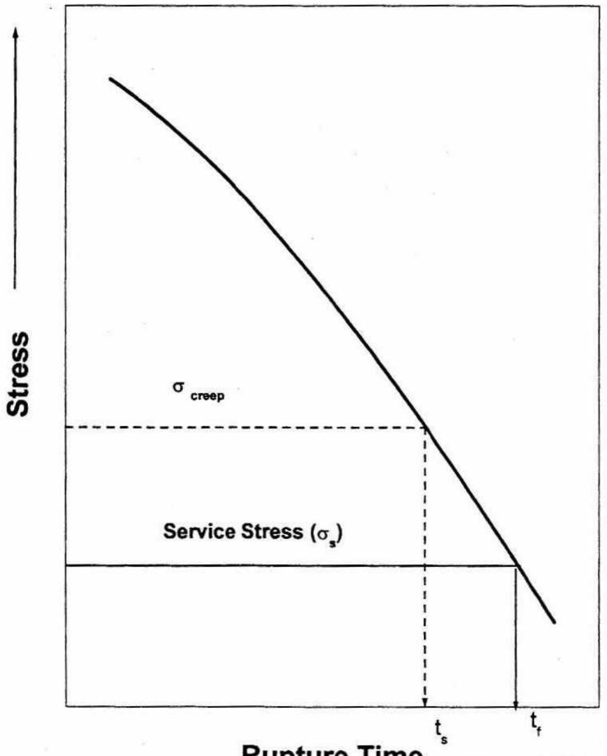

Fig. 12: .Schematic of stress versus rupture plot.

The higher the time margin, the better is the safety of operation for the service exposed materials. The values of the above margins as estimated from the stress rupture data in the present investigation for service exposed reheater and superheater outlet tubes are displayed in Table 6.

So far as the remaining life at 813 K / 40 MP concerned, it is possible to obtain a minimum life o 100,000 hours for the service exposed reheater superheater outlet tubes provided there is no evidence localised damage in the form of surface crac cavitation or dents. It is recommended to carry another check for safety of the service exposed pipes terms of residual life after expiry of 50,000 hours service life from the view of economical and saf reasons. Also during shut down of the plant, N (nondestructive) tests viz. dimensional (thickness a diameter) measurement, hardness measurement and *situ* metallography may be carried out to assess condition of the materials for their future serviceabili

4. CONCLUSIONS

The aforesaid study leads to the follow conclusions:

i) So far as the residual life at 813 K / 40 MP concerned, it is possible to obtain a minimum of about 100,000 hours for the service expo reheater, platen and final superheater outlet tu provided there is no evidence of localised dam in the form of surface cracks, cavitation or dents

ii) Analysis of tensile data revealed that there is so deterioration in yield stress (0.2 % Proof Stres ultimate tensile strength of the service expo reheater, platen and final superheater tu compared to those of the virgin tube reported literature, but these variations are within specified limits for similar grade of steels.

iii) The service exposed reheater, platen and final superheater outlet tubes appear to be in a reasonably good state of health. It is recommended to carry out another check for safety of the service exposed pipes in terms of residual life after expiry of 50,000 hours of service life from the view of economical and safety reasons. Also during shut down of the plant, NDT (nondestructive) tests, viz. dimensional (thickness and diameter) measurement, hardness measurement and *in situ* metallography may be carried out to assess the condition of the materials for their future serviceability

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