Journal of Manufacturing Engineering, 2007, Vol.2, Issue.2

SOME ASPECTS OF CREEP AND LIFE ASSESSMENT OF ENGINEERING COMPONENTS IN THERMAL POWER PLANTS

Dr. Satyabrata Chaudhuri

National Metallurgical Laboratory Jamshedpur 831007, India

Email: sc1@nmlindia.org

ABSTRACT

In thermal power plants, engineering components made of Cr-Mo/ Cr-Mo-V steels operate extensively at high temperature and pressure in corrosive environments to perform specific functions for a minimum specified period of time. In operation, several natural ageing processes such as creep, corrosion, fatigue etc. are responsible for accumulating micro structural damages thereby limiting the lives of the components. This paper describes some aspects of creep life assessment technology and a few case studies related to changes in microstructure due to ageing, failure and remaining creep life of components in thermal power plants. The failure investigation of final super-heater tubes showed that the failure took place due to short term overheating. The temperature excursion due to overheating as estimated from the kinetic data on oxide scale growth was about 830ºC. The circumferential expansion in this tube was about 19%. The wall thinning due to oxidation and creep are primarily responsible for failure of this tube. It had been established considering the influence of wall thinning that irrespective of operating temperature, pressure and damage development, modified 9Cr-1Mo steel exhibits longest life among various grades of Cr-Mo steels. The influence of prolong service revealed that un failed re-heater tubes exhibit higher tensile properties than that of platen super heater tubes. In contrast the creep rupture properties of both the tubes at 50 MPa meet the minimum creep rupture properties when compared with NRIM data. The remaining creep life of platen super heater tube as estimated at 50 MPa and 570ºC is more than 10 years and that of re heater tube at 50 MPa and 580ºC is 9 years.

Keywords: *Creep Life Assessment Technology, Microstructure Study of Ageing Failure*

1. INTRODUCTION

Engineering components in thermal power plants such as boiler tubes, headers, main steam pipes, HP, IP and LP cylinders, rotors etc. operate in a complex environment involving high temperature, pressure and corrosive atmosphere. During service depending upon the operating conditions, several mechanisms such as creep, fatigue, corrosion, oxidation etc. become operative. Accumulation of micro structural damages in the components due to prolong operation decreases their load bearing capacity. When it falls below a critical level determined by component geometry and loading, failure occurs. Such failure is the major problem concerning the availability of the plants. Life assessment exercise performed at regular intervals is a means to ensure avoidance of such failures. Some important remaining life assessment methodologies are based on empirical models using creep strain measurement, combined time temperature parameter, tube wall thinning, oxide scale thickness measurement, hardness measurement and micro structural assessment etc. The creep database of indigenously produced, service Low alloy ferritic and austenitic steels and alloys are exposed and failed component materials is used for their metallurgical assessment and remaining life prediction [1-8]. Low alloy ferritic and austenitic steels and alloys are extensively used for large-scale chemical, thermal and petroleum industries primarily due to their high temperature creep resistance [9-10]. Numerous research investigations have been carried out, as reported in the literature, to optimize the microstructures and mechanical properties of these alloys [11-15]. Major factors to be considered for selection of such steels and alloys are resistance to creep deformation and rupture, resistance to environmental attack, creep rupture strength and ductility of weld metal and heat affected zone, adequate ductility of base material to avoid sudden failure and also to allow the material to deform rather than fracture in the regions of high stress concentrations. Selection of material for high temperature application, based on temperature dependence of allowable stress, is an important consideration for improving the performance and extending the lives of the plants. The ASME boiler and Pressure Vessel Code, Paragraph A-150 of section I states the criteria for determining allowable stresses.

The allowable stresses are not to be higher than the lowest of the following:

- 1/4 of the specified minimum tensile strength at room temperature
- 1/4 of the tensile strength at elevated temperature
- 2/3 of the specified minimum yield strength at room temperature
- 2/3 of the yield strength at elevated temperature
- Stress to produce 1% creep in 100,000 hours
- 2/3 of the average stress or 4/5 of the minimum stress to produce creep rupture in 100,000 hours, whichever is minimum.

These criteria are employed to estimate allowable stresses for a range of steels as a function of temperature. A comparison of the allowable stresses at various temperatures for commonly used steels is shown in Figure.1 [16, 17]. For 2.25Cr-1Mo steel, it is the creep rupture strength that determines the allowable stress beyond 482oC. Therefore in the evaluation of creep behavior of Cr-Mo steels, estimation of long-term rupture strength has received considerable importance. Although remaining life assessment of aged components operating in power plant and process industries has attracted world wide attention both from economic and safety view points, a globally competitive and cost effective life assessment technology is yet to be developed.

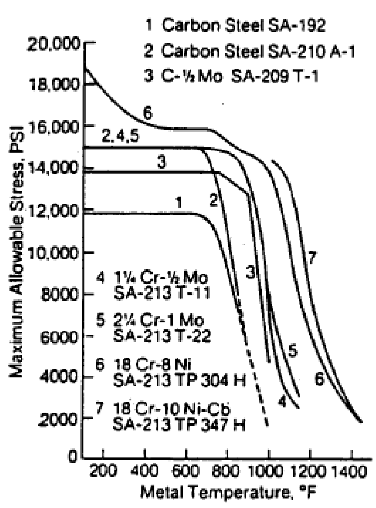

Figure 1 - Allowable stress for several grades of steel as a function of steel

2. CREEP LIFE ASSESSMENT METHODOLOGY

Life assessment methodology can broadly be classified into three levels [18]. Level 1 methodology is generally employed when service life of the components is less than 80% of their design lives. In level 1, assessments are performed using plant records, design stress and temperatures, and minimum values of material properties from literature. When service life exceeds 80% of the design life, Level 2 methodology is employed. It involves actual measurements of dimensions and temperatures, stress calculations and inspections coupled with the use of the minimum material properties from literature. However when life extension begins after attaining design life, Level 3 methodology is employed. It involves in-depth inspection, stress analysis, plant monitoring and generation of actual material data from samples removed from the component. The details and accuracy of the results increase from level 1 to level 3 but at the same time the cost of life assessment increases. Depending on the extent of information available and the results obtained, the analysis may stop at any level or proceed to the next level as necessary. One of the crucial parameters in estimation of creep life is the operating temperature. Although steam temperatures are occasionally measured in a boiler, local metal temperatures are rarely measured. Due to load fluctuations and steam-side oxide-scale growth during operation, it is also unlikely that a constant metal temperature is maintained during service. It is therefore more convenient to estimate mean metal temperature in service by examination of such parameters as hardness, microstructure, and thickness of the steam-side oxide scale for tubes. Because the changes in these parameters are functions of time and temperature, their current values may be used to estimate mean metal temperature for a given operating time. The estimated temperature can then be used in conjunction with standard creep rupture data to estimate the remaining life. Several methods for estimation of metal temperature have been reviewed elsewhere [19].

2.1. Hardness Based Approach

Changes in strength of low-alloy steel with service exposure depend on time and temperature. Thus change in hardness during service as shown in Figure. 2 may be used to estimate mean operating temperature for the component. This approach is particularly suitable when strength changes in service occur primarily as a result of carbide coarsening neglecting stress induced softening. The database on changes in hardness due to long-term service is employed to assess remaining life [19].

2.2. Microstructure based approach

Toft and Mardsen demonstrated that there are basically six stages of spheroidization of carbides in ferritic steels. Using Sherby-Dorn Parameter, they established a reasonable correlation of microstructure with mean service temperature [20]. Similar semi quantitative and qualitative approaches involving database on changes in micro structure as a function of service history have been widely used [21]

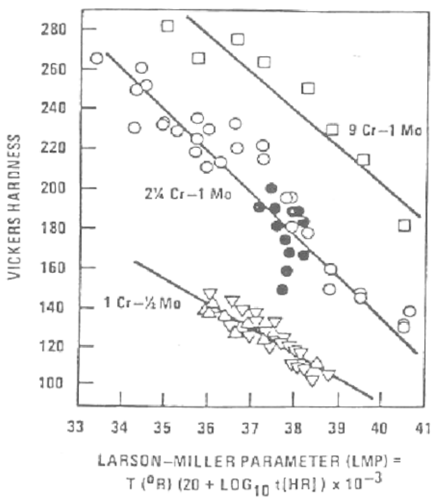

Figure 2 - Changes in Hardness with Larsen-Miller parameter

2.3. Oxide Scale Thickness Based Approach

Extensive data from literature indicate that in relatively pure steam, the growth of oxide scales is a function of temperature and time of exposure. Several expressions have been proposed in the literature to describe oxide scale growth kinetics [22, 23].

2. REMAINING LIFE ASSESSMENT OF ENGINEERING COMPONENTS

Remaining Life Assessment (RLA) is still a challenging task with its hard core; characterization and quantification of the real damage followed by co-relation of the damage with remaining life. Table 1 presents a summary of life-limiting factors for a variety of components in thermal power plants [24]. Factors other than the creep are rather very complicated metallurgical phenomena and are taken care in design indirectly by the safety factor. It is being increasingly realized that the design is conservative mainly on account of a high safety factor of 1.6 and conservative creep database (scatter of ± 20% on mean stress) used for the purpose. Consequently, the life can be extended several folds of the design life.

3. MICROSTRUCTURAL CHANGES DURING AGEING

Since the load bearing capacity of any engineering component is a strong function of microstructures, assessment of micro structural changes during ageing is an important consideration for residual life assessment. The factors which are primarily responsible for micro structural changes in a given component material are operating temperature, pressure and service (aged) life. Keeping this in view, microstructures of service exposed Final Super heater (FSH), Reheater (RH) and Low Temperature Super heater (LTSH) Tubes are shown in Figures. 3 to 5. Material specification, operating temperature, pressure, service life and hardness of the tubes are summarized in Table 2.

Table 1-Life limiting factors of power plant components operating at elevated temperatures

Plant Area	Critical Components	Typical Materials	Life-Limiting Factors
Boilers	Drums	C-steels	Creep, Thermal fatigue
	Headers	C-steels; Cr-Mo steel; Austenitic steels	Creep Thermal fatigue
	Furnace Wall Superheater and Reheater Tubing	C-steels Cr-Mo steels Austenitic steels	Fireside corrosion Waterside corrosion
Pipeworks	Main and Reheat Pipework	Cr-Mo, Cr-Mo-V Austenitic steels	Creep and thermal fatigue; Weld and HAZ cracking
Turbines	HP & IP Rotors	Cr-Mo-V (Nb,W)	Creep, Thermal fatigue
	LP Rotors Blades	Ni-Cr-Mo-V	Fatigue, Corrosion fatigue, Fretting fatigue, Pitting Stress-corrosion cracking, Temper embrittlement
	Steam Chests Casings	Cr-Mo, Cr-Mo-V	Creep, Thermal fatigue,
	High Temperature Bolts	Cr-Mo-V(B) Ni-base alloys	Creep, Thermal fatigue, Stress-corrosion cracking

Table 2 - Material Specification, operating parameters and service life

Table 2 Material specification, Operating Parameters and Service Life

Component	Material Specification	Operating Temperature°C	Operating Pressure Kg/cm²	Service Life Hours	Hardness VHN
FSH	2.25Cr-1Mo Steel	540	157	1,31,247	130
RH	2.25Cr-1Mo Steel	540	33.4	1,31,247	134
LTSH	1.25 Cr-0.5Mo Steel	453	182	1,31,247	175

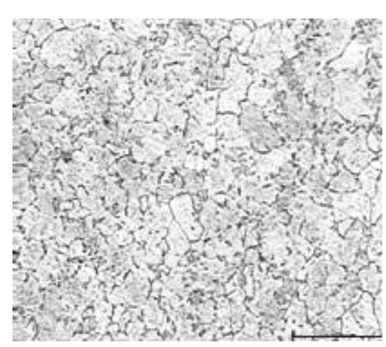

Figure 3 -. Micro structure of FSH tube

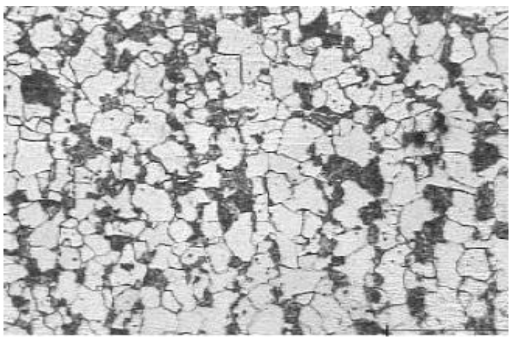

Figure 4 - Microstructure of RH tube

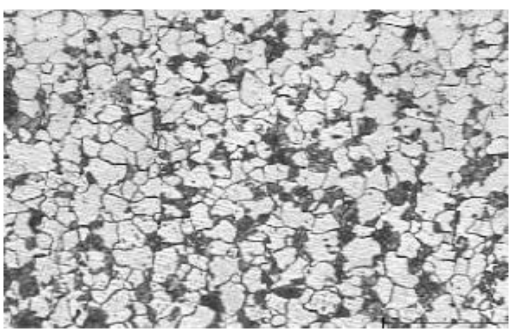

Figure 5 - Microstructure of LTSH tube

Micro structural changes reveal that the extent of degradation is more in FSH tube when compared with RH tube operating temperature and service life remaining the same. Prevalence of higher operating pressure in FSH tube appears to be responsible for such Micro structural degradation. In contrast the extent of degeneration in LTSH tube is not so significant due to prevalence of lower operating temperature. Continued development of such micro structural changes due to prolong service exposure would serve as a wealth of information for failure analysis and life assessment of power plant components.

4. FAILURE OF FINAL SUPERHEATER TUBES

Failure of final superheater tubes of a 500 M boiler occurred during trial run following a service exposure of about 100 hours [4]. Material specification and operating parameters of the tubes are summarized in Table 3. The tube samples selected for this investigation, as shown in Figure.6, are a piece of tube from the zone of failure, a piece of tube adjacent to the failed tube, termed as undamaged tube and a piece of virgin tube. The chemical composition of the failed and virgin tube, reported in Table 4, indicates that the chemistry of both tubes meets the ASTM specification. The outer diameter of the failed tube was found to be 49.2 mm against the original diameter of 44.5 mm. The significant point in this case is the gross circumferential expansion of the failed tube up to about 19%. Such an extensive expansion cannot be expected under normal operating condition within a short span of service exposure of about 100 hours.

Table 3- Material Specification and Operating parameters for super heater tubes

Material	2.25Cr-1Mo Steel ASTM A 213 T22
Outer diameter	44.5 mm
Thickness	10.0 mm
Steam temperature	560^oC - 580^oC
Steam Pressure	185 kg/cm^2
Steam flow rate	1700 tons/hr.

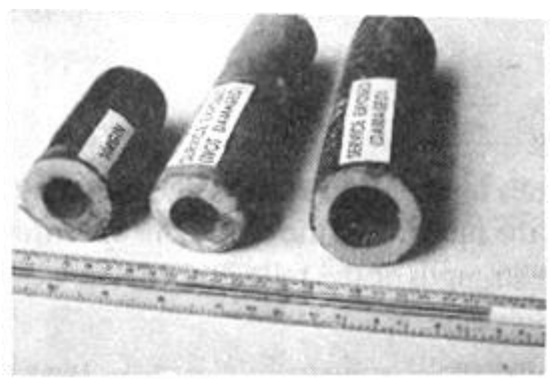

Figure 6 - Virgin, undamaged and failed super heater tube of 500 MW boiler

It is evident from the measurement of hardness at the inner surface, mid section and outer surface of all tubes (Table 5) that the hardness of the failed tube is significantly higher than that of virgin and undamaged tubes.

Table 4 - Chemical Composition weight percentage

Element	Failed Tube	Virgin Tube	Specification ASTM A213 T22
Carbon	0.12	0.1	0.06-0.15
Manganese	0.41	0.42	0.30-0.60
Silicon	0.22	0.22	0.50 max
Phosphorus	0.013	0.012	0.25 max
Sulphur	0.003	0.003	0.025 max
Chromium	2.16	2.13	1.90-2.50
Molybdenum	1.05	1.00	0.87-1.13

Table 5 - Hardness values of virgin undamaged, failed tubes

Tubes	Hardness, HV20		
	Inner	Middle	Outer
Virgin	145	149	151
Undamaged	143	143	145
Failed	179	178	180

The tensile properties of all tubes, as shown in Figure.7, revealed that irrespective of test temperature all the tubes meet the minimum specified properties of 2.25Cr-1Mo steel. The tensile strength of the failed tube is, however, significantly higher than that of the other tubes.

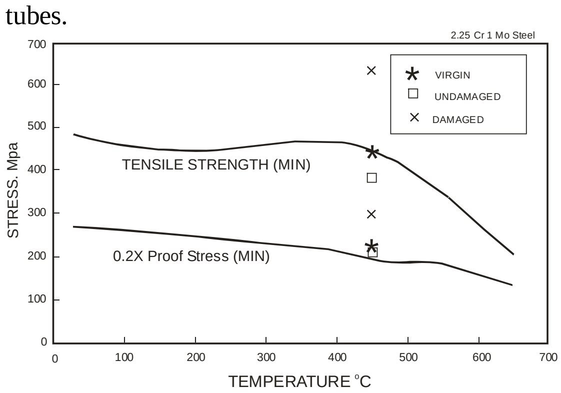

Figure 7 - Tensile Properties of virgin, undamaged failed and failed final super heater tube of 500 MW Boiler

The microstructures of virgin (Figure.8a) and undamaged (Figure.8b) tubes are almost similar, consisting of ferrite and tempered bainite. In contrast the microstructure of the failed tube (Figure.8c) showed the presence of freshly formed bainitic areas. Besides, the oxide scale thickness on the inner surface of the failed tube (Figure.9a) was found to be several folds more than that of the undamaged tube (Figure.9b). In the failed tube the oxide scale thickness was 0.25 mm.

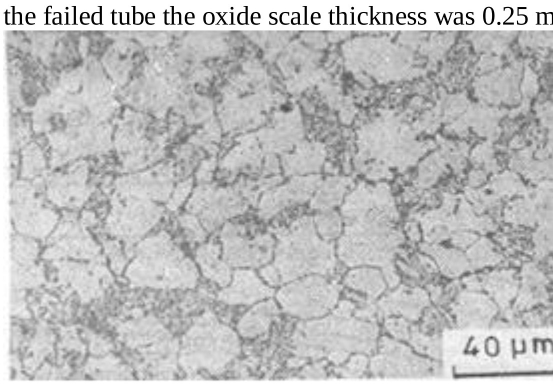

Figure 8a - Microstructures of Virgin tube

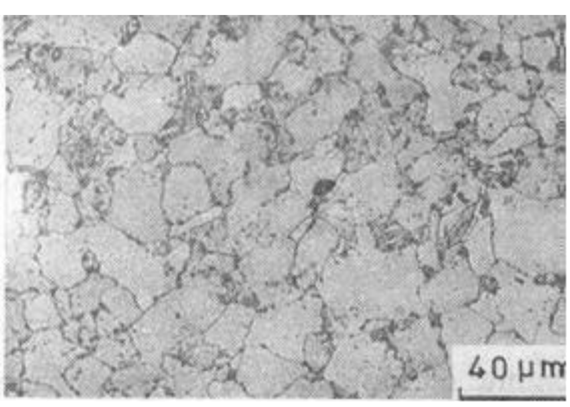

Figure 8b- Microstructures of Undamaged tube consisting of ferrite and tempered bainite

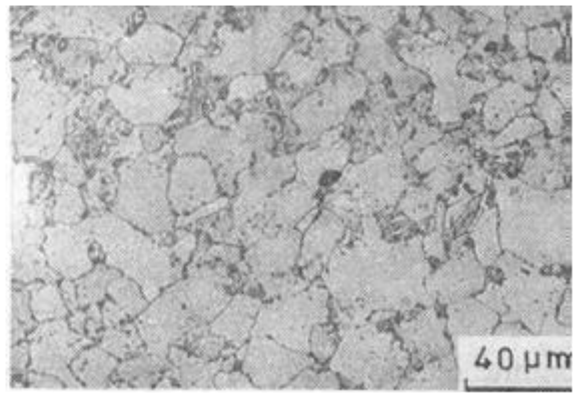

Figure 8c - Microstructures of a Failed tube showing freshly formed bainitic regions

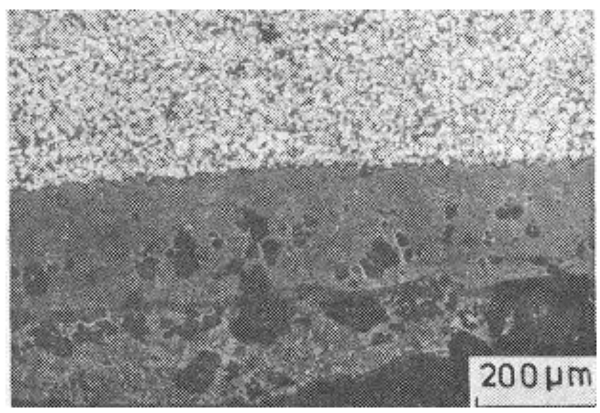

Figure 9a - 0.25 mm oxide scale at inner surface of failed tube

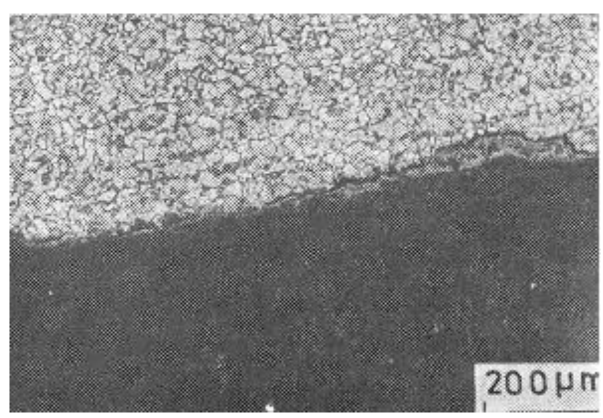

Figure 9b - Insignificant oxide scale at inner surface of the undamaged tube

All the above observations can be reconciled in a situation only if the temperature had exceeded the lower critical temperature, which is reported to be about 800ºC for 2.25Cr-1Mo steel. In order to predict the extent of temperature excursion beyond the critical temperature some detailed analysis was made based on oxide thickness as obtained on the inner surface of the failed tube. Published kinetic data on oxide scale growth of 2.25Cr-1Mo steel have been used for this purpose [17]. The predicted time-temperature profiles for a range of service exposure to develop 0.25 mm thick oxide at the inner surface of the failed tube are shown in Figure.10 Predicted time temperature profiles to develop 0.25 mm thick oxide layer at inner surface of failed tube Since the presence of freshly formed bainite is indicative of temperature excursion beyond the lower critical temperature, the most probable profile that the tube experienced is the one having an exposure of 2 hours, the maximum temperature being 830ºC. Corresponding to each time-temperature profile (Figure.10), accumulation of strain and the diametrical expansion of the tube have been calculated and presented in Figure.11. The creep strain predicted from the time temperature profile for 2 hours exposure comes to about 1%, which is indeed quite lower than the observed value of 19%. It is mainly because the existing material database in the temperature range of 500ºC to 600ºC has been used for extrapolation. Clearly there is a need to collect creep data at temperatures beyond 600ºC.

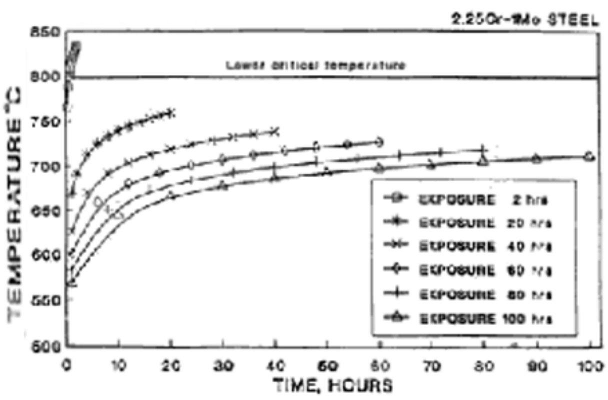

Figure 10 - Predicted time temperature profile to develop 0.25 mm thick oxide layer at inner surface of the failed tube

In order to ensure whether it is possible to achieve a creep strain of about 19% within a short time at 830ºC, a short-term creep test has been carried out in the laboratory. Based on this it has been established that a creep strain of about 16% is achievable in less than 2 hours at 830ºC and a stress level of 30 MPa, which represents the hoop stress corresponding to the maximum operating pressure of 185 kg/cm2 for the tube in question. This, therefore, conclusively proves that the failure of the tube took place due to short term overheating to a temperature of about 830ºC. Partial chocking of the tube by some foreign material could be responsible for such overheating. The other tubes, however, did not suffer any heavy temperature excursion beyond 650ºC.

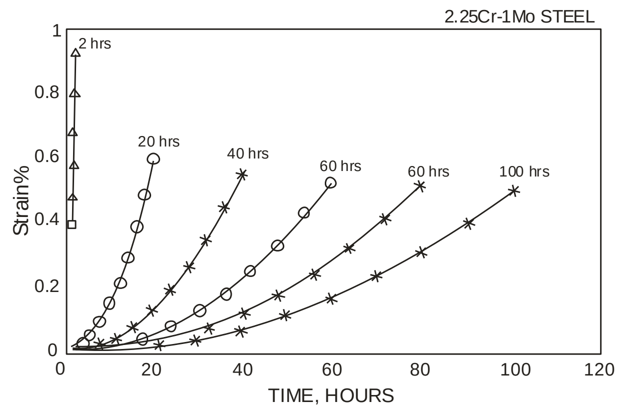

Figure 11- Predicted creep strain corresponding to time-temperature profile shown in Figure.10.

Although the high temperature mechanical properties of service-exposed components are often found to be better than the minimum specified level, the component dimensions often change as a result of prolonged service. The most prominent amongst these is the loss of tube wall thickness. The growth of oxide scale at tube surfaces is primarily responsible for this. Other external processes such as coal ash corrosion, flame impingement and fly ash erosion also contribute to such damage development in service. A need is thus felt to look into the life prediction problems considering the influence of wall thinning due to the existence of corrosion and erosion processes during operation of the plant. Keeping this in view the methodology recently developed in the laboratory for creep life estimation of boiler tubes under wall thinning condition highlighting some typical results has been discussed elsewhere [4].

5. CREEP LIFE ASSESSMENT OF PLATEN SUPERHEATER AND REHEATER TUBES

Service exposed Platen superheater (PLSH) and Reheater (RH) tubes of a thermal power plant were identified for remaining creep life assessment study [25]. The grade of steel, dimensions and identification nos of these tube samples are given in Table 6. The experimental work undertaken for assessing remaining life of service exposed boiler tubes includes tensile tests, hardness measurement, microstructural examination and creep rupture tests. The test data so generated have been analyzed and compared with National Research Institute for Metals (NRIM) data for 2.25Cr-1Mo steel to examine the influence of service exposure on mechanical properties and remaining life of boiler tubes. Standard specimens were made from the longitudinal direction of the service exposed boiler tubes to carry out tensile tests in air in the temperature range of 25ºC to 650ºC using Instron 8562 servo electric machine at a constant displacement rate of 0.008 mm/sec and creep rupture tests in air using Mayes creep testing machines in the temperature range of 600oC to 650ºC. The stress levels for creep rupture tests are selected to obtain rupture within a reasonable span of time. Hardness measurement at 25ºC was carried out on specimens selected from each type of boiler tube. The results of tensile tests viz. YS/0.2% PS, UTS and %Elongation as a function of temperature, hardness measurement as well as creep rupture tests viz. Rupture Time and %Elongation as a function of temperature and stress for PLSH and RH tubes are reported elsewhere [26].

Table 6 - Material Specifications for Boiler tubes

Tube Sample	Identification	Nominal Dimension ODXTh , mm	Measured Dimension ODXTh , mm	Grade of Steel
PLSH Coil (Outlet)	PLSH-Outlet	51 X 8.8	51.48 X 8.91	SA 213 T22
RH Coil (Outlet)	RH-Outlet	54 X 3.6	54.28 X 5.03	SA 213 T22

Table 7- Operating Parameters of service exposed tubes

Tube Sample.	Designed Steam Temperature°C	Operating Pressure Kg/ cm^2	Length of Service Hours	Zone
PLSH Coil(Outlet)	544 ° C	158.2	59,585	PlatenSuperheater
RH Coil(Outlet)	580 ° C	33.5	59,585	Reheater

The temperature dependence of 0.2% PS / YS data and UTS data of both the tubes are shown graphically in Figures. 12 and 13 respectively. For the purpose of comparison, the minimum NRIM data [27] are also shown in these Figureures. Larson-Miller-Parameter (LMP) calculated using the formula LMP = T(20 + log tr) where T is the temperature in ºK and tr is the rupture time in hours and their dependence on stress is shown graphically in Figure 14. For the purpose of comparison minimum NRIM data [27] are also superimposed in Figure 14.

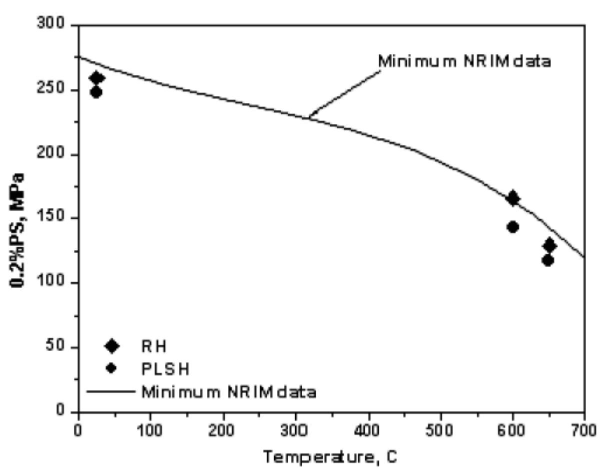

Figure 12 -Temperaature dependence of 0.2% PS of PLSH and RH tubes

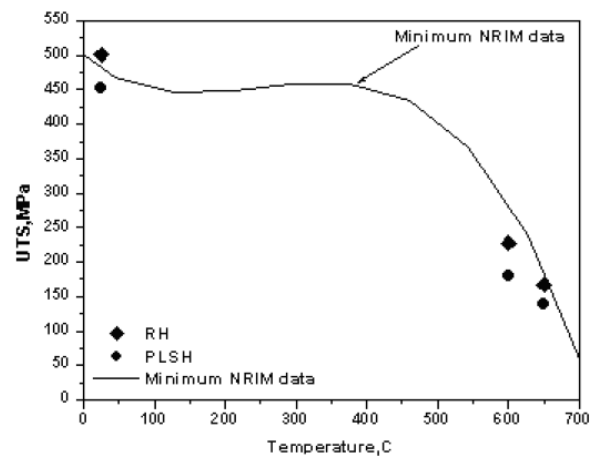

Figure 13 - Temperature dependence of UTS of PLSH and RH tubes

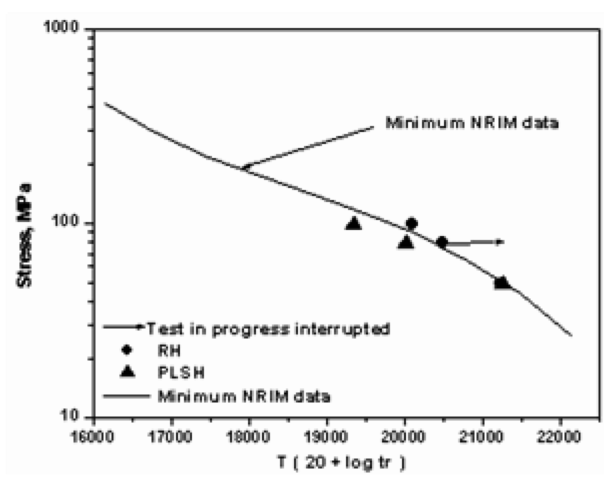

Figure 14 - Stress Vs LMP plot of platen super heater and reheater tubes

Visual examination did not reveal presence of any significant oxidation / corrosion damages on the outer surfaces of both tubes. The reduction in tube wall thickness in reheater and platen super heater tubes as obtained from measurement and their comparison with the specified thickness was not observed. In general, deterioration in 0.2%PS (Figure.12) and UTS (Figure.13) of both PLSH and RH tubes, when compared with minimum NRIM data [27], was observed. The RH tubes exhibit higher 0.2%PS and UTS than that of PLSH tubes irrespective of test temperature. The extent of degradation is more pronounced in case of PLSH tube. The microstructures, in general, consisted of degenerated bainitic regions in terms of spheroidisation of carbides, thin oxide scale at the inner surfaces of both the tubes but without any significant damages such as graphitisation, cavities, microcracks etc [26]. Such microstructural features are expected from the tubes, which have undergone a prolonged service exposure.

The remaining lives of service exposed tubes were estimated using Larson Miller Parameter (LMP). The results of accelerated creep rupture tests of service exposed PLSH and RH tubing steel as obtained in the laboratory are utilized for this purpose. In absence of virgin PLSH and RH tubes, the accelerated creep rupture data of service-exposed tubes are compared with minimum NRIM data [27]. In contrast to deterioration in 0.2%PS and UTS of both PLSH and RH tubes, the applied stress dependence of LMP for these tubes as shown in Figure. 14 clearly indicate that the creep properties of both tubes at 50 Mpa meet the minimum properties when compared with NRIM data. At a stress level of more than 50 MPa, the creep rupture data of PLSH tube fall marginally below the creep rupture data of RH tube. The deviation in terms of LMP is longer at higher applied stress of more than 50 MPa and gradually increases with increasing applied stress. Although the operating hoops stress as estimated from the nominal tube dimension and operating pressure is 37 MPa for PLSH tube and 16 MPa for RH tube, the remaining life has been estimated from experimentally obtained creep rupture data at the lowest stress level of 50 MPa and reported in Table 8.

Table 8 - Remaining life of PLSH and RH Tube

Tube Nos	Type of tube	Estimated Life, Years
PLSH-Outlet	Platen superheater tube	>>10 years at 570 ^{o} C; 50 MPa
RH-Outlet	Reheater tube	9 years at 580 ^{o} C; 50 MPa

Based on accelerated creep rupture tests and analysis of data, it can be said that the service exposed platen superheater and reheater tubes are in a good state of health for its continued service provided no localized damages in the form of tube wall thinning, circumferential expansion, excessive oxide scale formation, microstructural degradation etc are present besides adherence to the specified operating parameters in service. The PLSH tube may be allowed to remain in service for a period of 10 years under similar operating condition provided tube wall temperature does not exceed 570 o C. The RH tube may be allowed to remain in service for a period of 9 years under similar operating condition provided tube wall temperature does not exceed 580 o C. A more reliable estimate of remaining life is obtained by considering simultaneously NDT measurement at site and their analysis, actual operating history, destructive tests and their analysis in the laboratory.

6. REFERENCES

1. S. Chaudhuri and R. N. Ghosh, 1998, "*Some aspects of mechanisms and modeling of creep behavior of 2.25Cr-1Mo Steel",* ISIJ International, Vol 38, No.8, pp881-887
2. S. Chaudhuri, Stress rupture behavior of boiler steels, August 1997, in "*Power Plant Metallurgy"*, edited by R. Singh, S. K. Sinha and S. Chaudhuri, pp.56-73
3. S. Chaudhuri, N. Roy and R. N. Ghosh, 1993, "*Modeling high temperature creep of CrMo Steels"*, Acta. Metall. Mater, Vol. 41, No. 1, pp273-278
4. S. Chaudhuri and R. Singh, 1997, "*High temperature boiler tube failures - case studies"*, in Failure Analysis, edited by S. R. Singh *et. al*, February pp107-120
5. S. Chaudhuri, 1995,*" Life prediction of boiler tubes in corrosive environments"*, in Boiler Corrosion, Proceedings of the National Workshop (NWBC-95), edited by I. Chattoraj et. al., pp1-22
6. R. Singh, S. Chaudhuri et.al, Stress rupture properties of indigenously produced 2.25Cr- 1Mo steels, *NML Report* No. 11620034 December 1990
7. R. Singh, S. Chaudhuri et.al, December 1990, "Stress *rupture properties of indigenously produced 1.25Cr-0.5Mo steels"*, NML Report No. 11620035
8. S. Chaudhuri, 1993, *"Some aspects of creep behavior of 2.25Cr-1Mo steel",* Ph.D Thesis, IIT, Kharagpur,
9. S. Chaudhuri, September 1996, "*Some aspects of creep, creep resistant steels and data analysis for remaining life estimation",* Proceedings of a national workshop on Component Integrity Evaluation program & Life Assessment, pp55
10. John J. Jones, "Improved *Reformer Furnace Efficiency by changing the tube alloy"*, Paralloy Limited, Private communications.
11. T.Shinnoda, T.Ishii, R. Tanaka, K.Kinoshita and J. Minegishi, 1973, *"microstructures and mechanical properties Low alloy ferritic and austenitic steels", Metall Trans*, Vol 4, pp 1213.
12. H.J. Harding and R.W.K. Honeycombe, 1966, J.Iron Steel Inst,Vol 204, pp 259
13. R.D. Naybour: *J.Iron Steel Inst*., 1966, Vol 204, pp 1200
14. K.J.Irving, J.D. Murray and F.B. Pickering 1960, J.Iron Steel Inst, Vol 196, pp 166
15. Hou WEN-Tai and R.W.K. Honeycombe, 1985, Materials Science and Technology, Vol.1, pp385.
16. *ASME Boiler & Pressure Vessel Code*, Section 1, ASME, New York
17. R. Viswanathan, 1989 "*Damage Mechanisms and Life Assessment of High Temperature Components"*, ASM International,, pp185-229
18. R. Viswanathan and R.B. Dooley, April 1986, "*Creep Life Assessment Techniques for Fossil Power*

Plant Boiler Pressure Parts", International Conference on Creep, JSME, 1. Mech. E., ASME, and ASTM, Tokyo, 14-18, p349-359.

19. R. Viswanathan, J.R. Foulds, and D.A. Roberts, June 1988, "*Methods for Estimating the Temperature of Reheater and Superheater Tubes in Fossil Boilers"*, in Proceedings of the International Conference on Life Extension and Assessment, The Hague,
20. L.H. Toft and R.A. Mardsen, 1963, "*The Structure and Properties of 1% Cr-0.5%Mo Steel After Service in CEGB Power Stations"*, in Conference on Structural Processes in Creep, JISI/JIM, London, p p275
21. R. Coade, Feb 1985, "*Temperature Determination Based on Microstructural Changes Occurring in 1% Cr-0.5% Mo Steel"*, Report No.SO/85/87, State Electricity Commission of Victoria, Australia
22. I.M. Rehn and W.Apblett, 1981,"*Corrosion Problems in Coal Fired Fossil Boiler Superheater and Reheater Tubes"*, Report CS 1811m Electric Power Research Institute, Palo Alto, CA
23. S.R. Paterson and T.W. Rettig, 1987, "*Remaining Life Estimation of Boiler Pressure Parts-2.25Cr-1Mo Superheater and Reheater Tubes"*, Project RP 2253-5, Final Report, Electric Power Research Institute, Palo Alktio, CA
24. B.J.Cane, J.M. Brear and P.F.Aplin, 1987, " *Creep and Fracture of Engg. Materials and Structures"*, Edited by, Wilshire and R.W. Evans, The Institute of Metal, London, pp 853.
25. S. Chaudhuri, December 2004*, " Some Aspects of Metallurgical Assessment of Boiler Tubes"*, Proceedings of International Conference on Developments in Steel tube Technology- An Imperative for Auto and Engineering Industry, SNTI, Jamshedpur, pp 103-114
26. S. Chaudhuri, February 2006, " *Creep and Life Assessment of Engineering components in Power Plants and Process Industries",* Proceedings, International Conference on Pressure Vessels and Pipings, Chennai,
27. NRIM Creep Data Sheet No. 3A, 1976