Residual life estimation of super heater tubes based on oxide scale thickness measurement-A Case Study

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Abstract-A failure in any power plant will finally affects the shutdown of the plant and affects the Power supply by the plant that leads to the serious losses. The Failure of the power plant is mostly due to failure in the Boiler tubes of different zones such as Super heater and Re-heater tubes. Failure of tubes in boiler of the power plants may occur due to various reasons. These failure were mainly in the first row of the primary super heater tubes, therefore, these tubes are replace during the annual shutdown. As a tool for failure analysis, oxide scale thickness measurements were used to investigate the Remaining Life of tube. In this paper, the oxide scale thickness of these tubes were measured and used for analysis of remaining life of tube. The measurements also provide an illustration of the distribution of heat transfer of the primary super-heater tubes in the boiler system. For this analysis, were used pipes taken from the same power unit with different values of inner oxide layer thickness and with the same operation time.

Keywords—Super heater tubes; Oxide scale measurements; Overheating

1. Introduction

The residual life assessment (RLA) of critical components of Power plant through interrupted condition monitoring programs is an important activity in the overall power age group programmers. Super heater (SH) and re-heater (RH) tubes operate at temperatures ranging from 400°C to over 600°C depending on the location and design [10]. The SH or RH tube materials are subjected to accumulation of damage by creep and hence designed to give a finite service life. Periodic condition assessment of tubes for creep rupture life helps in preventive maintenance and in reducing forced outage due to tube failure. The service life of SH or RH tubes are greatly affected by the variation in the operating condition like the flame and flue gas temperature, flue gas velocity as well as fuel quality. The damage mechanism associated with failure of boiler tubes is well recognized and also the impact on the utilities profits loss associated with forced outages. Components operating at elevated temperature environment are designed to have a finite life predominantly when design conditions are observed and met. However, damage mechanisms such as creep, fatigue, creep-fatigue, erosion, localized corrosion can be limiting causes for components lives mainly when design conditions or quality assurance are not followed. Unexpected failure can be catastrophic and cost lives and money [12]. To avoid catastrophic failures or unplanned outage it is important to correctly assess the condition and the remaining life of these components operating at elevated temperatures. In the past three decades, life assessment procedures such as oxide scale measurements have become one of the major focuses for research [1]. Failed components operating at elevated temperatures are often complicated by the presence of thick oxide scale on the fracture surface. However, the knowledge of time, temperature and the nature of the oxidizing environment, and their correlation to oxide morphology, can provide a powerful alternative technique for investigation of service failures and can be used for the purpose of life assessment [6]. The thickness of the oxide of a component can also be used with unit operating data and wall thickness measurements to estimate the remaining creep-rupture life of a tube. In-oxide scale thickness measurement can be done on selected tubes for assessment of thickness of oxide scale grown and correlated to remaining life estimation by steam side oxide scale thickness.

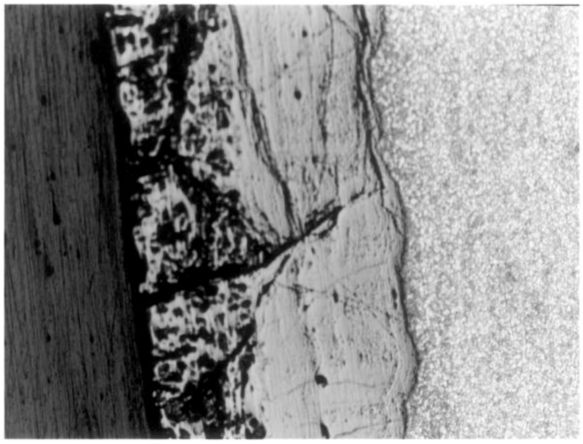

Fig.1.1 Steam side scale; cracking & separation of layer Mag. 50X

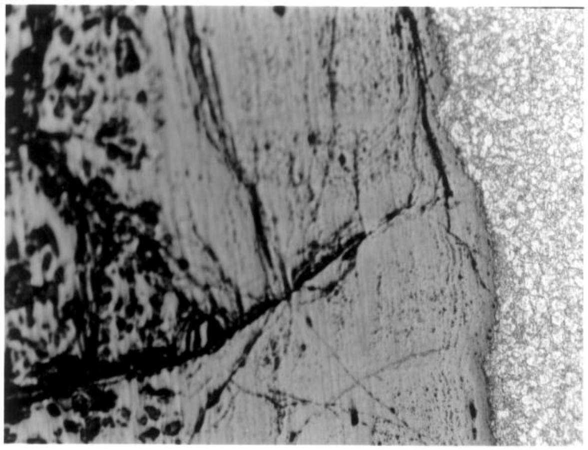

Fig.1.2 At higher magnification - 100X

Fig.1.3 Steam side scale in another tube sample; cracking & separation of layer; Mag. 50X

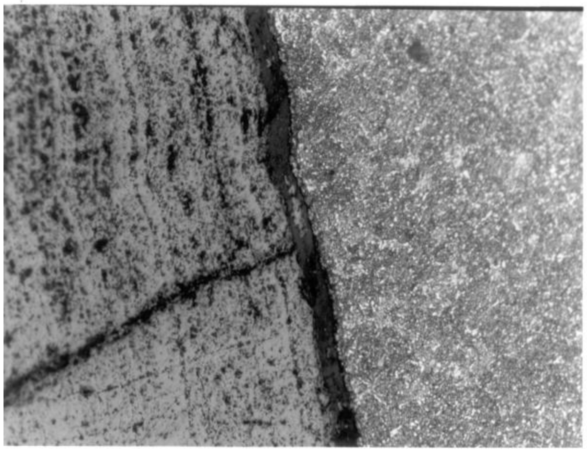

Fig.1.4 At higher magnification - 200X

2. Literature review

A Shibli et.al [1] explain about a relatively newer high Cr martensitic steels such as P91 have now been in use in power industry for over twenty years. Over this time there have been a number of incidents of cracking and failure in components made from P91 steel, both in thick and thin section apparatus mainly due to creep damage. The thick section components have been usually failing due to Type IV cracking associated with the elements while thin section components have been failing due to higher than expected levels of steam oxidation resulting in enhanced metal loss, increase in metal temperature above design, creep cavitations and cracking. However, it has not been possible to detect early stage creep damage or cavitations in high Cr martensitic steels using conventional replication type methods. This is because unlike the low alloy Cr Mo V steels spherodization of microstructure does not occur in high Cr martensitic steels and capitation clearly visible by traditional methods only appears later in life when the material is about to fail.

Greg J. Nakoneczny et.al [2] develops a method, which were aimed at quantifying swell due to creep. Condition assessment and remaining useful life analysis methods have evolved since these initial studies. Experience coupled with improved inspection methods and analytical techniques has advanced the life assessment of these high temperature headers. In the discussion that follows we will provide an overview of B&W's approach to header life assessment including the location and causes for header failures, inspection techniques and analysis methods which are all directed at determining the remaining useful life of these high temperature headers.

Heloisa C et.al [3] presents a comparison between internal oxide layer thickness measurements of pipes performed by ultrasonic (non-destructive technique) and by metallographic preparation associated to optical microscopy (destructive technique), in special ranges of thickness layers. Finally, the work analyzes the remaining life calculation based on the measurement of the oxide layer thickness. The results obtained from the calculation were corroborated with a micro structural characterization of the samples. For this analysis, were used pipes taken from the same power unit with different values of inner oxide layer thickness and with the same operation time.

J. Purbolaksono et.al [4] done a analysis on the SA213-T12 super-heater tube by visual inspection, in situ measurements of hardness and finite element analyses is presented. A primary Super-heater tube has failed with a wide open burst after running at around 28,194 h. Heavy clinkers were found to almost entirely cover the primary super-heater region. In situ hardness measurements were carried out on the selected primary super-heater first row tubes at the middle region between furnace rear screen tube and primary super-heater blower flow path. Hardness measurements are also taken on the as-received failed tube. Finite element analyses on possible features prior to failure are also conducted in order to illustrate and deduce the failure mechanism and failure root cause. Localized short-term overheating of the tube due to localized and concentrated flue gas flow resulted in a failure of the primary super-heater tube.

M. Alardhi provide et.al [5] an approximation for the temperature inside components such as re-heater and super-heater tubes. A number of failures were encountered in one of the boilers in one of Kuwaiti power plants. These failures were mainly in the first row of the primary super heater tubes, therefore, the specialized engineer decide to replace them during the annual shutdown. As a tool for failure analysis, oxide scale thickness measurements were used to investigate the temperature distribution in these tubes. In this paper, the oxide scale thickness of these tubes were measured and used for analysis. The measurements provide an illustration of the distribution of heat transfer of the primary super-heater tubes in the boiler system. Remarks and analysis about the design of the boiler are also provided.

P.M.Padole et.al [6] summarizes some of the major aspects of RLA for coal handling plant. The concept of NDT, discussed in this paper for Coal Handling Plant is to offer significant benefits. Guidelines for implementation of RLA in CHP are also discussed in this paper.
Generally, Non Destructive Testing techniques are adopted in the Residual Life Assessment (RLA) of power plant components like Boilers, Headers, Steam lines, Turbines, Feed water Heaters and Condensers. The reason for inspection depends on the component and its effect on plant operation. But one of the main and major systems of thermal power plant is coal-handling system. No such efforts are carried out to assess the life of coal handling plant component.

Praful R Dongre et.al [7] gives an overview of the high temperature assessment procedures with recent developments in procedures of residual life assessment. A failure in any power plant will ultimately affects the shutdown of the plant and affects the Power supply by the plant that leads to the heavy losses. The Failure of the power plant is mostly due to failure in the Boiler tubes of different zones. Failure of tubes in boiler of the power plants may occur due to various reasons. These include failures due to creep, corrosion, erosion, overheating, fatigue, welding defects etc. It needs to be addressed by a methodology that will be developed and incorporated into design codes such as ASME, as well as in Fitness for Service assessment procedures. This is due to the complex microstructures of well-meant that include base metal, heat affected zone and weld metal. The reliability of the structural assessments following the codes depends strongly on availability of reliable data required as input data. Micro cracks during production either at the parent metal or at the weld metal can affect the service condition of the component which affects the life of the component,

P.U.Pathy et.al [8] explain that Condition assessment plays a vital role in running plant without any interruption and meets increasingly stringent environmental regulations, planned outages, proper preservation and data collection in new as well as old plants. It is an ongoing procedure rather than one time activity. This paper enunciates salient features of condition assessment of boiler from the experience gained over the period of years in this arena to arrive the scope including metallographic spots, selection of non– destructive and destructive tests, planning, execution (bar charts) and reporting.

3. Life Assessment Methodologies for Boiler Tubes

Number of methodologies is available for life estimation of SH / RH tubes of boiler. All these methods are based on average metal temperature of in service tubes, creep properties and life fraction analysis. The methods generally adopted for assessing the remaining life of SH / RH tubes are-

- Laboratory evaluation of selected SH / RH tubes by accelerated uni-axial Stress rupture studies. The creep properties of various virgin Cr-Mo steels used in SH / RH panels are well established through stress rupture test under uni-axial load at a predetermined temperature.
- n-situ evaluation of SH / RH tubes which involves – field metallography for micro structural degradation analysis including hardness measurement and non-destructive evaluation (Ultrasonic) of steam side oxide scale thickness.

Since the stress rupture study needs long period for evaluation, though it gives accurate indication of remaining life, is not suitable for taking immediate strategic decisions at site regarding repair / replacement. The creep-exposed materials generally suffer from micro structural degradation in terms of grain growth, grain boundary thickening and carbide precipitation resulting in loss in strength. The metallographic evaluation is qualitative in nature and generally gives an indication of time required for evolution of damage from one stage to another. Non-destructive evaluation of steam side oxide scale thickness gives clear indication of average tube metal temperature, since the growth of oxide scale is a function of time and temperature.

Principle of oxide scale measurement

Ultrasonic technique using high frequency probes is employed for measurement of thickness of steam side oxide scale. The ultrasonic method used is based on transmitting a sound wave through the tube thickness. The thickness is calculated by measuring the time difference between the signals reflected from the metal / scale interface and the tube ID surface. The outer surface of the tube under inspection region is made free of fireside oxide deposits and polished to expose the base metal. The ultrasonic energy of high frequency (25 MHz) from a specially designed focused beam type transducer is transmitted through the sample tube. The display in the ultrasonic equipment is adjusted so as to view the region where the ultrasonic beam passes through metal – oxide interface and tube ID at the test region. The A – scan shows a small interface echo (tube metal / oxide layer) in front of a high back wall echo from ID side of the tube. The difference in time of flight of these echoes is proportional to the thickness of the layer.

3.1 Steam side oxide layer growth measurement

The temperature of the tubes operating in creep regions increased during its life time because the buildup of steam side oxide insulates the tube metal from the flow of cooling steam. As the tube metal temperature increases, rate of internal scale formation also increases. As the scale thickness increases continuously, therefore does the metal temperature and the cycle continues progressively, becoming higher and higher each year. Therefore, a method which takes into account the continuous increase in metal temperature as a result of oxide layer built up is necessary in order to estimate the remaining life of high temperature tubing’s operating in creep region. One of the earlier attempts to describe steam side oxide scale growth in low alloy ferritic steel (1 to 3% Cr) as a function of time and temperature is carried out by S. N. Ojha et.al [13]. Their results showed a linear variation of logarithmic oxide scale thickness and penetration depth (metal lost of oxidation) with Larson-Miller parameters as:

$\text{Log}_{10}\, x = 0.00022\, P - 7.4$ …………… (1)

Where, $P = T(20 + \log_{10} t)$

X = Thickness of oxide scale in mils. (1 mil = 25.4 microns)

T = Maximum temperature that metal has seen.

(^{0}F + 460)

t = Time to rupture.

Although this co-relation has been proposed for low alloy ferritic steel, data of the higher alloy of 9Cr-lMo steel also showed agreement to some extent to the above correlation.

3.1.1 Remaining Life of Tube of Platen Super-heater

By using equation (1) remaining service time can be measured for platen super-heater.

Tube material-T22
Elevation- Top Elevation LHS
Test location-Inside furnace
Total time expended in hrs-50000
Dimensions of tube in mm-51*7.0
Steam pressure in ksc-183

Table3.1 Table for Remaining Life of Tube of Platen Super-heater

Coil No. LHS to RHS	Tube No. Front to Rear	Tube Thickness (mm)	Oxide Thickness (µm)	Temp Rankine	Time to Rupture	Remaining Life of tube in		
						Hours	Years	Rounded off to years
1	6	8.05	150	1469	219703	169771	19.38	19
	7	7.80	150	1469	192549	142598	16.28	16
	8	7.50	150	1469	165842	115877	13.23	13
	9	7.70	150	1469	182965	133014	15.18	15
	10	7.80	150	1469	192549	142598	16.28	16
	11	7.80	150	1469	192549	142598	16.28	16
	12	8.05	150	1469	219703	169771	19.38	19
	13	8.05	150	1469	219703	169771	19.38	19
	14	7.65	150	1469	178436	128486	14.67	14
	15	7.65	150	1469	178436	128486	14.67	14
	16	7.55	150	1469	169900	119931	13.69	13
	17	8.10	150	1469	225677	175759	20.06	20
	18	7.85	150	1469	197611	147660	16.86	16
	19	7.80	150	1469	192549	142598	16.28	16
	20	8.00	150	1469	213906	163966	18.72	18
	21	7.80	150	1469	192549	142598	16.28	16
	22	7.70	150	1469	182965	133014	15.18	15
	23	7.35	150	1469	154619	104646	11.95	11
	24	7.60	150	1469	174119	124146	14.17	14
	25	8.05	150	1469	219703	169771	19.38	19
	26	7.65	150	1469	178436	128486	14.67	14
	27	7.85	150	1469	197611	147660	16.86	16
2	6	7.75	150	1469	187668	137716	15.72	15
	7	7.60	150	1469	174119	124146	14.17	14
	8	7.95	150	1469	208286	158342	18.08	18
	9	7.60	150	1469	174119	124146	14.17	14
	10	7.70	150	1469	182965	133014	15.18	15
	11	7.75	150	1469	187668	137716	15.72	15
2	12	8.00	150	1469	213906	163966	18.72	18
	13	7.80	150	1469	192549	142598	16.28	16
	14	7.95	150	1469	208286	158342	18.08	18
	15	7.50	150	1469	165842	115877	13.23	13
	16	7.30	150	1469	151131	101164	11.55	11
	17	7.65	150	1469	178436	128486	14.67	14
	18	7.55	150	1469	169900	119931	13.69	13
	19	7.90	150	1469	202855	152907	17.46	17
	20	7.80	150	1469	192549	142598	16.28	16

	21	7.60	150	1469	174119	124146	14.17	14
	22	7.70	150	1469	182965	133014	15.18	15
	23	7.55	150	1469	169900	119931	13.69	13
	24	7.65	150	1469	178436	128486	14.67	14
	25	7.50	150	1469	165842	115877	13.23	13
	26	7.40	150	1469	158252	108273	12.36	12
	27	7.65	150	1469	178436	128486	14.67	14
3	6	7.25	150	1469	147843	97862	11.17	11
	7	7.75	150	1469	187668	137716	15.72	15
	8	7.95	150	1469	208286	158342	18.08	18
	9	7.75	150	1469	187668	137716	15.72	15
	10	7.25	150	1469	147843	97862	11.17	11
	11	7.60	150	1469	174119	124146	14.17	14
	12	7.95	150	1469	208286	158342	18.08	18
	13	7.95	150	1469	208286	158342	18.08	18
	14	7.90	150	1469	202855	152907	17.46	17
	15	7.50	150	1469	165842	115877	13.23	13
	16	7.80	150	1469	192549	142598	16.28	16
	17	8.00	150	1469	213906	163966	18.72	18
	18	8.00	150	1469	213906	163966	18.72	18
	19	7.50	150	1469	165842	115877	13.23	13
	20	7.80	150	1469	192549	142598	16.28	16
	21	7.35	150	1469	154619	104646	11.95	11
	22	7.75	150	1469	187668	137716	15.72	15
	23	7.95	150	1469	208286	158342	18.08	18
	24	7.75	150	1469	187668	137716	15.72	15
	25	7.80	150	1469	192549	142598	16.28	16
	26	7.90	150	1469	202855	152907	17.46	17
	27	7.85	150	1469	197611	147660	16.86	16
4	6	7.75	150	1469	187668	137716	15.72	15
	7	8.05	150	1469	219703	169771	19.38	19
	8	7.60	150	1469	174119	124146	14.17	14
	9	7.80	150	1469	192549	142598	16.28	16

3.1.2 Remaining Life of Tube of Re-heater Inlet Coil inside Furnace

By using equation (1) remaining service time can be measured for Re-heater Inlet Coil inside Furnace.

Tube material-T22 **Elevation**-Bottom Elevation LHS
Test location-Inside furnace **Total time expended in hrs**-50000
Dimensions of tube in mm-54*4.5 **Steam pressure in ksc-52.5**

Table3.2 Table for Remaining Life of Tube of Re-heater Inlet Coil inside Furnace

Coil No. LHS to RHS	Tube No. Front to Rear	Tube Thickness (mm)	Oxide Thickness (μm)	Temp Rankine	Time to Rupture	Remaining Life of tube in		
						Hours	Years	Rounded off to years
16	20	5.00	150	1469	358229	308285	35.19	35
	21	5.10	150	1469	394191	344256	39.3	39
	22	5.00	150	1469	358229	308285	35.19	35
	23	5.25	150	1474	153088	103112	11.77	11

17	20	4.70	150	1469	266445	216479	24.71	24
	21	5.05	150	1469	375970	326056	37.22	37
	22	4.95	150	1469	340910	290992	33.22	33
	23	5.50	150	1474	158838	108864	12.43	12
18	20	5.00	150	1469	358229	308285	35.19	35
	21	5.00	150	1469	358229	308285	35.19	35
	22	5.10	150	1469	394191	344256	39.3	39
	23	5.30	150	1474	154294	104322	11.91	11
19	20	5.20	150	1469	430810	380898	43.48	43
	21	5.00	150	1469	358229	308285	35.19	35
	22	4.95	150	1469	340910	290992	33.22	33
	23	5.75	150	1474	163831	113858	13	12
20	20	5.00	150	1469	358229	308285	35.19	35
	21	5.30	150	1469	466585	416686	47.57	47
	22	4.85	150	1469	308604	258654	29.53	29
	23	5.50	150	1474	158838	108864	12.43	12
21	20	5.00	150	1469	358229	308285	35.19	35
	21	4.95	150	1469	340910	290992	33.22	33
	22	5.00	150	1469	358229	308285	35.19	35
	23	5.60	150	1474	160884	110922	12.66	12

3.1.3 Remaining Life of Tube of re-heater inlet coil inside furnace

By using equation (1) remaining service time can be measured for platen super-heater

Tube material-T22 **Elevation**- Top Elevation

Test location-Inside furnace **Total time expended in hrs**-50000

Dimensions of tube in mm-54*5.0 **Steam pressure in ksc** 52.5

Table3.3 Table for Remaining Life of Tube of Re-heater Inlet Coil inside Furnace

Coil No. LHS to RHS	Tube No. Front to Rear	Tube Thickness (mm)	Oxide Thickness (µm)	Temp Rankine	Time to Rupture	Remaining Life of tube in		
						Hours	Years	Rounded off to years
1	20	5.15	150	1469	412444	362554	41.39	41
	21	5.05	150	1469	375970	326056	37.22	37
	22	5.05	150	1469	375970	326056	37.22	37
	23	5.40	150	1474	159789	109821	12.54	12
2	20	5.20	150	1469	356013	306097	34.94	34
	21	5.10	150	1469	323390	273441	31.21	31
	22	4.90	150	1469	267515	217551	24.83	24
	23	5.50	150	1474	161800	111843	12.77	12
3	20	5.00	150	1469	358229	308285	35.19	35
	21	4.80	150	1469	293669	243717	27.82	27
	22	4.85	150	1469	308604	258654	29.53	29
	23	5.50	150	1474	161800	111843	12.77	12
4	20	4.85	150	1469	308604	258654	29.53	29
	21	5.20	150	1469	430810	380898	43.48	43
	22	5.05	150	1469	375970	326056	37.22	37
	23	5.55	150	1474	162769	112818	12.88	12

5	20	5.05	150	1469	375970	326056	37.22	37
	21	5.10	150	1469	394191	344256	39.3	39
	22	5.05	150	1469	375970	326056	37.22	37
	23	5.05	150	1474	151640	101680	11.61	11
6	20	5.25	150	1469	448823	398955	45.54	45
	21	5.25	150	1469	448823	398955	45.54	45
	22	5.20	150	1469	430810	380898	43.48	43
	23	5.70	150	1474	162836	112885	12.89	12

Other method for remaining life of tube is developed. S. N. Ojha et.al [13] has developed a co-relation between steam side oxide scale thickness and operating temperature of the form.

$$\log_{10}X = C_1T + C_2T + C_3T \log_{10}t \ldots (2)$$

Where 'X' is the scale thickness expressed in mils and 'T' is mean operating temperature in rankings and

$C_1 = -6.839869$

$C_2 = 0.003860$

$C_3 = 0.000283$

This co-relation also gives prediction similar to as expressed by S. N. Ojha et.al [13] over the normal temperature range of interest. Having known the equivalent temperature of operation of tubes with the help of above correlations of scale growth with Larson- Miller Parameter (LMP), the next step is to find out the representatives stress of tubes under the given operating conditions. Commonly used equations for calculating the representative tube stresses for this purpose are:

(i) Maximum elastic Hoop stress

(ii) Minimum diameter stress and

(iii) Tresca reference stress.

Among all these criteria maximum elastic Hoop stress criteria gives the most conservative value and hence is very widely used. This is represented by the following equation.

Maximum Elastic Hoop Stress

$$(s_h) = P\,(b^2 + a^2)/\,(b^2 - a^2) \ldots (3)$$

Where P = working pressure (N/mm^2)

b = outer radius (mm)

a = inner radius (mm)

Once equivalent temperature of operation of tube (T_S) is known, representative stress ($s_h s$) of tube is known , time to rupture (t) of the tube is determined either from the proposed relationship between LMP and the rupture stress of the tube or with the help of following type of equations :

$$P = T_S\,(20 + \log_{10} t_r)$$

$$= A(\log_{10} s_h s)^2 + B(\log_{10} s_h s) + C \ldots (4)$$

Where P is the Larson-Miller Parameter and A, B and C are constants. Hence knowing the value of tr (time to rupture) and t (service time in hours), expended life fraction of the tube at the equivalent temperature of operation (T_S) can easily be calculated and thus remaining life of tube is predicted.

The various oxide scale thickness-temperature correlations described above have all been developed from data on aging times representing a small fraction of service life, so their applicability to general long term service is yet unproven. The data used in deriving the various correlations are different and hence lead to large variations in estimated temperatures. Therefore, preference for a particular co-relation must at this time be considered subjective.

In spite of these limitations, the oxide scale thickness measurement has become a standard tool in life prediction of high temperature. For a boiler tube operating at high temperature an estimate of steam side oxide scale thickness with L-M parameter is first established. The equivalent temperature of operation of tube is thus estimated from the practical data of oxide layer thickness and the duration of service exposure. Knowing the value of equivalent temperature and the applied stress, the tr (time to rupture) is estimated based upon the proposed relationship between L-M parameter and the rupture stress for that steel. From the knowledge of expended life, the remaining life is thus predicted. Therefore, once L-M parameter relationships for steam side oxide scale growth kinetics and rupture stress for the particular steel are established, the method is the simplest approach for remnant life prediction. Alternatively, to increase the accuracy of prediction, current effective temperature of the tube is determined from the proposed relationship of oxide scale thickness and Larson- Miller parameter. The tube dimensions are used to calculate the effective current stress using maximum elastic hoop stress criteria or Tresca reference stress criteria. The temperature and stress values are then extrapolated back to the initial conditions assuming linear growth of oxide scale and fireside corrosion. The service life up to present time is divided into three months intervals. For each interval, the oxide scale thickness and reduced wall thickness are estimated using linear kinetics of scale growth and hot corrosion. The life fraction expended at each three months interval is computed from the temperature increase caused by steam side oxide scale, the hoop stress and the stress rupture curve at each calculated temperature. These life fractions are summed to evaluate the expended life up to present time and their subtraction from unity determines the remaining life fractions of the tubes [13]. When the total expended life fraction comes to a value of unity, the end of the life is deemed to have reached.

4. Conclusions

The analysis is based on measurement of remaining life of many tubes of a super heater where more failures usual were encountered that carried out, which have led to the following conclusions:

1. Thick oxide layers were found in both fireside and steam side of the boiler, therefore Residual life assessment will help in identification of critical components that require replacement or modification.
2. The measurements of steam side oxide scale thickness indicate elevated temperature exposure than design working conditions which is believed to be the cause of repeated failures in this super heater,
3. Micro structural degradation in a form of decarburization and spheroidization were noticed in some tubes which require more analysis to find the root cause of this degradation.
4. The use of the measures and methodology described in this paper may be applied in the field without difficulty, effectively aiding decision making during a shutdown for boiler inspection in industrial plants.
5. This approach will enable repair, up gradation, replacements of essential components and addition of life of remaining components

Therefore, it is suggested that boiler firing should be checked and adjusted to fit the initial design.

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