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Life Assessment of Super Heater and Reheater Tubes through Steam Side Oxide Scale Measurements-CPRI Experience

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High temperature pressure parts of boilers where in creep is the major damage mechanism, are required to be assessed periodically (after 100000 hrs) for remaining life. Creep life estimation could be made by destructive and non destructive techniques. This paper highlights the use of ultrasonic technique for assessment of creep life of SH/RH tubes by in-situ steam side oxide scale measurement. The scope for future studies are also given in the paper.

1.0 INTRODUCTION

The remaining life assessment of critical components of power plant through periodic condition monitoring programs is an important activity in the overall power generation programme. Super heater (SH) and reheater (RH) tubes operate at temperatures ranging from 400°C to over 600°C depending on the location and design. The SH/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[1,2]. The service life of SH/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 established as also the impact on the utilities revenue loss associated with forced outages.

Two predominant damage mechanisms which influences the service life of SH/RH tubes are

- The fire side corrosion due to molten alkalies present in hot flue gas and erosion due to flyash particles. The fire side corrosion causes wall thinning of tubes resulting in increased operating stress levels.
- Overheating of the tube material caused by insulation effect of steam side oxide scale. The poor thermal conductivity of oxide layer (approx. 40 times less than metal) affects the heat transfer and thereby increases the metal temperature.

SH/RH in modern utility boilers are manufactured from various materials ranging from carbon steel in the cooler section to stainless steel grades in the hottest outlet sections. The ASME Code defines the allowable stress levels for design purposes, the permissible stress levels in the final stage SH/RH sections are generally governed by the finite creep - rupture life. There are many computer codes developed by various agencies like EPRI, SI, B&W etc. and used under the trade name of TUBELIFE, NOTIS, TUBECALC or TUBEPRO[3]. These codes are designed to calculate remaining life taking into account the oxide scale thickness, metal loss due to fireside corrosion.

This paper deals with creep life estimation of SH/RH tubes of power plant boiler based on steam side oxide scale.

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2.0 LIFE ASSESSMENT METHODOLOGIES FOR BOILER TUBES

Number of methodologies are 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[4].

The methods generally adopted for assessing the remaining life of SH/RH tubes are

a) Laboratory evaluation of selected SH/RH tube sample 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 predetermined temperature.
b) In-situ evaluation of SH/RH tubes which involves - field metallography for microstructural 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 microstructural 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 evalution 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.

2.1 Creep Life Based on Oxide Scale

During normal service life, the SH & RH tubes experiences large variation in the stress & temperature conditions owing to the fire side corrosion/erosion and steam side oxide scale layers. In order to take into account of these fluctuations in the operating conditions during creep life estimation of these tubes, creep life fractions are used. The general procedure adopted during remaining life estimation involves dividing of past service life into no. of equal time intervals and estimation of the temperature and stress for each interval assuming an linear oxide scale growth rate. A creep life fraction is the ratio of time a tube spends at a specific stress & temperature (t) to the time it would take under these conditions to cause creep rupture failure (t_r). The creep damage accumulation over the service time is estimated by Robinson's life fraction rule given by

$$\sum \frac{t}{t_r} = 1.$$

That is the sum of life fractions associated with each set of conditions equal to 1 at rupture.

Evaluation of creep life of in service tube material requires the information with regard to its service temperature and the operating hoop stress. Number of algorithms based on steam side oxide scale growth kinetics are available for determination of average tube metal temperature and hence the remaining life estimation of SH/RH tubes. The general forms of oxide correlation used for Cr-Mo steels are given in Table 1. The creep data is generally expressed in the form of widely accepted parameter called "Larson - Miller Parameter (LMP)". LMP is a function relating temperature (T) and time (t) as defined by the following equation.

$$\text{LMP} = T(20 + \log t)$$

where T = Test Temperature in Rankin (Deg. F + 460)
and t = Rupture Time in hours of the material at temperature "T".

TABLE 1

OXIDE GROWTH KINETICS IN CR-MO STEELS

Expressions	Corresponding approximation	Researcher [Reported under reference 5]
$\text{Log}\, x = A + B*(\text{LMP})$	$X^3 = kt$	Rehn and Apblett
$\text{Log}\, x = A + B*(\text{LMP})$	$X^{2.1 \text{ to } 2.6} = kt$	Paterson and Rettings
$X^2 = kt$	$X^2 = kt$	Dewitte and Stubbe
$X = (At/B + Ct) + dt$	$X = kt$	Roberts
$X = k(t, A, P)^{1/3.0 \text{ to } 1/2.6}$	$X^{2.6 \text{ to } 3.0} = kt$	Paterson et al

The relationship between the thickness of oxide scale and the LMP for commonly used tube materials containing 1–3% Cr is given by the following equation[6]

$$\text{Log } X = 0.0002176 * \text{LMP} - 7.1438$$

where X = Oxide scale thickness in mils

The creep rupture properties of commonly used virgin tube materials have been made available in the form of standard ISO curves relating the stress and LMP.

With the knowledge of working hoop stress and metal temperature, it is possible to determine the time to creep rupture failure from the ISO data of specific tube material. The remaining life of the tube is the difference between total expected creep rupture life at a given set of conditions minus the actual time the tube has spent at those conditions.

The temperature of the tube metal is calculated for every 1000 hours interval from the beginning of service iteratively under non isothermal conditions. The life fraction expended at each 1000 hour interval is computed from the temperature increase caused by the steam side oxide, the hoop stress and the stress rupture curve at each calculated temperature. Life fractions are summed to determine total life expended and hence the remaining life of tubes.

2.2 Oxide Scale Formation in SH/RH Tubes

The operating temperature of SH/RH is generally 540 deg. C in utility boilers. The steam side oxide scale in RH/SH tubes is produced by oxidation mechanism through the reaction of steam with steel. The build up of scale occurs when the tubes have experienced high temperatures for extended periods of time. The formation of ID scale reduces heat transfer and results in further increase of tube metal temperature. This increased service temperature promotes further growth of oxide scale. The result is the ID scale feeds on itself and increases in thickness as it continues to grow.. The increase in ID scale and the associated tube metal temperatures promotes creep in the tube metal. Formation of creep results in a loss of strength at high temperature. The final outcome is a thick lipped, long term overheat failure.

The ID oxide scale is generally a concern for high temperature sections of RH/SH. The scale thickness in these sections may vary because of the range of temperatures. Maximum thickness of scale is expected on tubes that are in the hottest sections of the boiler. The observations made on different samples of oxide scale using Scanning Electron Microscope (SEM) shows two distinct layers as shown in Fig. 1. Thick coherent oxide layer is observed adjacent to the metal ID surface followed by less coherent layer showing brittle fracture appearance. The layers were generally observed to be arranged with the most metal - rich oxide next to the metal, progressively less metal in succeeding layers and finally the most oxygen-rich layer on the outside. Within each layer, a concentration gradient exists with higher metal ion concentration closest to the metal wall.

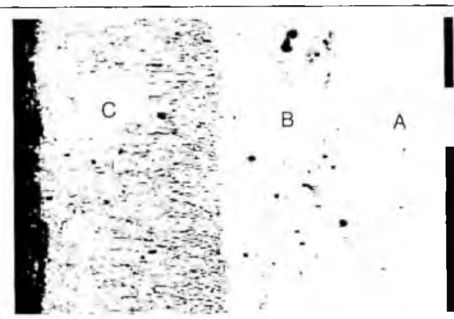

FIG. 1. SCALE MORPHOLOGY IN AS OBSERVED UNDER SEM A - TUBE METAL B-METAL - RICH COHERENT INNER OXIDE LAYER C - POROUS OUTER LAYER

3.0 PRINCIPLE OF OXIDE SCALE MEASUREMENT

Ultrasonic techniques 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 oxide thickness is calculated by measuring the time difference between the signals reflected from the steel/scale interface and the tube ID surface. The outer surface of the tube under inspection region is made free of fire side oxide deposits and polished to expose the base metal.

Figure 2 shows the arrangement of Pulser-Receiver Transducer coupled on the surface of sample boiler tube. 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 marked as "D". The typical A - scan output recorded during the measurement is shown in Fig. 3. The A-Scan shows a small interface echo (tube material/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.

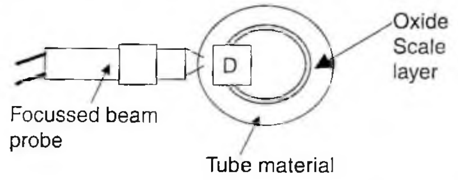

FIG. 2. SCHEMATIC ARRANGEMENT OF OXIDE SCALE MEASUREMENT SET-UP

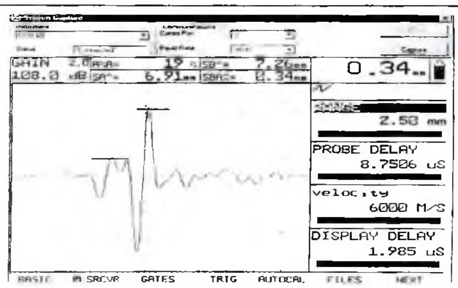

FIG. 3. TYPICAL A - SCAN FOR MEASURED VALUE OF 340 MICRON SCALE INDICATION

4.0 RESULTS & DISCUSSION

CPRI has conducted in-situ oxide scale measurement in SH & RH tubes of boilers of 62.5 to 500 MW power plant. The measurement was carried out inside the furnace on final stage SH/RH outlet coils where the temperature is maximum. The specific test locations were decided based on the past failure history of tubes and in consultation with operating engineers. The range of oxide scale observed in general is 200–250 microns for a completed service life of about 100000 hours. The average metal temperature was calculated using LMP assuming linear oxide growth rate. The thickness of tube metal is also measured by ultrasonic technique at the oxide measurement location and OD value as given in drawing are used to determine the hoop stress level to which tube is subjected to during normal operation.

The variation in the oxide thickness and corresponding average metal temperature observed in various tubes in a 3rd stage RH outlet coil of a typical 500 MW boiler is shown in Fig. 4. Also, the measurements were carried out in panels extensively where increased rate of failures were observed. The measurements indicated that the range of oxide scale in these regions (RHS side panels) were high compared to other side panels. Thus the measurement of oxide scale in various tubes of SH/RH gives an indication of temperature profile across the furnace and the results are given in Fig. 5. Based on these observations, it is possible to attribute the problem of overheating precisely viz. shift in the fire ball linked to burner tilt or increased flue gas velocity etc.

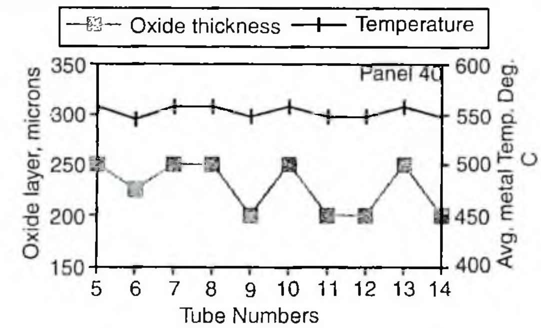

FIG. 4. VARIATION OF OXIDE THICKNESS & TUBEMETAL TEMP. IN RH PANEL AFTER 100000 HRS OF OPERATION

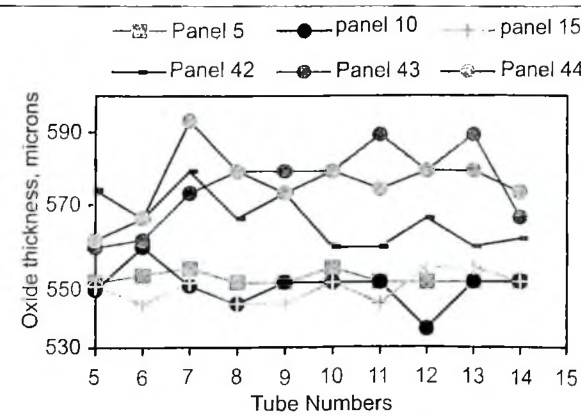

FIG. 5. VARIATION OF TUBE METAL TEMP. IN DIFFERENT RH PANELS AFTER 100000 HRS

The remaining life estimated for final stage super heater outlet coil tubes in a typical 210 MW boiler are given in Table 2. The life calculations were made using a custom built software taking into account the avg. tube metal temperature as determined by steam side oxide scale measurement. The wall thinning due to fire side corrosion has not been considered.

TABLE 2

TYPICAL RESULTS OF REMAINING LIFE OF T22 TUBES OF SH PANEL OF 210 MW PLANT CALCULATED BASED ON STEAM SIDE OXIDE SCALE

Oxide Thick-ness (μ)	Avg. tube metal temp. (°C)	Time to rupture Hrs	Remaining Life	
			Hours	Years
200	535	542000	392000	44
250	546	423400	273000	31
300	554	345000	195000	22
350	560	290000	140000	15
400	566	250000	100000	11
450	572	219000	69000	7
500	576	195000	45000	5

5.0 SCOPE FOR FUTURE STUDY

- Comprehensive evaluation of SH/RH tube life by combining the oxide scale method and metallographic studies
- Sensitivity of measurement techniques and adaptability of results
- Oxidation mechanisms and their implication on the expert system formulation for critical components of power plant taking into account the O& M aspects in the Indian Context.

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