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RECENT TECHNIQUES FOR LIFE ASSESSMENT OF BOILER COMPONENTS

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ABSTRACT

Boiler components like headers, pipes and tubes operating at high temperatures-high pressures have only limited life due to the accumulation of creep damage during the normal/abnormal operating periods of the boiler. The rate of damage accumulation is to be assessed in these components in such a way that they do not lead to catastrophic consequences in the boiler, causing thereby loss of power generation and concomitant lower availability of steam generators. Although the methodology adopted for the assessment of residual creep life of high temperature headers is well defined, large number of techniques are employed to evaluate the damage rate, both on the base material and on the weldment. In addition to normal routine non-destructive methods, like ultrasonic testing, surface replication etc., a few advanced techniques like on-line strain monitoring by photogrammetry, post-exposure accelerated creep-rupture test on miniature specimen, extricated from headers and shot punch tests are adopted. In the case of pipes, both destructive and non-destructive tests are carried out. Advanced techniques like Hardness Differential Method (HDM) and Replica Strain Monitoring (RSM) are developed to evaluate especially mid-life weldment cracking. The other advanced techniques are UT noise analysis, Magnetic Barkhausen Emission (BME) for damage assessment and Fibre-Optic-Remote-Monitoring-of-Structures (FORMS) for effective and cost-benefit analysis of critical piping systems. A host of techniques are available for estimating the remnant life of boiler tubes. A few off-line methods *viz.* Laser Shearography for detecting tube defects like erosion and corrosion, and ultrasonic measurement of internal steam side oxide scale thickness for creep damage assessment are practised. A new on-line monitoring technique, called Thin Layer Activation (TLA) is employed for measuring the rate and extent of tube metal erosion/corrosion. In this lecture, the above mentioned life assessment methods and prediction procedures will be dealt extensively.

INTRODUCTION

The integrity of pressure vessels operating at high temperatures and high energy piping system has become a growing concern for electric utilities, as the existing equipment/vessels are ageing due to normal/abnormal operating conditions. A greater awareness has been infused all over the world, and in India, this is especially catching the attention of techno-economic personnel. A dire need has, thus, emerged as to how to assess the condition of the components and to extend their life, if required. Although the cost of setting-up new power plants has escalated beyond economic limits, the extension of life of power plant would, definitely off-set the cost, if not fully, at least partially. Another pertinent aspect in the life extension of power plant component is the avoidance/prevention of catastrophic consequences in certain seam welded components. In order to realise this aspect, the rate of damage accumulation is to be assessed accurately and the integrity of the component is evaluated precisely. In this paper a few recent techniques, which are in the process of development in India and in the world, are elaborated, in addition to a few techniques adopted for headers, pipes and tubes within BHEL.

METHODOLOGY

Degradation of materials in high temperature power plants can result from various forms of mechanical loading and environmental attack, in spite of the component, designed as per codes. Current remaining life methodologies normally involve two distinct approaches:

I. Those involving the acquisition and monitoring of operating parameters, the use of standard materials data and the life fraction rule.

II. Methods based-on post-service examination and testing, which require direct access to the component for sampling and measurement.

In addition to the above, there are a few on-line monitoring methods to currently assess the condition of the components. These methods may form a part of approach I, which involves processing of data from available historical temperature and pressure monitoring records. Processed information is combined with standard creep-rupture data and inverse design stress calculations, which in association with simple damage summation rules, produce a preliminary estimate of remnant life. This step is synonymous with Level I approach according to EPRI guidelines. Although a certain amount of pessimism is built-in in this approach, it serves to identify components or areas of components that require either on-line monitoring or operational monitoring.

Methods in approach II are both destructive and non-destructive, and the choice any combination will depend upon component type, the location of critical areas and economic factors. The major methods of assessment of remnant life in II approach are categorised as follows:

a. Creep and rupture testing

b. Microstructural degradation and cavitation damage

c. Component strain measurement on-line or off-line monitoring

These methods position the component material within the standard scatter band by assessing their properties. Alternatively, they involve assessment of extent of damage experienced by the component as a consequence of the actual service.

CREEP DAMAGE MECHANISM

Before describing the advanced techniques employed for assessing the condition/residual life of the components which are undergoing creep damage due to high temperature and high pressures, it is worth while to dwell upon creep damage processes in the material. To determine remaining service life by component examination or measurement, models for damage evaluation and failure are required for relating the damage feature or property to the life fraction consumed. In general the processes leading to elevated temperature failure under service conditions can be broadly classified as:

i. creep strain accumulation with no significant decrease in creep strength compared to the virgin material
ii. structural degradation causing a continuous reduction in creep strength
iii. creep cavitation
iv. environmental attack

Process (i) is applicable to cavitation-resistant, microstructurally stable materials. Here the onset of failure is governed only by the increase in net section stress, as the specimen extends with an accompanying increase in strain-rate. Processes (ii) and (iii) are creep damage phenomena that will enhance the strain rate leading to tertiary creep and failure. Process (iv) occurs due to external scaling, grain-boundary penetration or internal oxidation. In many circumstances, some of these processes occur simultaneously. For materials that cavitate readily and produce closely spaced cavities in the material during operation, creep-cavitation is the significant damage feature leading to low-ductility failure. On the other hand, when the material is more cavitation resistant, the cavities are fewer in number and loss in external section or metallurgical degradation contributes more significantly.

Microstructural degradation

The majority of alloy steels used in boilers depend on finely dispersed precipitates to provide resistance to deformation. The creep rate is primarily dependent on the inter-particle spacing and the associated mechanism by which dislocations overcome the particles. It is also known that thermally induced coarsening of these particles or gradual replacement with more stable particles at operating temperatures can bring about tertiary creep leading to failure.

Cavitation damage

Creep cavities nucleate and grow predominantly on grain boundaries oriented normal to the maximum principal stress. The density of cavities in ferritic steels used in boilers is dependent on the grain- boundary chemistry, strain and stress. Numerous controlling mechanisms are propounded for creep cavitation, namely vacancy flow, continuum or power-law growth and constrained cavity growth.

Effect of environment

Creep in aggressive environments including air normally leads to changes in rupture life and ductility. The low alloy steels, used in boilers, form oxides which spall during exposure, reducing the load-bearing cross-section and accelerating creep. At service temperatures the oxide is strongly adherent and is likely to bear some of the load because it generally creeps more slowly than the metal. In this case, the rate of attack is controlled no longer by inward diffusion of oxygen, but by the frequency of surface cracking. The extent of oxidation is dependent on strain rate as well as time.

RECENT TECHNIQUES

On-line strain monitoring method

This is a new technique being developed in the European and American utilities. For geometrically symmetrical thick walled components, an assessment of strain and strain rate by physical measurements is the obvious route to remnant life prediction[1]. Bow-gauge micrometer has been extensively used, during the shut down time, to measure the creep-strain, and remaining life prediction is made based on strain-time model. But there are two other on-line strain monitoring methods developed abroad.

a. capacitance strain-gauge

b. photogrammetry

Capacitance strain-gauge

The capacitance strain gauges are of planer design, consisting of two arches of similar plan but different heights, each carrying an insulated capacitance plate as shown in Fig. 1. When the gauge is extended or compressed, the arches rise or fall by different amounts, thus causing a change in capacitance. The materials of the capacitance gauge are so chosen that they would operate for many thousands of hours at temperatures up to 650°C. The gauge is 4mm wide with overall length of 24mm and a nominal gauge length of 20mm. It is necessary to calibrate gauges individually. The gauges are to be matched with thermal expansion coefficients of ferritic or austenitic steels. The capacitance strain gauges have been used extensively on headers, pipes and their weldments in European utilities for monitoring hoop and axial strain changes with time. But there is one limitation in the application of these gauges, in that the typical service strain rates (10^{-8}/h) is almost equal to drift rate of such gauges. If large strain rates are envisaged, this is quite useful. Use of high temperature strain gauges in Indian utilities has not picked-up.

Photogrammetry

The photogrammetry is a three dimensional photographic technique of lattice marks made on a header body area of 200x200mm, with an accuracy of 0.001mm. These lattice marks are photographed in the subsequent shut downs and dis-positioning of the marks due to creep strain is measured.

The following table shows the reproducibility/accuracy of the strain measurement methods.

Method	*Accuracy (mm)*	*Repeatability (mm)*
Bow gauge	± 0.01	± 0.7
Bow gauge with creep pits	± 0.01	± 0.07
Photogrammetry	± 0.001	± 0.005

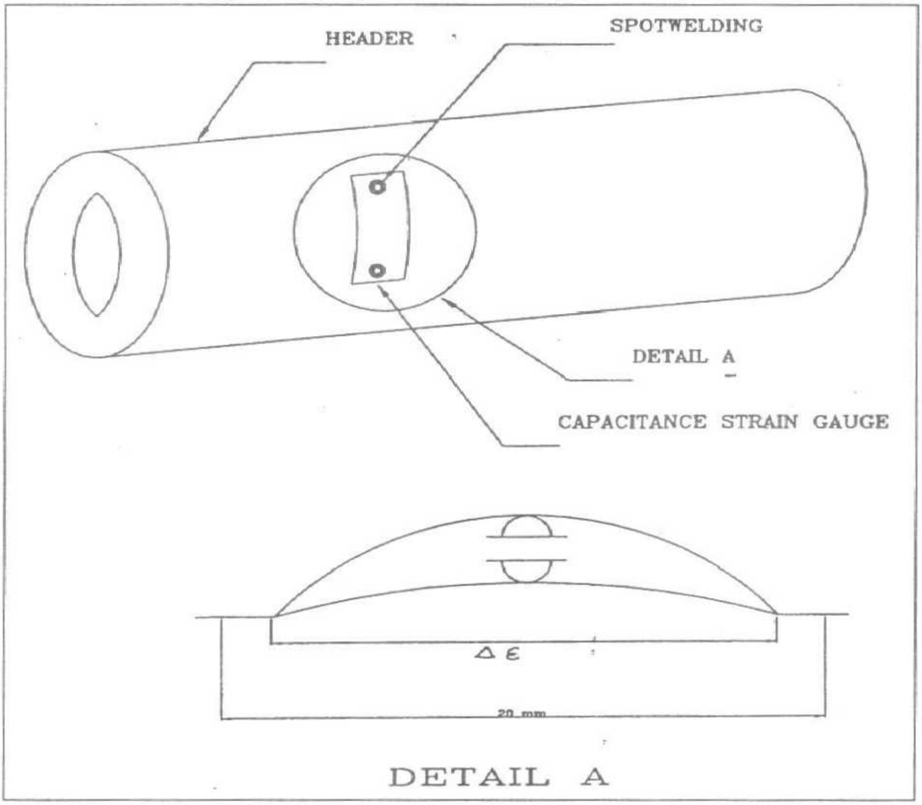

Fig. 1: A planer capacitance strain gauge

The first two methods are adopted in Indian utilities to measure strain/ strain rate and subsequent life assessment of headers and pipes, whereas the third method has not caught the attention, due to prohibitive cost.

Post exposure test method

Post exposure creep-rupture accelerated testing of material removed from the component is one of the most valuable tools for estimation of remaining life [2]. In the case of boiler tubes, sample tubes of superheater/reheater coils are removed and are subjected to biaxial iso-stress rupture conditions. The residual life is obtained by extrapolation to operating temperature. But in the case of thick-walled components, like headers and pipes, boat like samples of size of 10x50mm are excavated and weld-repair is carried out in the excavated area.

Miniature specimens of 2mm dia and 10mm gauge length are finish-machined from the boat sample. These specimens are electron-beam welded to a set extension pieces for gripping and are subjected to uni-axial creep-rupture test under iso-stress conditions in an inert atmosphere. In both the cases, life fraction rule can be adopted. For a particular condition, the life fraction is expressed as follows:

$$\frac{t_s}{T_s} + \frac{t_t}{T_t} = 1 \qquad \ldots(1)$$

where t_s = time in service, T_s = total rupture time under service condition, t_t = time to rupture of the service specimen under accelerated test, T_t = time to rupture of virgin material under the above accelerated condition

T_s is evaluated and T_s - t_s gives the residual life. But there is one shortcoming of this method, in that the availability of virgin material is a problem. This can be over come by removing samples after 10,000 hours of subsequent operation and by conducting accelerated tests under identical conditions.

Shot punch test

This is also called Small Punch (SP) test. Low alloy ferritic steels of Cr-Mo type, which are used in high temperature and high pressure services, undergo two embrittlement mechanisms, potentially causing a degradation of material toughness during service [3]. One is known as temper embrittlement, which is attributed to impurity elements like phosphorous and sulphur segregating to the grain boundary. The other mechanism is carbide-induced embrittlement, which is attributed to the precipitation of coarse alloy carbides such as M_7C_3, $M_{23}C_6$ in Cr-Mo steels. Both forms of embrittlement are manifested by a decrease in material fracture toughness, K_{Ic} and an increase in the Charpy ductile-to-brittle transition temperature or fracture appearance transition temperature (FATT). The small punch test for estimating FATT is carried out on test set-up shown in Fig. 2 and the specimen sizes are 0.5mm thick and 6.35mm diameter. By conducting tests at different temperatures, a curve of absorbed energy versus temperature can be developed, that is very similar to that of a Charpy-energy *vs.* temperature curve, with the difference that small punch test curve is shifted

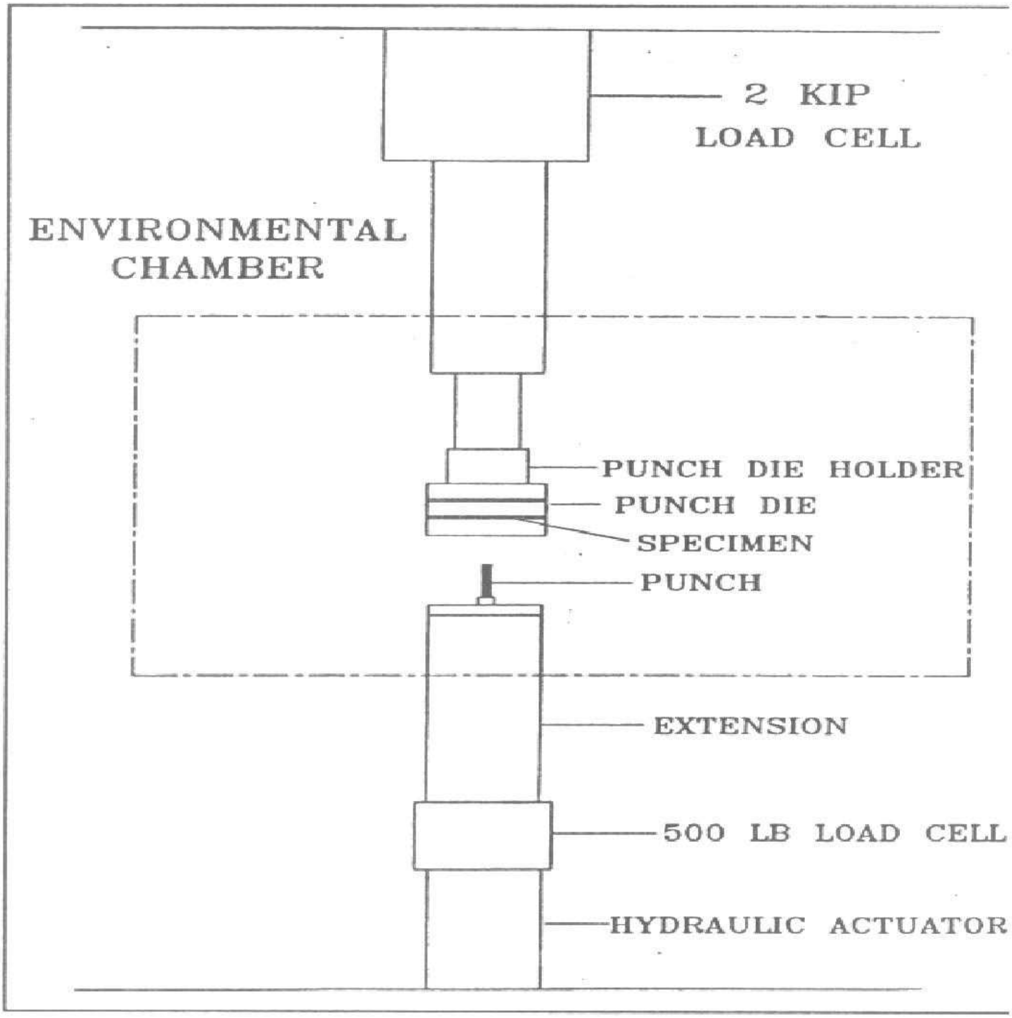

Fig. 2: Small punch test setup.

laterally to lower temperature along the temperature axis compared to Charpy curve. The small punch transition temperature, T_{sp}, representing the temperature at which the energy is the mean of the upper and lower shelf, was estimated by the intersection of smooth curve fit as shown in Fig. 3. Specimens of SP test can be easily removed from critical locations of thick-section components (like headers & rotors), where severe thermal stresses are occuring during start-up/shut-down transients causing failures by rapid brittle fracture. The crucial last step in remaining life analysis of either header-nipple crack or ligament cracking of stubs on the inside surface of header, is the determination of critical crack size, based on a knowledge of the current toughness of header at that critical location. The T_{sp} and FATT are well correlated. From well-established correlation of FATT and K_{Ic}, the critical crack-size for failure can be evaluated.

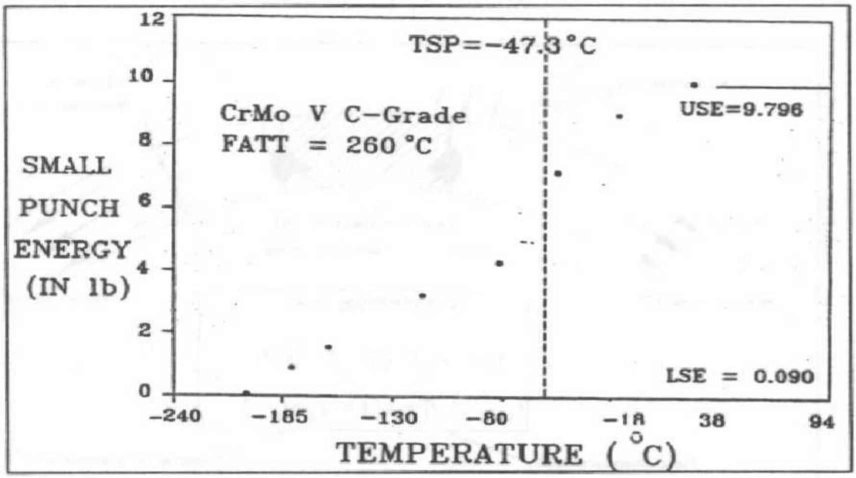

Fig. 3: Transition temperature, T_{sp}

Although BHEL has developed methods for removal of samples from thick-walled components for carrying out post-exposure accelerated creep rupture test, the Small Punch test method has not been established.

Hardness difference method (HDM)

The performance of high temperature ferritic steel pipe work is frequently dictated by creep damage accumulation in the weldments. The cracking that occurs, particularly, in circumferential welds of pipes is called type IV cracking or mid-life weldment cracking [4]. The cracks initiate in the weak intercritically transformed microstructure at the HAZ/base metal interface. During welding, the effect of inter critical heat treatment is such that the carbide dissolution in the tempered base metal is incomplete with alloying elements remaining in the spheroidised carbides which in turn render the material less hardenable.

Mid-life cracking is often due to high system stresses acting across the weldment from poor design or operation of the plant such that pipe-work systems are inadequately supported. Although stress analysis considerations take care of this, the cracking occurs in the pipe- work weldment, while operating in the creep range, where load redistribution is not uniform due to thermal expansion, hanger lateral stiffness, residual weld strains, internal pressure and incorrect support of the dead weight. In the low-alloy ferritic steels, hardness provides a quantitative measure of thermal softening and strain softening.

In the newly developed method at EPRI, the hardness is measured at different locations of the weld zone. A typical hardness differential method is shown in Fig. 4. Here a relation is found between the ratio of maximum hardness difference, *Hp*, at the cusp and the degree of creep damage in this region, indicated by the cavity density. A quantitative assessment of remnant life using pipe thickness and hardness measurements can be made as shown in the Fig. 4.

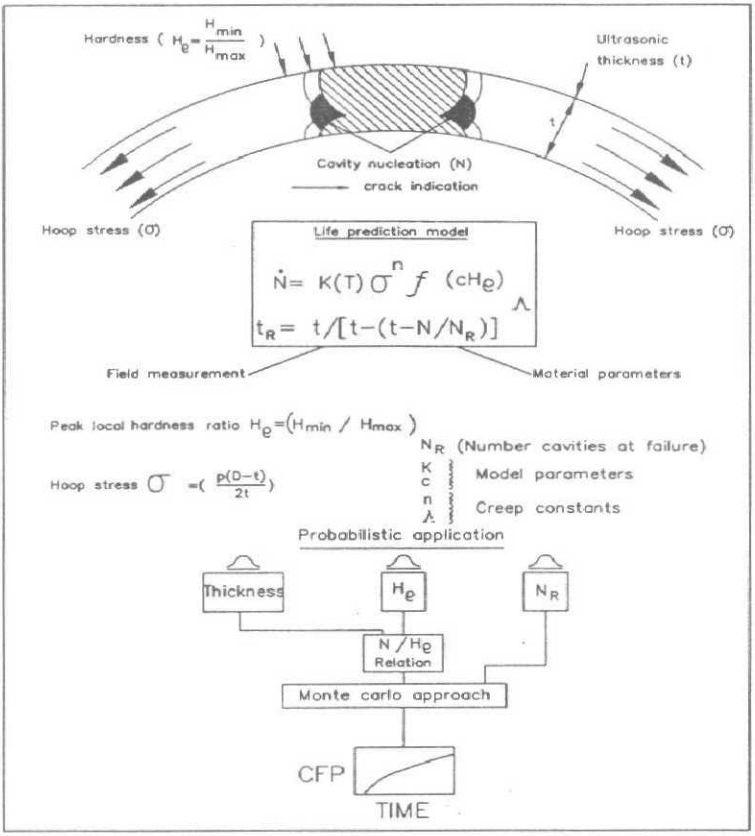

Fig. 4: Hardness difference method..

Replication strain monitoring (RSM)

As a corollary to the above HDM, RSM has been developed in other countries [5]. The cavitation damage is assessed by replication method. The damages are classified as shown in Fig. 5.

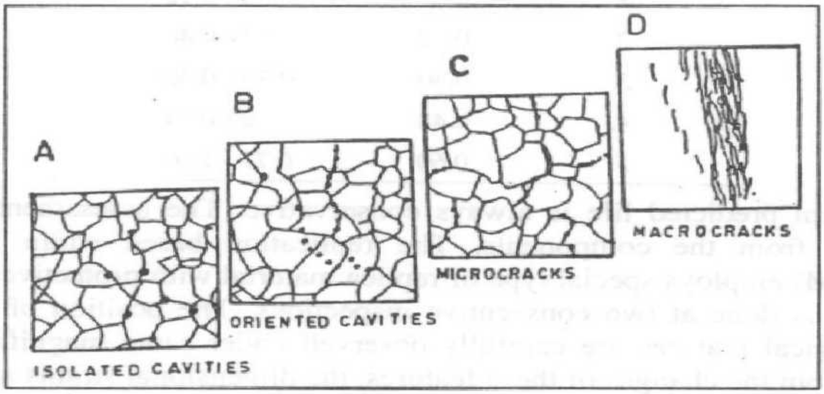

Fig. 5: Classification of creep damage.

From the figure the damage rate and minimum life are given as follows:

Damaged rating	*Damage level*	*Minimum life*
Undamaged	1	$t_{rem} = 7.33\ t_{exp}$
Isolated cavities	2	$t_{rem} = 1.17\ t_{exp}$
Oriented cavities	3	$t_{rem} = t_{exp}$
Microcracked	4	$t_{rem} = 0.19\ t_{exp}$
Macrocracked	5	$t_{rem} = 0$

Alternatively, 'A' parameter technique is employed. 'A' parameter is defined as number fraction of cavitated grain boundaries encountered in linear traverses parallel to the axis of maximum principal stress and it is measured using optical microscopy. If number of damaged boundaries is n_D and undamaged boundaries n_U , then number fraction of cavitating boundaries 'A' is defined by

$$A = \frac{n_D}{n_D + n_U} \qquad ...(2)$$

If the current service exposure and remaining service life are t_{exp} and t_{rem}, then

$$t_{rem} = t_{exp}\frac{0.517}{A + 0.186} - 1 \qquad ...(3)$$

For a typical low-allow steel, correlation of damage level and life fraction consumed is given as below:

Damage level	*Max.* **A**	*Consumed life fraction range*
1.	0	0.00 - 0.12
2.	0.12	0.04 - 0.46
3.	0.30	0.30 - 0.50
4.	0.48	0.30 - 0.84
5.	0.60	0.72 - 1.00

The minimum predicted life is always conservative. The assessment is made on replicas taken from the components. The replication based strain measurement technique (RSM) employs special type of replica material with protective coatings and the replication is done at two consecutive inspections. The position of carbides and other metallurgical features are carefully observed under same magnification in the microscope. From the changes of these features, the dimensional strains are calculated. Although this method seems to be simple, the actual calibration and standardisation techniques are highly cumbersome. This method is under development, in India and abroad.

Magnetic Barkhausen Emission (MBE) method

The changes in microstructures of ferritic steels undergoing creep during operation at high temperatures can be evaluated by a new method called Magnetic Barkhausen Emission (MBE) [6]. The ferromagnetic materials consist of magnetic domains, separated from each other by domain walls. When a smoothly varying magnetic field is applied to the material, the net magnetisation of the bulk material is the average of the magnetisation within all domains. If the domain wall is made to move the magnetising field, the magnetisation within the area, swept by the wall, will change to other direction. This sudden and abrupt change generates an electrical voltage pulse, which is picked-up by a coil wrapped around the sample. Discontinuous movements of the domain wall under the influence of an external magnetic field are primarily responsible for MBE. The dynamics of domain wall movement—the Barkhausen emissions—are sensitive to microstructural features such as grain size, dislocations and texture.

Magnetic Barkhausen measurements were performed on typical piping steel, which had undergone an extended period of service. The samples of the pipe were magnetised at a magnetising frequency of 8Hz. The pick-up voltage was measured in the form of Barkhausen emission signals. The variation of number of MBE per cycle with applied magnetising field is shown in Fig. 6. These MB emissions are correlated to the creep damage of the material and to the type of stresses (compressive or tensile). These were corroborated by scanning electron microscopy and x-ray diffractometry.

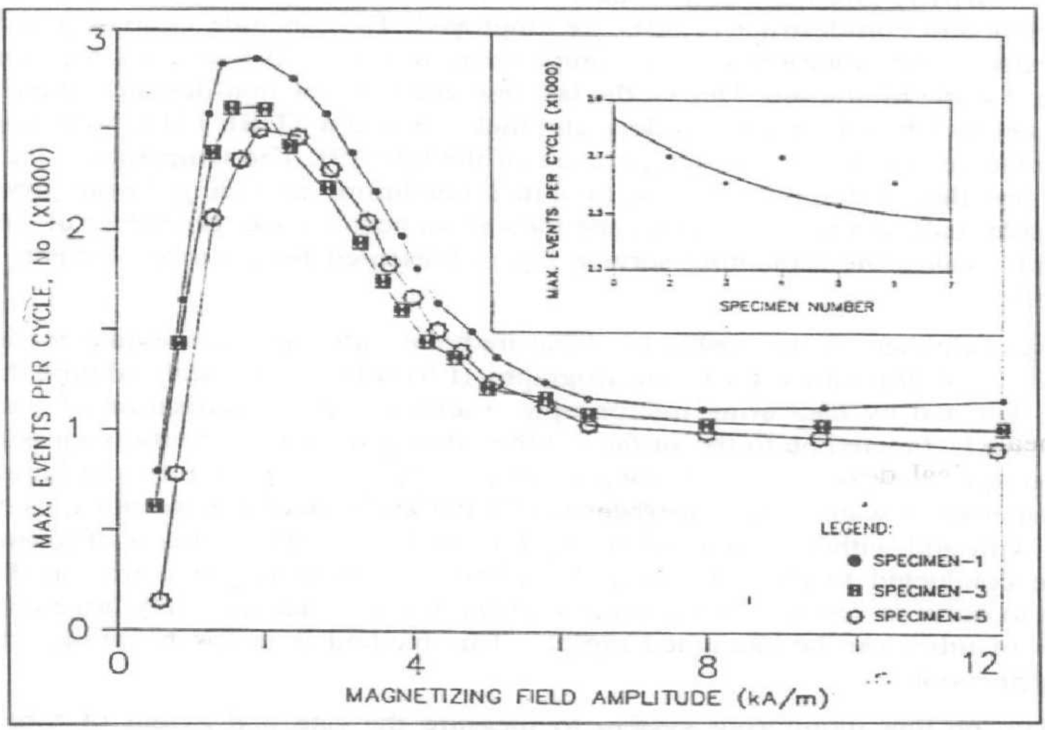

Fig. 6: MBE vs. magnetising field.

One of the major problems of using MBE method is sensitiveness of magnetic parameters with factors like stress, microstructure etc., which can change simultaneously, while the material is in service. Extensive research is done in India and abroad for implementing this technique.

Fibre Optic-Remote - Monitoring of Structures (FORMS)

This is a real time or periodic monitoring of strain in critical piping system Flexible fibre-optic borescopes permit manipulation of the instrument around corners through passages with several directional changes [7]. Woven stainless steel sheathing protects the image relay bundle during repeated flexing and manoeuvring. They are designed to provide sharp and clear images of components and interior surfaces to visually monitor the defects/ cracks. With the remote end-tip deflection, it is possible to have access to bends over a 100° field of view and tip deflection of ±90°. The physical changes inside the piping system can be monitored and recorded. In the subsequent inspection, the rate of deformation is calculated based on final observation.

This technique is being further developed in ERA England.

Tube life assessment

There are a number of well - established methods for assessing remaining creep life of super heater (SH) and reheater (RH) tubes. As it is well known that creep rupture failure of SH/RH tubes is a major cause of the forced outages of utility boilers, a few destructive and non-destructive tests are employed. They include uniaxial and biaxial accelerated creep rupture testing on samples removed from the strategic locations [8]. There are some limitations. During the last few years, a new non-destructive technique was developed based on steam side scale thickness and a TUBE LIFE code was used to calculate 'equivalent' metal temperature of the tube [9]. The temperature and stress values are then extrapolated back to initial conditions assuming linear growth of steam-side scale and fire-side stage, and the known heat-transfer properties of steel and the oxide scale. The remaining service life is presented for all tube elements in the assembly.

There is another off-line method to measure boiler tube degradation like erosion and corrosion [10]. It is called Laser Shearography (LS) with which localised tube thinning can be detected by measuring microscopic strains during pressurisation of a tube. A laser beam is directed on to the surface of the tubes and the reflectivity is measured by electron-optical device. The laboratory mock-up tests on boiler tube configurations, representative of water-wall, superheater, reheater and economiser sections, using new tubing with and without machined internal as well as external defects of known size will be conducted to characterise and calibrate the erosion and corrosion damage, known to occur in service. The main advantage of LS is that relatively large areas and lengths of tubes can be examined rapidly. This method is in the beginning stage of field application.

A new on-line monitoring system to measure the rate and extent of tube metal wastage has been developed, in England [11]. To take into account of changes of coal type and combustion parameters that can dramatically alter erosion rates, and to accurately predict the life of tubes during long-term degradation by erosion/corrosion, the metal wastage must be continuously monitored. This technique is known as Thin Activation Layer (TLA) [12]. With this technique, the surface of the component or an implanted or attached sample is activated using a particle accelerator. The accelerator beam-species and energy can be altered to generate a number of radio-nuclides, which have suitable half-life and gamma ray energy characteristics for monitoring. The radiation damage and alteration in composition caused by the beam have negligible effect on mechanical properties. The number of gamma rays emitted by the component is reduced as metal wastage occurs by erosion/corrosion. The wastage can be accordingly quantified. The method does not either pose any health hazard, in terms of penetration through boiler wall, or result in contamination of ash. It is easily shielded during maintenance.

The principal advantages of TLA are:

i. it is highly sensitive with a resolution of 0.5 micron

ii. wastage can be monitored over many years.

iii. Installation in-situ, with minimum disturbance to plant and without the need to remove tubes for activating them.

BHEL'S EXPERIENCE

Over the period of ten years BHEL has carried out RLA on a large number of boilers of different-make and different capacities using a few of the afore mentioned techniques.

CONCLUSION

1. stage in India as well as abroad and are in the process of field application.
2. There is a good potential to exploit these techniques for accurate life assessment of high temperature-high pressure components.

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