

# Mechanical Property Evaluation and Remaining Life Assessment of Service Exposed Steam Pipe of Boilers in a Thermal Power Plant

A.K. Ray, Y.N. Tiwari, R.K. Sinha, S.K. Sinha, P.K. Roy, R. Singh  
and S. Chaudhuri

*Materials Evaluation Division, National Metallurgical Laboratory  
Jamshedpur-831107, India*

## ABSTRACT

This paper is aimed at investigating the residual life of more than eleven years service exposed main steam pipes of various boilers in a thermal power plant. The remaining life assessment for safety was made using destructive accelerated stress rupture and tensile tests at different temperatures, and some non-destructive tests. There was no evidence of localised damage in the form of surface cracks, cavitation or dents in the service exposed main steam pipes of all the boilers. So far as the remaining life at 550°C is concerned, it is possible to obtain a life of greater than 100,000 hours, both at the allowable as well as operating hoop stress levels of the service exposed pipes, provided no localised damage in the form of cracks or dents has been developed. It is recommended that a health check should be carried out after 50,000 hours of service exposure at 550°C.

**Key Words:** Service exposed, steam pipe, boilers, stress rupture test, tensile properties, residual life.

## 1. INTRODUCTION

It is widely known that carbon and Cr-Mo steels are extensively used as high temperature components in power plants /1-7/. Even though most of these components have a specific design life of 20 years, many of these are known to have survived much longer. In view of the increasing cost of setting up a new plant, there is now considerable interest in life extension of the existing units. In order to arrive at a quantitative estimate of the remaining life of such ageing components, it is necessary to have some creep and stress rupture data.

The latest studies on the design methodology and life estimation for major components for steam turbines were reviewed /3/. Relationships which enable the calculation of actual creep damage were

clarified by many studies. Several revolutionary devices have been introduced which enable the detection of local creep and fatigue damage. Studies of life estimation of welded joints in the design stages were discussed. It was shown that the remaining life of such components can be analysed from creep and stress rupture properties by defining a reference stress such that the component life equals the life of a simple specimen tested at the reference stress. Keeping this in view, over the years attempts are being made to generate such data on similar components /4-7/.

The aim of the present work is therefore to evaluate the remaining life of more than eleven years service exposed main steam pipes of boilers, based on experimentally determined tensile and stress rupture properties of service exposed materials.

## 2. MATERIAL AND HISTORY OF THE SERVICE EXPOSED MAIN STEAM PIPES OF THE BOILERS

The material specifications, listing service conditions and history of operation of the service exposed main steam pipe of all the boilers under the same operating conditions but with different service exposures, are given in Tables 1A and 1b respectively.

**Table 1a**

Material Specifications and Service Conditions of the Service Exposed Main Steam Pipes

<i>Material</i>	1 Cr-0.5 Mo-0.25 V – Russian Graded Steel (12 × 1M4)
<i>Design Stress:</i>	45.8 MPa
<i>Operating temperature:</i>	550°C
<i>Allowable stress:</i>	65 MPa
<b>Service Conditions:</b>	
<i>Steam pressure in the main steam pipes:</i>	90 ± atm
<i>Steam temperature:</i>	535 ± 13°C
<i>Boiler capacity:</i>	240 tonnes of steam/hour

**Table 1b**

History of Operation

<i>Sl. No.</i>	<i>Type of Main Steam Pipe</i>	<i>Service Exposure (hrs)</i>
1	Boiler E	167000
2	Boiler D	166000
3	Boiler F	106000
4	Boiler G	105000
5	Boiler H	100000
6	Boiler I	112000

## 2.1. Dimension and visual examination of the pipe

The outer diameter and length of the pipes were 273 mm and 450 mm respectively. The average wall thickness of the main steam pipes varied between 20 – 23 mm. There was also no evidence of localised and general corrosion/oxidation on either external or internal surfaces of the pipes. Dimensions of the outer diameter (OD) were measured at two mutually perpendicular directions along the length of the pipe at an interval of 150 mm.

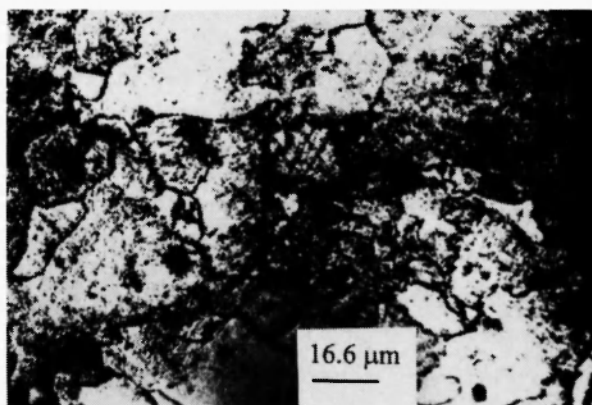
## 3. EXPERIMENTAL

Chemical analysis as revealed in Table 2 shows that the materials in the present investigation are basically Cr-Mo steels conforming to the Russian Grade specified.

Optical metallographic examinations (Figs. 1 and 2) were carried out on the virgin, service exposed

**Table 2**  
Chemical analysis and virgin and service exposed boilers

Sl. No	Type of Main Steam Pipe	Wt % of Elements present											
		C	Mn	Si	S	P	N	Cr	Mo	V	Ni	Cu	Sb
1	Virgin	0.08	0.40	0.17	0.025	0.025	-	0.90	0.35	0.20	0.25	0.20	-
2	Boiler D	0.10	0.50	0.25	0.011	0.007	-	1.11	0.25	0.23	-	-	-
3	Boiler E	0.12	0.56	0.28	0.011	0.007	-	1.11	0.22	0.22	-	-	-
4	Boiler F	0.10	0.54	0.24	0.012	0.008	-	1.12	0.27	0.23	-	-	-
5	Boiler G	0.06	0.56	0.25	0.011	0.007	-	1.13	0.27	0.24	-	-	-
6	Boiler H	0.08	0.61	0.26	0.033	0.013	-	1.25	0.22	0.29	-	-	-
7	Boiler I	0.08	0.61	0.26	0.033	0.013	-	1.25	0.22	0.29	-	-	-



**Fig. 1:** Optical micrograph of the virgin pipe at  $\times 600$ , revealing ferrite grains dispersed with carbides. There is no evidence of graphitization and creep damage in the form of cavities and decarburization.



**Fig. 2:** A typical optical micrograph of service exposed main steam pipe of boilers at  $\times 300$ , revealing ferrite grains dispersed with carbides. There is no evidence of graphitization and creep damage in the form of cavities and decarburization. This photomicrograph is for boiler D.

**Table 3**

Hardness values of the virgin and service exposed main steam pipes

Sl.No	Type of main steam pipe	Hardness Value (VHN)
1	Virgin	153
2	Boiler D	143
3	Boiler E	149
4	Boiler F	145
5	Boiler G	150
6	Boiler H	151
7	Boiler I	142

main steam pipes of all boilers (D, E, F, G, I and H). The hardness values in the base for boilers are shown in Table 3.

Tensile tests at room temperature, 350°C, 400°C, 450°C, 500°C, 550°C, 600°C and 650°C of the service exposed base metal were performed using a digitally controlled 8562 Instron servo-electric testing system, equipped with a 3-zone split furnace with PID control. Standard tensile specimens were made from the service exposed materials as per ASTM E8-79 specification. Tensile tests were carried out on the base only from the longitudinal direction of the main steam pipes of the service exposed boilers. During tensile testing, constant test temperature of  $\pm 2^\circ\text{C}$  and a constant displacement rate of  $\pm 0.2$  mm/min were maintained. The variation of the Yield Strength (0.2% Proof Stress) and Ultimate Tensile Strength (UTS) with temperature of testing is shown in Figs. 3a and 3b. Figures 3c and 3d show the variation of % RA (reduction in area) and % EL (elongation) with temperature of testing respectively.

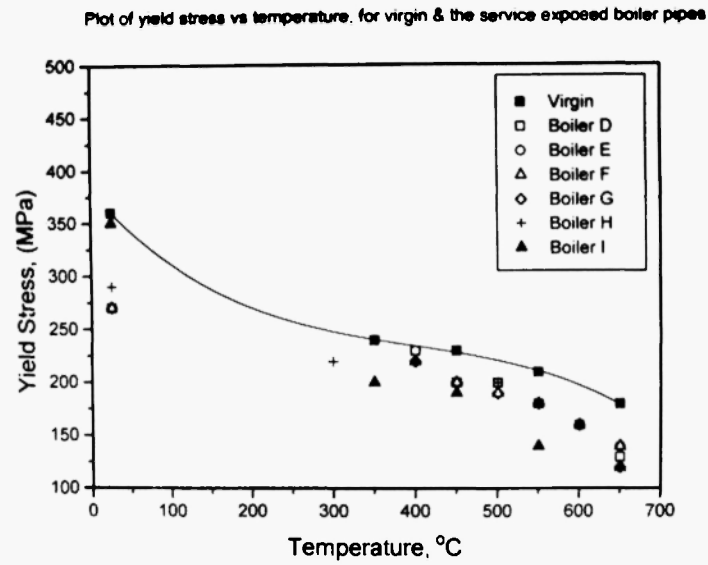


Fig. 3a: Plot of yield strength (0.2% proof stress) vs test temperature for virgin and service exposed boiler pipes.

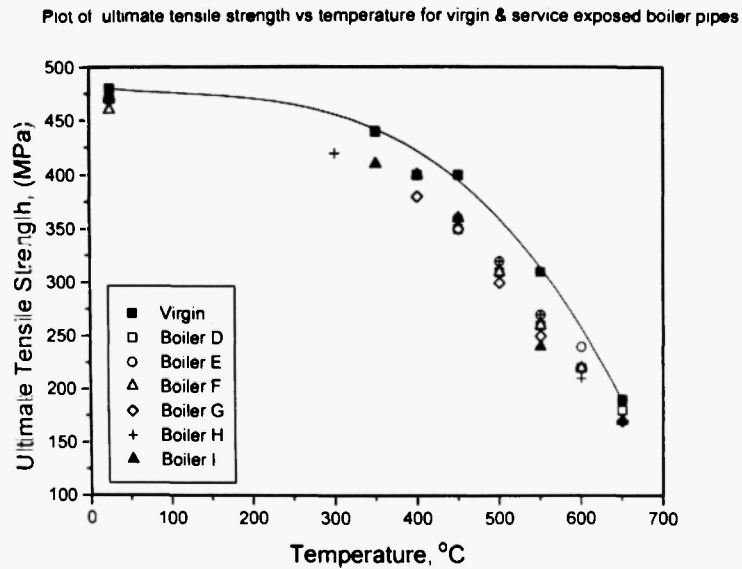


Fig. 3b: Plot of ultimate tensile strength (UTS) vs test temperature for virgin and service exposed boiler pipes.

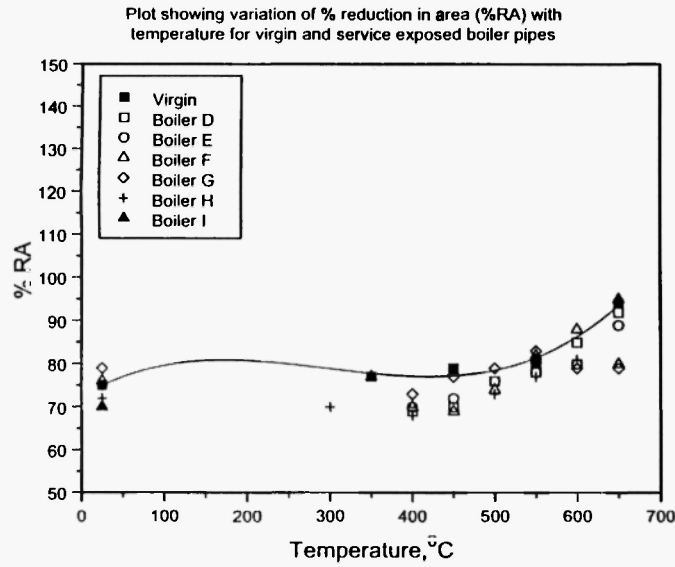


Fig. 3c: Plot showing variation of % reduction in area (%RA) with test temperature for virgin and service exposed boiler pipes.

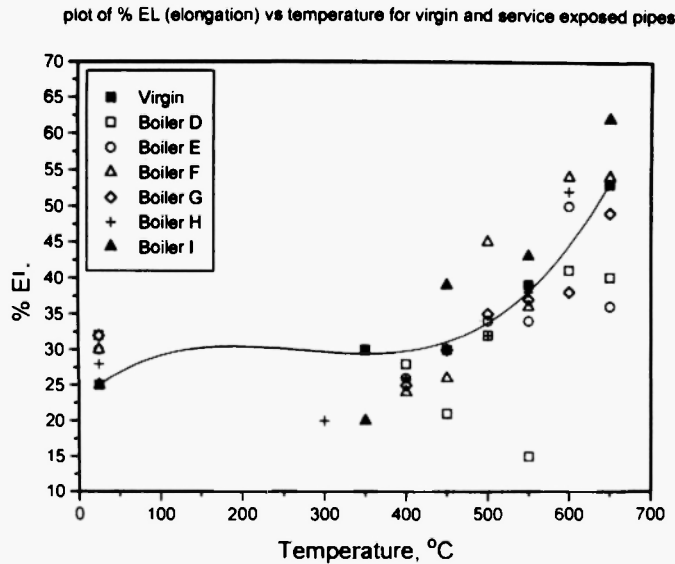


Fig. 3d: Plot showing variation of % elongation (%EL) with test temperature for virgin and service exposed boiler pipes.

The hoop stress  $\sigma_h$  acting on the service exposed pipes was calculated using the following formula to predict the remaining life:

$$\sigma_h = PD/2t$$

where  $P$  is the operating pressure in MPa,  $D$  is the mean diameter in mm and  $t$  is the thickness of the pipe in mm. The operating hoop stresses for the different main steam pipes of boilers D, E and F as evaluated from the above formula were 52.1 MPa, 50 MPa and 58 MPa respectively. Incidentally, the operating hoop stresses for boilers H and I were the same as that for boiler E. Also the operating hoop stress for the main steam pipe of boiler G was the same as that of boiler F.

Although the design stress and operating temperature were 45.8 MPa and 550°C respectively, it was decided that the accelerated stress rupture tests to be carried out in the range of 525°C to 690°C and the lives were evaluated at 65 MPa, since the allowable stress level of the boilers is 65 MPa. Accelerated stress rupture tests using Mayes creep testing machines were carried out as per ASTM 139/83 specification with specimens made from the chordal direction of the main steam pipe of each boiler. These tests were carried out at various stress levels in the range of 65-200 MPa for the virgin pipe and 65-190 MPa for the service exposed steam pipes, to generate data with high extrapolation capability. The stress levels above the operating hoop stress at each temperature were selected in such a way as to obtain rupture within a reasonable span of time.

The generation of stress rupture data was carried out in two ways.

- a) *Increased temperature tests:* At a constant stress of 65 MPa, acceleration was achieved by increasing the test temperature above the specified service temperature which is about 550°C. The range of temperature selected for the tests for various service exposed main steam pipes varied from 525°C to 690°C. To generate more meaningful stress rupture data for life prediction methodology, stress levels even beyond 65 MPa (allowable stress) to a maximum of 190 MPa were selected.
- b) *Increased stress test:* Acceleration was achieved by increasing the stress level beyond 65 MPa which is the allowable stress level specified. Keeping the temperature constant at 550°C, the stress levels selected for these tests were in the range 110-190 MPa.

The stress rupture data under the above stipulated conditions of acceleration are given in Table 4.

The rupture data for the specimens have been plotted in terms of log (stress) vs Larson-Miller Parameter  $\{LMP = T(20 + \log tr)\}$ , where  $T$  is the absolute temperature in °K and  $tr$  is the rupture time in hours. For the purpose of comparison, the best fit curve using third order polynomial for the virgin pipe has been superimposed on this plot. Regression analysis of stress rupture data for virgin as well as service exposed main steam pipes has been carried out using a standard software package, in order to evaluate the long term rupture strength of the components over a range of temperatures.

**Table 4**  
Stress rupture properties of virgin and service exposed boiler pipes

Material	Sl No	Test Temp (°C)	Stress (Mpa)	Rupture Time (hrs)	% EL	% RA
Virgin (Increased stress test)	1	550	200	46	32	56
	2	550	180	205	36	54
	3	550	150	960	36	56
	4	550	140	1440	25	71
	5	550	130	6048	Interrupted	-
	6	550	120	11088	Interrupted	-
Virgin (Increased temperature test)	1	690	65	77	13	71
	2	670	65	218	17	85
	3	650	65	672	15	80
	4	630	65	1673	10	18
	5	610	65	5032	10	210
Boiler D (Increased stress test)	1	525	180	170	53	80
	2	525	170	441	47	79
	3	525	160	432	54	80
	4	525	140	2688	53	72
	1	550	160	70	53	77
	2	550	150	242	52	77
	3	550	140	730	51	75
	4	550	130	1739	54	77
	5	550	110	5352	24	47
	1	600	120	121	58	80
	2	600	110	912	45	67
	3	600	100	1656	17	53
	4	600	90	2544	27	42
	5	600	80	5352	16	50
	Boiler D (Increased temperature test)	1	670	65	466	43
2		650	70	610	38	44
3		630	75	2696	31	51
Boiler E (Increased stress test)	1	525	180	178	54	82
	2	525	170	533	55	82
	3	525	160	264	53	77
	4	525	140	1512	55	82
	1	550	160	103	56	80
	2	550	150	270	48	77
	3	550	140	462	38	83
	4	550	130	4104	35	65
	5	550	110	6216	45	76
	1	600	120	216	51	71
	2	600	110	556	27	77
	3	600	100	1288	27	67
	4	600	90	3905	42	71
	5	600	80	6672	Interrupted	-

**Table 4** (continued)  
Stress rupture properties of virgin and service exposed boiler pipes

Material	Sl No	Test Temp (°C)	Stress (MPa)	Rupture Time (hrs)	% EL	% RA	
Boiler E (Increased temperature test)	1	670	65	269	49	88	
	2	650	70	740	52	88	
	3	630	75	2940	44	84	
Boiler F (Increased stress test)	1	550	110	11232	Interrupted	-	
	2	550	130	1728	48	67	
	3	550	140	658	46	68	
	4	550	150	254	81	76	
	5	550	160	54	49	74	
	1	525	160	304	55	79	
	2	525	170	284	48	76	
	3	525	180	187	48	76	
	1	600	80	4296	8	22	
	2	600	90	2736	11	44	
	3	600	100	928	30	44	
	4	600	110	504	39	47	
	5	600	120	238	50	49	
	Boiler F (Increased temperature test)	1	630	75	2952	18	36
		2	650	70	648	28	56
3		670	65	418	17	28	
Boiler G (Increased stress test)	1	550	110	6936	47	71	
	2	550	130	744	55	71	
	3	550	140	432	40	79	
	4	550	150	161	25	56	
	5	550	160	32	57	77	
	1	525	140	864	52	74	
	2	525	160	264	53	77	
	3	525	170	163	59	76	
	4	525	180	120	52	77	
	1	600	80	5616	08	39	
	2	600	90	1512	28	38	
	3	600	100	672	38	48	
	4	600	110	462	32	59	
	5	600	120	76	58	67	
	Boiler G (Increased temperature test)	1	630	75	2769	20	44
2		650	70	768	24	44	
3		670	65	336	32	48	

**Table 4** (continued)  
Stress rupture properties of virgin and service exposed boiler pipes

Material	Sl No	Test Temp (°C)	Stress (MPa)	Rupture Time (hrs)	% EL	% RA
Boiler H (Increased stress test)	1	550	190	24	23	78
	2	550	170	97	39	98
	3	550	150	264	37	75
	4	550	130	993	39	78
	5	550	110	5137	40	80
	6	550	90	9182	Interrupted	
Boiler H (Increased temperature test)	1	690	65	18	45	89
	2	670	65	198	38	79
	3	650	65	686	13	44
	4	630	65	1602	22	33
	5	610	65	5236	30	40
Boiler I (Increased stress test)	1	550	190	04	26	79
	2	550	170	69	38	84
	3	550	150	89	76	84
	4	550	120	1539	48	87
	5	550	100	5724	49	85
Boiler I (Increased temperature test)	1	690	65	39	63	80
	2	670	65	54	52	88
	3	650	65	312	33	78
	4	630	65	321	34	77
	5	610	65	2021	35	78
	6	600	65	4150	Interrupted	

The Larson-Miller Parameter ( $LMP$ ) =  $T(C + \log tr) = a_0 + a_1 (\log S) + a_2 (\log S)^2 + a_m (\log S)^m$

where  $T$  = Temperature in °K

$tr$  = Rupture time in hrs

$S$  – Rupture strength in MPa

$m$  = Order of polynomial

$C$  = 20

$m$ ,  $a_0$ ,  $a_1$ ,  $a_2$  and  $a_3$  are polynomial constants, Table 5 shows the rupture strengths ( $S$ ) of the service exposed pipes for various rupture times and at  $m = 3$ .

**Table 5**  
Estimated rupture strength in MPa

Type of main steam pipe	Order of polynomial	Temperature, °C	Time, hrs		
			tr =10,000	tr =30,000	tr =100,000
Virgin	m =3; C = 20	550	108	93.00	78.70
		500	119	103.00	86
		-	-	-	-
Boiler D	m =3; C =20	500	142	128	115
		525	123	110	97
		550	106	93	79
		575	89	76	62
Boiler E	m =3; C =20	500	143	130	116
		525	125	112	100
		550	107	94	79
		575	89	76	60
Boiler F	m =3; C =20	500	144	131	119
		525	125	113	100
		550	108	96	83
		600	74	59	-
Boiler G	m =3; C =20	500	138	127	114
		525	120	109	97
		550	103	92	81
		600	88	77	67
Boiler H	m = 3; C =20	550	96	84	72
		550	99	86	73
		550	91	79	70
Boiler I	m =3; C =20	500	123	110	98
		525	106	95	84
		550	91	81	72
		575	78	70	6

#### 4. RESULTS AND DISCUSSION

##### 4.1. Visual observation and metallography

Dimensional measurement revealed that there was no change in outer diameter and thickness of the service exposed pipes. It seems that the pipes have not undergone any appreciable deformation during actual operating conditions. Any evidence of localised and general corrosion/oxidation was not observed on either external or internal surfaces. The hardness level of the virgin and service exposed main steam pipe of various boilers revealed (see Table 3) no significant variation in hardness values with exposure lives.

The microstructure of the virgin material mainly consisted of ferrite grains dispersed with carbides

(Fig. 1). A typical micrograph of service exposed main steam pipes is shown in Fig. 2. Evidence of graphitization and creep damage in the form of cavitation and decarburisation was not observed in any of the service exposed main steam pipes. Therefore, it is clear that the virgin as well as those of the service exposed main steam pipes of all the boilers have had hardly any appreciable degradation from the microstructural point of view.

#### 4.2. Mechanical properties

Room temperature as well as high temperature tensile properties as obtained from experiments are reported, Fig. 3. It is evident from the results that 0.2% proof stress (yield strength) and the UTS (ultimate tensile strength) values for the service exposed pipes showed a decreasing trend with increasing temperature. However, % RA (reduction in area) and % EL (elongation) showed an increasing trend with temperature. This is the common trend observed for materials tested at elevated temperature /12,13/. Analysis of tensile data revealed that there is some deterioration in yield stress (0.2% proof stress), ultimate tensile strengths (see Figs. 3a and 3b), % RA and % EL (see Figs. 3c and 3d) of the service exposed main steam pipes of all the boilers compared to those of the virgin pipe, due to service exposure. However, these variations fall within the specified limits for a similar grade of steels, viz. 1Cr- $\frac{1}{2}$  Mo-02.5V steels, as reported in the literature /12/.

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

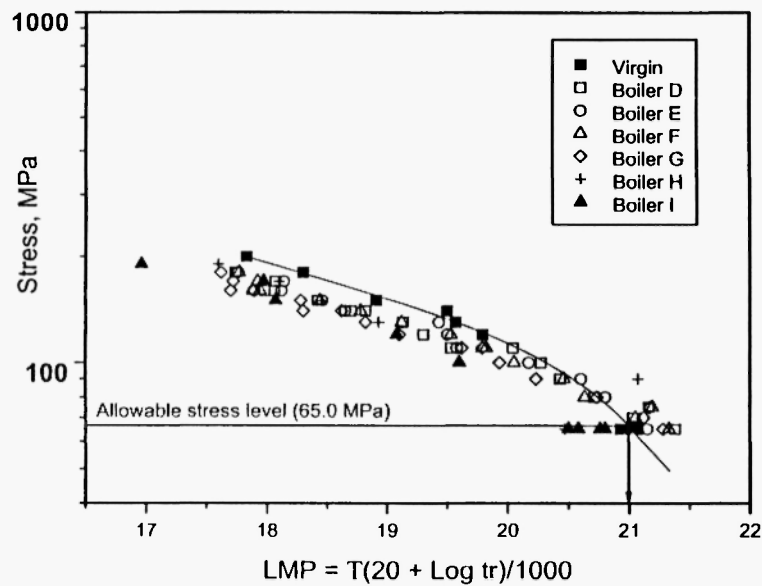
In the present investigation, long term rupture strengths were estimated with best fitted curves for third order polynomial. For different orders of the polynomial, the average sum square error (*ASSE*) was estimated from the following equation:

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

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

Analysis of rupture data clearly indicates that the properties of the present steel are closely comparable to those of the virgin pipe (Fig. 4), suggesting no appreciable creep damage. The data points of the stress vs. LMP plots (Fig. 4) for all the service exposed materials fall within the  $\pm 20\%$  scatter band of the virgin material. The best fit curve for the virgin material has been extrapolated to a lower stress value beyond 65 MPa which is the allowable stress level of the service exposed main steam pipes of all boilers, for the purpose of life prediction (Fig. 4). Previous investigators /9,10/ have

Plot of stress vs Larson-Miller parameter (LMP) for various boilers and virgin pipe



**Fig. 4:** Plot of stress vs Larson-Miller Parameter (LMP) for virgin as well as service exposed boiler pipes.

estimated the remaining life of such ageing components by comparing the upper limit of the data scatter band in stress rupture tests with the ASTM and BSS mean data line. However, for life prediction in the present investigation, it was found that superimposition of ISO-206 mean data line does not aid discussion on the influence of service exposure on the main steam pipe of the boilers. Therefore the experimental data for the virgin pipe was superimposed on the service exposed data for the boilers for the purpose of comparison and life prediction of the service exposed pipes. At higher stress levels, creep rupture data fall outside the  $\pm 20\%$  scatter band limit of the virgin pipe which is indicative of creep properties inferior to the standard material. On the other hand, at low stresses, the experimental data for the service exposed boilers approaches that of the virgin material (Fig. 4). This is a typical trend that is observed with service exposed material. At low stress levels, the service exposed main steam pipes of some of the boilers have superior stress rupture properties compared to that of the virgin pipe (see Fig. 4). In fact it is seen from Fig. 4 that at the allowable stress and operating hoop stress levels, the life of boilers D, E and F is even greater than that of the virgin material. This is mainly because stress rupture data usually exhibit a wide scatter of about  $\pm 20\%$  around the mean data. A minor variation in chemical composition and section size of the test specimen may have a significant influence on rupture lives [12,13]. At lower stress levels, scatter is even higher, as reported in the literature [12,13]. Hence a slightly higher residual life of some of the boilers D, E and F, as estimated in the present investigation, is not unusual.

The remaining lives of all the service exposed main steam pipes of all the boilers predicted at 65 MPa and at 550°C are shown in Fig. 4. At this stress level for all the service exposed pipes, the LMP value as read from the plot of stress vs LMP (Fig. 4) is about 21000. Nevertheless, at the respective operating hoop stress level for various boilers, the LMP values as read from Fig. 4 varied between 21150 to 21300. At this value of LMP, one would expect a very long life. As a rule, an inspection life of >100,000 hours is recommended.

Since it is not always possible to give the precise residual life in view of some uncertainties, including the over extrapolation, it should also be the practice to make use of the following criteria to decide the serviceability (see Fig. 5) of such service exposed components /11/:

- a) Time margin  $= t_f / t_s > 3$   
 b) Stress margin  $= \sigma_{creep} / \sigma_s > 1.00$

where  $t_s$  = service life  
 $t_f$  = rupture life at service stress ( $\sigma_s$ )  
 $\sigma_s$  = service stress  
 $\sigma_{creep}$  = stress for rupture corresponding to the service life.

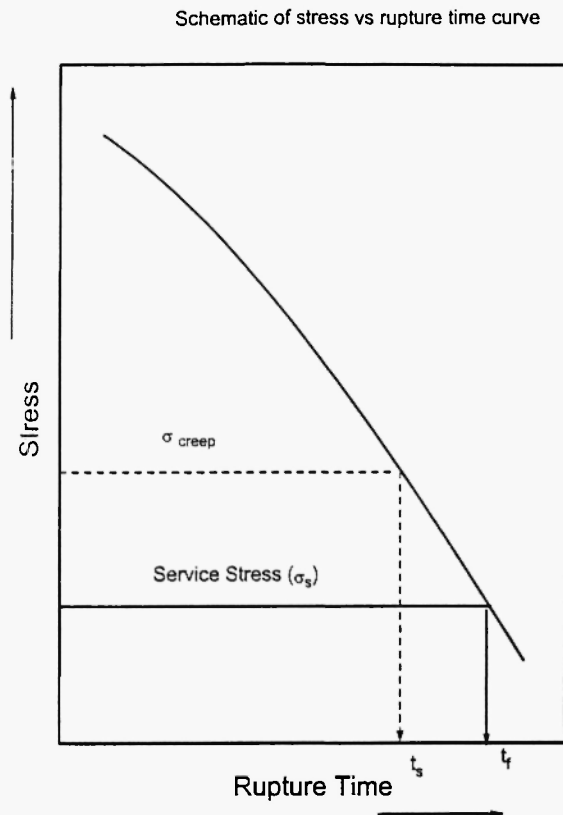


Fig. 5: Schematic of stress vs rupture plot.

**Table 6**  
Stress and time margin at 550°C

Type of Main Steam Pipe	Stress Margin at Operating hoop stress levels	Stress Margin at Allowable stress level (65 MPa)	Time Margin at operating hoop stress levels	Time Margin at allowable stress level (65 MPa)
Virgin	-	-	-	-
Boiler D	1.14	1.41	5.12	6.05
Boiler E	1.09	1.41	5.4	3.44
Boiler F	1.27	1.41	5.58	7.17
Boiler G	1.26	1.41	5.63	6.30
Boiler H	1.09	1.41	8.9	3.99
Boiler I	1.09	1.41	8.03	3.56

The higher the time margin, the better is the safety of operation for the service exposed materials. The values of the above margins as estimated from the stress rupture data in the present investigation for service exposed main steam pipes of boilers are displayed in Table 6.

So far as the remaining life at 550°C/65 MPa is concerned, it is possible to obtain a minimum life of >100,000 hours for the service exposed main steam pipes provided there is no evidence of localised damage in the form of surface cracks, cavitation or dents. Another check for safety of the service exposed pipes in terms of residual life is recommended to be carried out after expiry of 50,000 hours of service life for reasons of economy and safety. Also, during shut down of the plant, NDT (non-destructive) tests, viz. dimensional (thickness and diameter) measurement, hardness measurement and *in situ* metallography may be carried out to assess the condition of the materials for their future serviceability. NDT examination of the weld joints at regular intervals during operation is desirable as the microstructural examination of the welding in some cases revealed the presence of defects like microporosities.

## 5. CONCLUSIONS

This study leads to the following conclusions:

- i) So far as the residual life at 550°C is concerned, it is possible to obtain a minimum life of about 100,000 hours for the service exposed main steam pipes provided there is no evidence of localised damage in the form of surface cracks, cavitation or dents.
- ii) Analysis of tensile data revealed that there is some deterioration in yield stress (0.2% proof stress), ultimate tensile strength, % RA and %EL of the service exposed main steam pipes of all the boilers compared to those of the virgin pipe, but these variations are within the specific limits for similar grades of steels, as reported in the literature.

- iii) The service exposed main steam pipes of all the boilers appear to be in a reasonably good state of health. Another check for safety of the service exposed pipes in terms of residual life is recommended to be carried out after expiry of 50,000 hours of service for economical and safety reasons. Also during shut down of the plant, NDT (non-destructive) tests, viz. dimensional (thickness and diameter) measurement, hardness measurement and *in situ* metallography may be carried out to assess the condition of the materials for their future serviceability. NDT examination of the weld joints at regular intervals during shut down is desirable, as the microstructural examination of the welding in some cases revealed the presence of defects like microporosities.

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