COMPARATIVE STUDY

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Evaluation of Creep Life Prediction Models for Low Alloy Creep Resistance Steel Grade 22 (2.25Cr-1Mo) using Short-term Creep Test

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Abstract

Traditional Power Law equations and modern creep equations were evaluated to estimate long term creep life of Grade 22 material. Evaluation of models made on a short-term database for predicting its capacity of precise long-term creep life. Linear trend line curve fitting method used for extrapolation of data for long-term creep life. Open SourceNRIM creep rupture data for Grade 22tube in annealed/tempered condition and plates in quenched/tempered plates used in this evaluation. This evaluation is helpful for power plant industries for selecting an economically viable and precise model.

Keywords: Creep, Creepmodels, Long-term creep, Stressrupture.

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Introduction

High-temperature components such as tubes, plates, piping's and headers in boilers and Petrochemicals plants are made of low alloy steel. These components are normally designed for creep life of @ 250,000 hours. All such components sometimes may experience change in operating conditions. This change in operating conditions influences its creep life. Forreasonsofeconomy and CO_2 emissions, it becomes necessary to predict the remaining life accurately. Since the last sixty years, many attempts have been made to formulate procedures that can estimate creep life based on short-term testing.

This paper evaluates the different creep models for their capability to predict long term creep life

based on short-term test data. Models that can predict precise life in short-term tests are the prime necessities of boiler industries to plan their maintenance activities. Evaluation of models made using the National Institute of Materials Science (NIMS) creep dataGrade 22 Steel (2.25Cr-1Mo) [1, 2, 3]. It is to be noted that this paper is not an exhaustive comparison of all possible creep models. Rather, it is an overview and evaluation of the most commonly employed creep models.

Material

NIMS Creep data for Grade 22 is used to evaluate creep models. For over half a century, grade 22 (2.25Cr-1Mo) steels have been extensively used in boilers for headers and piping

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and tubing. Open source creep data at various temperatures and stress is already available. It can help to check the accuracy of extrapolation made from short-term data for long-term creep life. National Institute for Materials Science (NIMS), Japan, has various sets creep data for 2.25Cr-1Mo steels at different heat treatment conditions, such as -

a) Plate for
   i. Pressure vessels in quenched and tempered condition,[1]
   ii. Boilerandpressurevessels in normalized and tempered condition[2] and
b) Tubes for boilers and heat exchangers,[3]

The data also has detailed microstructural analysis ofas-received and crept condition.[4]

Chemical composition of NIMS [12] Grade P22 is within limits(wt%) as per ASME, Such as 0.05-0.15C(max); 0.3-0.6Mn;0.025P(max); 0.025 S(max);0.5 Si;1.9-2.6 Cr; 0.87-1.3 Mo.

The heat treatments cycle as below

- Plate – Normalized and Tempered Hot rolled 930˚C/60 min AC, 740˚C / 120 min AC, 700˚C / 240 min FC
- Plate – Quenched and Tempered Hot rolled 930˚C / 6 hours WQ, 635˚C / 6 hr AC, 600˚C / 2 hours FC
- Tubes - Hot extruded & cold drawn 920˚C/1 h - 740˚C / 1.5 hours AC

Microstructures of above grade as below.[4,5]

- For tube material – about 80% ferrite and 20% bainite.
- For plate material – bainitic microstructures for both the quenched/tempered and annealed/tempered plate

Evaluation of Creep Models

In this section, some of them are explored for their capabilities to predict creep life based on short-term data. Here capabilities are tested based on only two points data. Third point, which is long-term creep life, is predicted based on two points data set and compared with actual test results stated in NIMS data set. Hence only those data sets are selected which have minimum three data points for comparison.

Traditional Approach

Most of Creep models have been formulated using a power law equation. This equation states the relationship between temperature (*T)* and stress (σ). This relationship is first described by Arrhenius[1]given as below:

$$\acute{\varepsilon}_c \alpha \exp(-Q_c/RT) \quad (1)$$

Norton[2]also expressed this relationship though equation (2):

$$\acute{\varepsilon}_c \alpha\ \sigma^n \quad (2)$$

Here$\acute{\varepsilon}_c$issecondary creep rate or steady state creep rate; $Q_c$is activation energy for creep; n is stress exponent and *R* is the universal gas constant.

Using above equations (1) & (2)basic power law relationship can be made as per equation as:

$$\acute{\varepsilon}_c \alpha \sigma^n \exp(-Q_c/RT) \quad (3)$$

TheLarson-MillerParameter

The Larson-Miller Parameter is the most worldwide used techniques. It is based on the basic power law equation under constant stress, varying temperature. The Larson-Miller Parameter is given by:[6]

$$P_L = T(C_L + \log t_f) \quad (4)$$

Here C_L is Larson-Miller constant and $P_L$is Larson-Miller parameter.

C_L is generally taken as 20 for metallic materials.[7,8] This means that for the identical or similar test conditions failure time is same for all metallic materials. But it is not.

To find value of $C_L$and P_L for specific material, log $t_f$plotted against1/T. A liner trend line then fitted in which gradient is equal to PLM and intercept is equal to CLM. NRIM Data used for this approach is as per Table 1. A graph is shown in Figures 1 and 2.

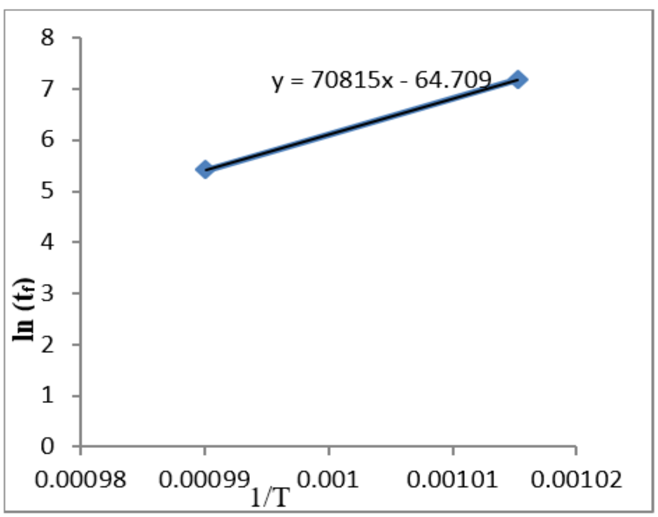

Figure 1: P22 – Norm & Tempered Steel Plate

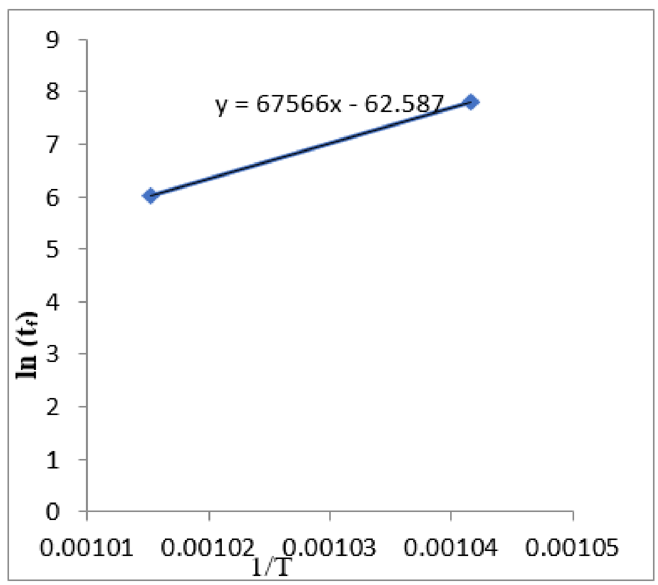

Figure 2: P22 – Quench & Tempered Steel Plate

Note – For Annealed Steel graph is not plotted due to data limitation for constant stress

Table 1: NRIM Grade 22 material data

Steel	*Heat*	*Temp*	*Stress*	*Actual time to rupture*
Quench & Temp Plate	MnG	525	294	406.6
Quench & Temp Plate	MnG	500	294	2426.4
Norm & Temp Plate	MaC	550	177	222.5
Norm & Temp Plate	MaC	525	177	1318.8

Using NRIM Data Sheet following set of parameters used to plot the graph

The Manson-Haferd Model

Manson-Haferd expresses relation between time and temperature in his model[9] as below

$$P_{MH}=(\log t-\log t_a)/(T-T_a) \quad (5)$$

Here P_{MH} is Manson-Haferd Parameter, t_a is time constant and T_a is temperature constant. The variable t represents time. This may be either time to fracture (t_f) or time to a pre-defined strain (t_ε).T is the creep test's absolute temperature.

For our calculation, we will consider $t=t_f$. To get P_{MH}, T_a and t_a, plot log(t_f) vs. T. Then fit liner trend line for the constant stress dataset. The slope of line is P_{MH}, For getting T_a and log(t_a) need more than one data set for different stress level. Then the coordinates at which all the straight line intersect will give Ta and log(ta). This is the limitation of this model. Also, there are likely chances that all data set trend line will intercept. Hence determining the value of $T_a$andlog(t_a) will be difficult. We have a limited data set with no three points available for each data set in considered material. Hence this model is not viable for predicting life on short data set with limited data availability

The Orr-Sherby-Dorn Model

The model given by Orr-Sherby-Dorn (OSD)[10] is given by equation (6).

$$P_{OSD}=\log t_f-C_{OSD}/T \quad (6)$$

Here $P_{OSD}$is the Orr-Sherby-Dorn parameter and $C_{OSD}$is constant. We need to plot log(tf) vs. 1/T for constant stress to determine these two values. And then linear trend line is to be fitted. Gradient is equal to C_{OSD} and the intercept equal to P_{OSD}. This is similar to Larsen Millar model.

Again, there is hardly any difference in the LMP and Orr-Sherby-Dorn approaches. Linear curve fitting and graph is the same in both the cases i.e., log(tf) vs. 1/T. Hence there is no much difference in approach. It has been excluded from finding parameters.

TheManson-SuccopModel

The Manson-Succop[11] model given in equation (7) states log$t_f$is proportional to T for iso-stress condition. It is given as below:

$$P_{MS}=\log t_f+C_{MS}T \quad (7)$$

P_{MS} and C_{MS} are the Manson-Succop parameter and constant. To determine the value of these two, we need to plot log(tf) vs. T for constant stress. The difference in LMP and Manson-SuccopApproach is that the data is plotted against T instead of 1/T. NRIM Data used for this approach is as per Table 2. Fig 3 and 4 shows the graph plotted using this approach to evaluate constant.

The Monkman-Grant Approach

In Monkman-Grant relationship[12] minimum creep rate is linked to the time to fracture t_f as below

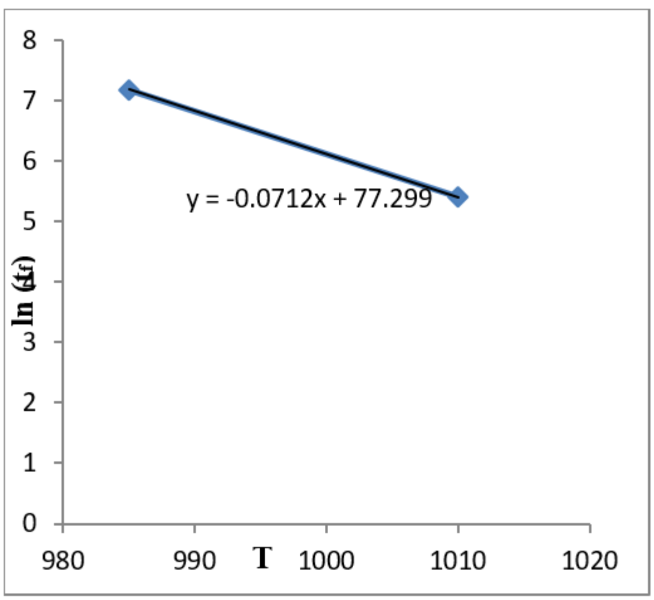

Figure 3: P22 – Norm & Tempered Steel Plate

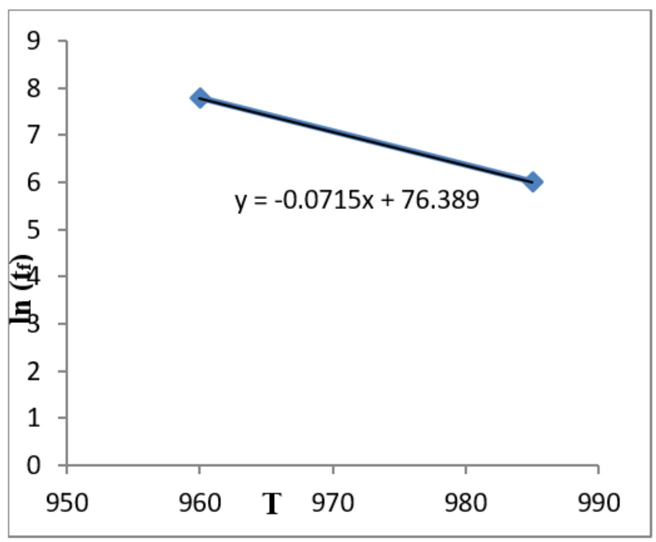

Figure 4: P22 – Quench & Tempered Steel Plate

Table 2: NRIM Grade P22 Material Data for Iso -Stress Condition

Steel	*Heat*	*Temp*	*Stress*	*Actual time to rupture*
Quench & Temp Plate	MnG	525	294	406.6
Quench & Temp Plate	MnG	500	294	2426.4
Norm & Temp Plate	MaC	550	177	222.5
Norm & Temp Plate	MaC	525	177	1318.8

$$(\dot{\varepsilon}_{min})^m . t_f = C_{MGR} \quad (8)$$

$\acute{\varepsilon}_{min}$ = min creep rate, t_f is time to failure and C_{MGR} are constants. By Plotting graph of natural log (t_f) vs log($\acute{\varepsilon}_{min}$) can determine the constants. NRIM data set for evaulating MGC approach is as per Table 3. Fig 6 and 7 shows the constant to be determined from graph.

TheGoldhoff-SherbyModel

TheGoldhoff-Sherbymodel [13] issimilartotheManson-Haferd model. The difference in this model is that the iso-stress lines need to converge to a point ($1/T_a$, t_a):

$$P_{GS}=(\log t - \log t_a)/(1/T - 1/T_a) \quad (9)$$

Here$t_a$is time constant, $T_a$is temperature constant.

P_{GS} is the Goldhoff-Sherby parameter. The variable t can be either the time to failure t_f, or the time to a specific strain t_ε.To determine P_{GS}, T_a and t_a we can plot log(t_f) vs 1/T. We then fit straight lines to each of the constant stress datasets. There are two things we need from this graph. The gradient of each line, PGS, and the coordinates all straight lines intersect give 1/Ta and log(t_a). This is also similar to Manson-Succom approach. Getting need Ta and log(ta) need more than one data set for different stress levels. Then the coordinates at which all the straight line intersect will give Ta and log(t_a).

This is limitation of this model. Also there are likely chances that all data set trend line will intercept. Hence determining the value of Ta andlog(t_a) will be difficult.We have a limited data set where there are no three points available for each data set in considered material. Hence this model is not viable to predict life on short data set with limited data availability

The Soviet Prediction Approach

In this approach, two models are specified [14,15]:

$$\text{Model(1): } \log t = a + b\log T + c\log\sigma + d/T + f\cdot\sigma/T \quad (10)$$

$$\text{Model(2): } \log t = a + b\log T + c\log(\sigma/T) + d\cdot\sigma/T + f/T \quad (11)$$

Here a, b, c, d and f are constants. In this method, there are many constants and greater sensitivity. However, they are not separable from the variables T and σ. This will give more than one value for a, b, c, d and f. Their values are obtained from regression analysis by using Software packages such as PD6605.[16] Hence this model is also not economically viable.

The Minimum Commitment Approach

The model in Minimum Commitment approach[17,18] is given by equation (12):

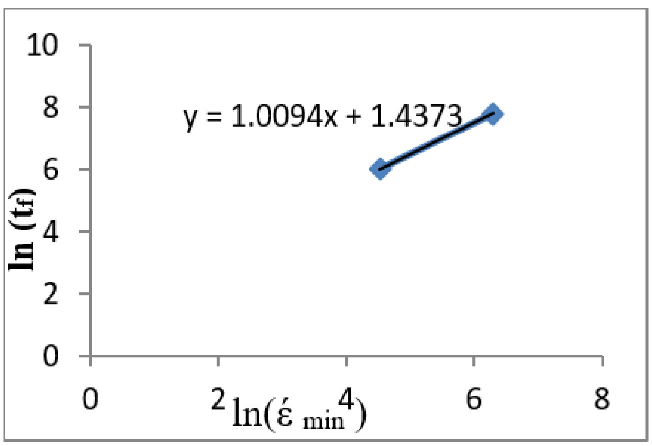

Fig. 6: P22 – Quench & Tempered Steel Plate

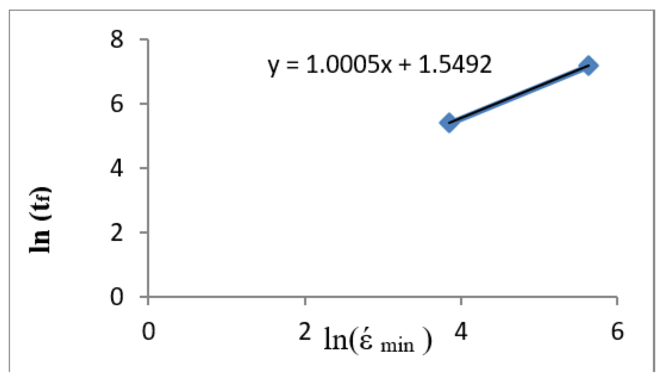

Figure 7: 1 P22 – Norm & Tempered Steel Plate

Table 3: NRIM Grade 22 Material Data for Iso-Stress Condition

Steel	*Heat*	*Temp*	*Stress*	*Actual Time to Rupture*
Quench & Temp Plate	MnG	525	294	406.6
Quench & Temp Plate	MnG	500	294	2426.4
Norm & Temp Plate	MaC	550	177	222.5
Norm & Temp Plate	MaC	525	177	1318.8

Table 4: NRIM Grade 22 Material Data for Iso-Thermal condition

Steel	*Heat*	*Temp*	*Stress*	*Actual Time to Rupture*
Quench & Temp Plate	MnG	450	373	3130
Quench & Temp Plate	MnG	450	392	1579.1
Quench & Temp Plate	MnG	450	431	419.3
Norm & Temp Plate	MaC	450	333	222.5
Norm & Temp Plate	MaC	450	294	1318.8

$$\log t = a + b\log\sigma + c\cdot\sigma + d\cdot\sigma^2 + f\cdot T + g/T \quad (12)$$

There are six constants it is cumbersome to determine its value. Again this is similar to soviet prediction approach. Not suitable for limited data approach.

Modern Creep Life Approaches

In this study, only two models from modern creep life approaches which are very known are considered.

The Hyperbolic-Tangent Model

Rolls-Royce plc (London, UK)[19,20,21] developed this model in 1990. It related the accumulated creep strain to current time, stress and temperature. This model is presented as below:

$$\sigma = \sigma_{TS}/2\{1 - \tanh[k\cdot\log(t_f/t_i)]\} \quad (13)$$

Here k and t_i are curve fitting parameters

Rearranging the above equation we get it into a linear form:

$$\log (t_f)\ \sigma = \{\tanh^{-1}[1 - 2\ k\cdot]\} + \log(t_i) \quad (14)$$

We nowcan plot graphlog(t_f) vs.tanh^{-1}\{1 – 2 k· \} for each temperature. When a linear trend line is fitted the gradient is equal to *1/k*, and the intercept equal to *log(t_i)*. NRIM data as per Table 4 is used to plot graph given in Fig. 8 and 9.

The Wilshire Model

Wilshire from Swansea University,[22,23] presented his model as below.

$$\acute{\varepsilon}_m = A^*\cdot(\sigma/\sigma_{TS})\cdot\exp(-Q_c^*/RT) = M/t_f \quad (15)$$

Here $A^* \neq A$ and $Q_c^* \neq Q_c$. $\sigma_{TS}$is maximum stress / tensile strength of material at a specific creeptemperature. Augmenting Equation (13), creeplife is given by[22,23,24]:

$$\sigma/\sigma_{TS} = \exp(-k_1[t_f\cdot\exp(-Q_c^*/RT)]^u) \quad (16)$$

$$\sigma/\sigma_{TS} = \exp(-k_2[t_f\cdot\exp(-Qc^*/RT)]^v) \quad (17)$$

The Wilshire Equation like the previous method uses normalized stress. Here three constants to determine. k_1, k_2, u or v.Qcis activation energy at normalized constant stresses.

This is cumbersome method. For constant collecting data at constant normalized stresses is difficult. All NIMS data is either at constant stress or it can be at constant temperature. Above this, it is difficult to have constant normalized stresses

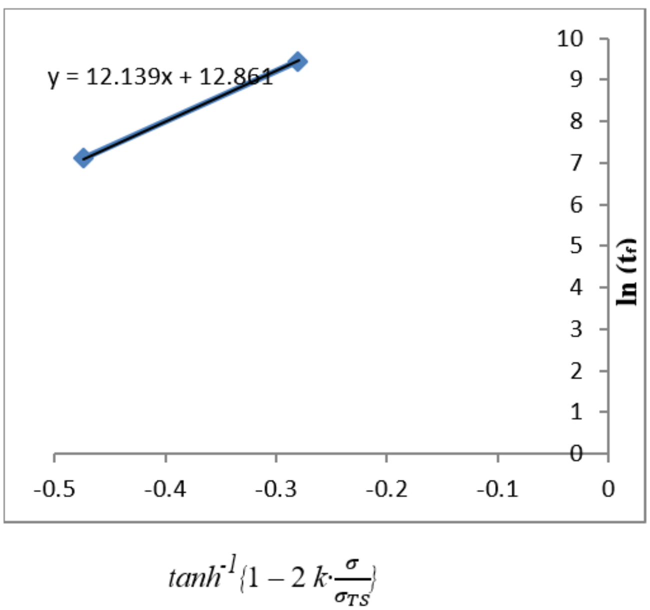

Figure 8: P22 – Norm & Tempered Steel Plate

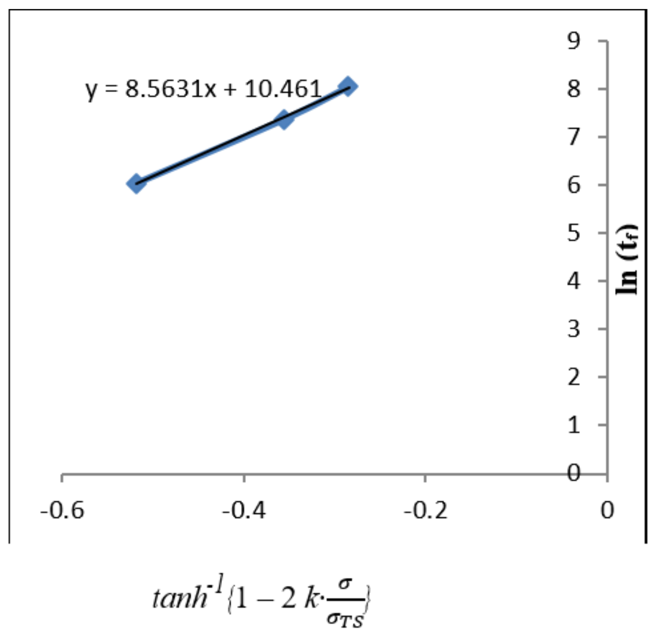

Figure 9: P22 – Quench & Tempered Steel Plate

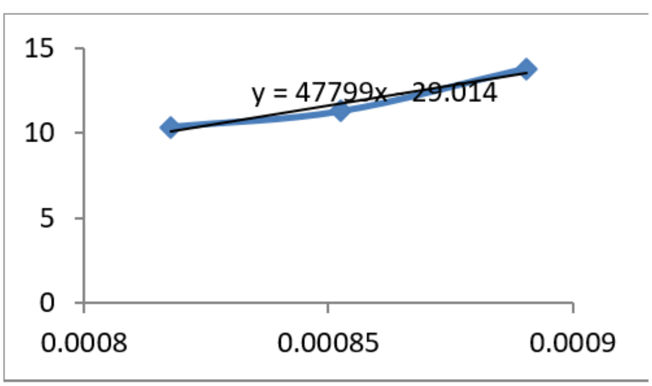

Figure 10: P22 – Norm & Tempered Steel Plate

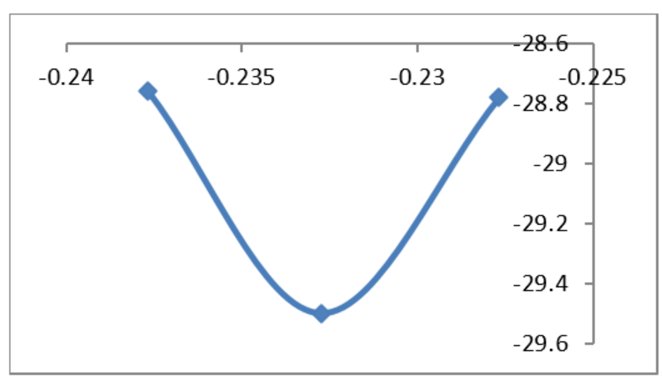

Figure 11: P22 – Quench & Tempered Steel Plate

To get Qcneed to plot first ln(t_f) vs. 1/T at constant normalized stress. Fitting a linear trend line to each dataset the gradient is equal to Qc/R. Ref Fig. 10 and 11 for determining constants from Graph is plotted using data given in Table 5A. To determine k_u and u, need to plot ln(-ln(σ/σ_{UTS})) vs. ln(tf.exp(-Qc*/RT)) for all the data. The gradient of this graph is equal to u, and the intercept equal to ln(k_u).Now if we examine closely to find ku and u, another set of data is required and it should not be constant normalized stress. Else we will not be able to plot ln(-ln(σ/σ_{UTS})) vs. ln (t_f. exp(-Qc*/ RT))

Table 5A: Grade P22 Creep Data [27]

Stress (MPa)	*Temperature (C)*	*UTS (Mpa)*	*Rupture time (s)*
450	1073	1000	2391800
400	1123	887	313830
400	1123	887	967620
350	1173	773	76750
300	1223	660	30427

NRIM data is not suitable for assessing this model as there is no any data available at constant normalized stress. Hence this model is also not viable for predicting long term creep life based on short term creep data with minimum set of data.

Results

The Larson-Miller Parameter

Table 5B: Time to rupture using LMP.

Steel	*Heat*	*Temp*	*Stress*	*Time to Rupture*	*LMP*	*Predicted Time to Rupture*	*Error*
Quench & Temp Plate	MnG	475	294	8841.7	9.676102	15932.27	0.809425277
Quench & Temp Plate	MnG	450	294	112506	11.66135	116000.7	0.39894026

The Manson-Succop Approach

Table 6: Time to Rupture using MSA

Steel	*Heat*	*Temp*	*Stress*	*Time to Rupture*	*MSC*	*Predicted Time to Rupture*	*Error*
Quench & Temp Plate	MnG	475	294	8841.7	9.5365	13856.37	0.572450385
Quench & Temp Plate	MnG	450	294	112506	11.324	82784.82	3.392828675

The Monkman-Grant Approach

Table 7: Time to Rupture using MG Approach

Steel	*Heat*	*Temp*	*Stress*	*Time to Rupture*	*MGC*	*Predicted Time to Rupture*	*Error*
Quench & Temp Plate	MnG	475	294	8841.7	9.09761	8933.917	-0.010527087
Quench & Temp Plate	MnG	450	294	112506	11.91316	149217.3	-4.190785504

Modern Creep Life Approaches

The Hyperbolic-Tangent Approach

Table 8: Time to Rupture using Hyperbolic-Tanget Approach

Steel	*Heat*	*Temp*	*Stress*	*Time to Rupture*	*Hyperbolic Tangent*	*Predicted Time to Rupture*	*Error*
Quench & Temp Plate	MnG	450	294	112506	10.40235	32936.86	9.083235015
Quench & Temp Plate	MnG	450	333	18347.2	9.250651	10411.34	0.905920474
Quench & Temp Plate	MnG	450	353	6852.9	8.645407	5683.982	0.133438182

Error analysis

The accuracy of Creep Models in predicting creep life was evaluated by calculating error in predicting rupture is calculated by

$$Error = \sqrt{\frac{\text{Actual time to rupure in hours} - \text{Predicted time to rupture in hours})^2}{\text{No of hours in year}^{\,2}}} \tag{18}$$

There are various numerable approaches to error calculation based on no data points, This is simple clear and an aggressive approach and it is suitable where there is no multiple set of data points.

Error analysis for various creep models carried out are presented below. Refer Table 9.

- At low temperature (450°C), Larsen-Miller approach has shown good accuracy
- For temperature 500°C, Mockman-Grant creep model stands better option. However error Calculated is for very short duration creep test

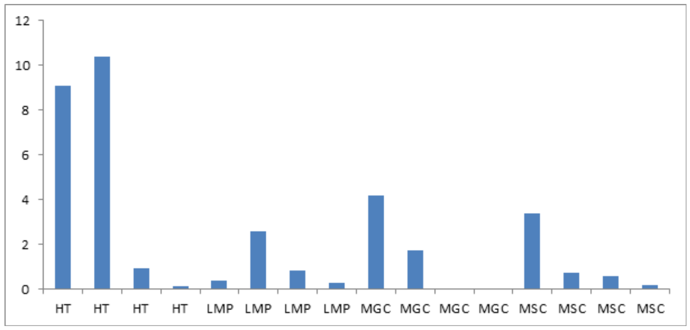

Figure 12: Error analysis of creep lifing models . HT – Hyperbolic Tangent; LMP – Larsen Miller Parameter; MGC-Mockman Grant Constant; MSC-Manson Succop Constant

Table 9: Error Analysis

Creep Model	*Steel*	*Heat*	*Temp*	*Stress*	*LMP*	*Actual Time to Rupture*	*Predicted Time to Rupture*	*Error*
MGC	Quench & Temp Plate	MnG	450	294	11.91316	112506	149217.3	4.190785504
LMP	Quench & Temp Plate	MnG	450	294	11.66135	112506	116000.7	-0.39894026
MSC	Quench & Temp Plate	MnG	450	294	11.324	112506	82784.82	3.392828675
HT	Quench & Temp Plate	MnG	450	294	10.40235	112506	32936.86	9.083235015
HT	Norm & Temp Plate	MaC	450	245	12.1244	93446.3	184314.8	-10.37311295
LMP	Norm & Temp Plate	MaC	475	177	11.02897	38955.4	61633.94	-2.588874026
MGC	Norm & Temp Plate	MaC	475	177	10.8966	38955.4	53992.53	-1.716566995
MSC	Norm & Temp Plate	MaC	475	177	10.727	38955.4	45569.78	-0.755065916
HT	Quench & Temp Plate	MnG	450	333	9.250651	18347.2	10411.34	0.905920474
LMP	Quench & Temp Plate	MnG	475	294	9.676102	8841.7	15932.27	-0.809425277
MSC	Quench & Temp Plate	MnG	475	294	9.5365	8841.7	13856.37	-0.572450385
MGC	Quench & Temp Plate	MnG	475	294	9.09761	8841.7	8933.917	-0.010527087
HT	Quench & Temp Plate	MnG	450	353	8.645407	6852.9	5683.982	0.133438182
LMP	Norm & Temp Plate	MaC	500	177	9.056625	6115.4	8575.161	-0.280794588
MSC	Norm & Temp Plate	MaC	500	177	8.947	6115.4	7684.803	-0.179155575
MGC	Norm & Temp Plate	MaC	500	177	8.684916	6115.4	5913.042	0.023100236

- For temperature 475°C, Manson-Succup has better capability for creep life prediction in the range of 50000 hours.

Discussion & Conclusions

Alloy steel Grade 22, one of the most widely used materials for high-temperature application in Power Plant and Petroleum Plant. The ageing of Plant calls for reliable methods to predict this material's long-term creep life to plan for predictive maintenance. Since plants are running continuously, it is necessary that this long-term creep life be estimated based on a short-term test with reliable accuracy. Considering this requirement, Traditional Creep Models and Modern Creep Models studied to evaluate their capability to predict creep rupture time based on limited set of data. The study allows a user to select a model for its predictive maintenance, which is economical and has greater accuracy. Hyperbolic-Tangent, Soviet, Minimum Commitment and the Wilshire approaches are computationally more complex and require large number of data sets.

Traditional approaches based on Power law equations are good under constant load condition. Larsen Miller Parameters capability to predict creep life based on a limited data set even for a two-point data set is highly accurate compared to all other approaches at low temperature (< 500 C) conditions.

Mockman Grant relations can also be good option in Iso-stress conditions for predicting creep life. However, it needs to studied and verified for its capability to predict creep life greater than 100000 hours expenses.

The study did not aim to find the whole creep curve prediction capability. However, it aimed to find the most suitable method when there is limited data with a short duration test (less than 1000 hrs). This is most of the boiler user’s requirement for better planning preventive maintenance and related capital expenses.

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Author Contributions

The co-authors, Dr. Nagesh Kini & Dr. Anand Bewoor guided this paper's publication in its final format. Their support for timely review, selecting and plotting the data made helped to complete this study.

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