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ECCC RECOMMENDATIONS - VOLUME 5 Part Ib [Issue 2]

RECOMMENDATIONS AND GUIDANCE FOR THE ASSESSMENT OF CREEP STRAIN AND CREEP STRENGTH DATA

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RECOMMENDATIONS AND GUIDANCE FOR THE ASSESSMENT OF CREEP STRAIN DATA

PREPARED BY ECCC-WG1

Mr P Auerkari	VTT, Finland (1997-)	
Mr M Askins	Innogy, UK (2001-)	
Dr D R Barraclough	ASTEC, UK (1992-4)	
Dr P Bernasovsky	Slovakian Welding Institute (2001-)	
Dr-Ing B Buchmayr	Technische Univ. Graz, Austria (1992-)	
Dr C K Bullough	ALSTOM Power (ETC), UK (1992-96)	
Ir C Coussement	Belgian Welding Institute, Belgium (1997-99)	
Prof E Gariboldi	Politecnico di Milano, Italy (2001-)	
Dr-Ing J Granacher	IfW TU Darmstadt, Germany (1992-)	
Dr R Hales	ETD, UK (2001-)	[Secretary
Dr S R Holdsworth	ALSTOM Power, UK (1992-)	[Convenor]
Mr S Holmström	VTT, Finland (2000-)	
Dr-Ing A Klenk	MPA Stuttgart, Germany (1997-)	
Dipl-Ing H König	ALSTOM Power, Germany (1992-2000)	
Dr P McCarthy	ALSTOM Power, UK (2002-)	
Dr P F Morris	CORUS, UK (2000-)	
Dr-Ing G Merckling	Istituto Scientifico Breda, Italy (1992-)	
Dipl-Ing K Niel	Siemens KWU, Germany (1992-5)	
Mr J Orr	CORUS, UK (1992-99)	
Mr J H Rantala	JRC IAM Petten (1997-2001)	
Dr D G Robertson	ERA Technology Ltd, UK (1997-2001)	
Dr-Ing W Rohde	VDEh, Germany (1992-96)	
Prof R Sandström	SIMR, Sweden (1992-)	
Dr M Schwienheer	University of Darmstadt, Germany (2001-)	
Dr P Seliger	Siempelkamp, Germany (2001-)	
Dr I A Shibli	ERA Technology Ltd, UK (1995-6)	
Dr S Spigarelli	University of Ancona, Italy (2001-)	
Dipl-Ing H Theofel	MPA Stuttgart, Germany (1992-6)	
Dr A Vanderschaeghe	Stein Industrie, France (1992-4)	

EDITED BY: S R HOLDSWORTH

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ABSTRACT

ECCC Recommendations Volume 5 Part Ib provides guidance for the assessment of creep strain and creep strength data sets. It recognises that it is not practical to recommend a single model equation or assessment procedure for all materials and data set types, and promotes the innovative use of post assessment acceptability criteria to independently test the effectiveness and credibility of creep property predictions.

The guidance is based on the outcome of several work programmes involving the evaluation of a number of assessment procedures by several analysts using large working data sets. The results of these exercises highlight the risk of unacceptable levels of uncertainty in predicted behaviour without the implementation of well defined assessment strategies including critical checks during the course of analysis. The findings of these work programmes are detailed in appendices to the document.

ECCC Recommendations Volume 5 Part Ib user feedback is encouraged and should be sent to:

Dr S R Holdsworth [ECCC-WG1 Convenor, Document Controller]
ALSTOM Power,
Willans Works, Newbold Road,
Rugby CV21 2NH, UK.
Tel: +44 1788 531138
Fax: +44 1788 531469
E-mail: stuart.holdsworth@power.alstom.com

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CONTENTS

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1. INTRODUCTION

ECCC Recommendations Volume 5 Part Ib provides guidance for the assessment of creep strain data. It covers the analysis of individual $e(t)$ creep curves and $e(T,s,t)$ creep curve families.[1] In addition, it provides guidance for the determination of creep strength values and their prediction to long times. Emphasis is placed on pre-assessment and the use of post assessment acceptability criteria to independently test the effectiveness and credibility of the main assessment model equation(s) to characterise the creep behaviour of a material with the available data.

Part Ib originates from the version of Volume 5 Part I issued in 2001 [2a]. Rrference 2a is now split into three parts covering the assessment of (a) creep-rupture data, (b) creep strain data and creep strength data, and (c) stress relaxation data.

The current issue of Part Ib is based mainly on existing ECCC recommendations for creep strength assessment contained in the previous version of Volume 5 Part I [2a]. Work to underpin recommendations for creep strain data assessment is in progress, and findings from the first phase of this activity provide the basis of Sect. 2. The more comprehemsive recommendations for the assessment of creep strength are contained in Sect. 3.

2. CREEP STRAIN DATA ASSESSMENT

2.1 Overview

Creep strain $\varepsilon_f(t)$ or $e_{per}(t)$ curves are determined from the results of continuous-measurement or interrupted tests involving the application of a constant load (or stress) to a uniaxial testpiece held at constant temperature (Fig. 1). In continuous-measurement tests, the creep strain, e_f, is monitored without interruption by means of an extensometer attached to the gauge length of the testpiece. In interrupted tests, the permanent strain, e_{per}, is measured optically at room temperature during planned interruptions ($e_{per} = e_i + e_f - e_k$, Fig. 2).

Depending on the nature of the creep model application, the analysis will be of several $\varepsilon_f(t)$ or $e_{per}(t)$ curves determined for a single heat or several heats of the specified material. The creep strain curves may have originated from a matrix of $t(T,s_o)$ tests for which T and s_o are *i)* relatively homogeneously distributed or *ii)* inhomogeneously distributed. Case *i)* is the ideal situation and generally arises within R&D projects or from well co-ordinated data generation activities. Case *ii)* is more typical of large multi-national datasets gathered to produce creep strength values for standards. The following recommendations are based mainly on the results of a creep strain assessment inter-comparison using a case *i)* dataset (characterised in App. A1).

There are several model equations available for characterising the primary, secondary and tertiary creep deformation characteristics of engineering materials, ranging in complexity from simple-phenomenological to full-constitutive. A number of these and their range of application are reviewed in App. B1. The detailed findings of the creep strain assessment inter-comparison of the case *i)* dataset for a 10CrMo9-10 steel are given in App. C1.

2.2 Recommendations for the Assessment of Creep Strain Data

The following recommendations concern determination of the $e(T,s_o,t)$ creep characteristics of a material from the analysis of a series of individual $e(t)$ records. This usually involves fitting a given model equation (e.g. App. B1) to individual $e(t)$ test records and then rationalising the fitting constants as a function of temperature, stress and possibly other variables (e.g. material pedigree factors) to obtain the parameters for the $e(T,s_o,t)$ master-equation.

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[1] For information on ECCC terms and terminology, the reader is referred to reference 1.

1) The effectiveness of the $e(T, s_o, t)$ master-equation depends on the goodness of fit of the selected model equation to the individual $e(t)$ records. Best results are obtained by optimising the fitting procedure to suit the characteristics of the selected model equation and the material under investigation (e.g. independently minimising residual errors during curve-fitting different sections of the creep curve).

2) Prior to the main-assessment, a pre-assessment should be performed which takes cognisance of the guidance given in Sect. 2.3.

3) The determination of $e(T, s_o, t)$ master-equations from multi-cast datastets should incorporate material characterising parameters in the model equation.

4) The results of the main-assessment should satisfy the requirements of the ECCC CSA post assessment acceptibility criteria (Sect. 2.4).

2.3 Pre-Assesssment

Pre-assessment should include:

(i) confirmation that the data meet the material pedigree and testing information requirements recommended in ECCC Recommendations Volume 3 [4],

(ii) confirmation that the material pedigrees of all casts meet the specification set by the instigator(s) of the assessment,

(iii) examination of the quality of individual creep test records to confirm that there are sufficient $e(t)$ data co-ordinates to fully represent the character of the creep curve

2.4 Post Assessment Acceptability Criterion

The CSA post assessment acceptability criteria evaluate

- the physical realism of the master-equation
- the effectiveness of the model description within the range of the input data

These are investigated in the following post assessment tests.[2]

Physical Realism of the Master-Equation

Visually check the credibility of the $e(T, s_o, t)$ master-equation fit to individual $e(t)$ test records.

Effectiveness of Model Description within Range of Input Data

To assess the effectiveness of the model to represent the behaviour of the complete dataset, plot predicted time to specific strain versus observed time to specific strain for all input $e(t)$ data (e.g. Fig. C6-C13, App. C1). Diagrams should be prepared for times to *a)* 0.2% strain, *b)* 1.0% strain, and *c)* a user defined creep strain, if appropriate, to test the model for a specific application.

The $\log t_{pe}^*$ versus $\log t_{pe}$ diagrams should show:

- the $\log t_{pe}^* = \log t_{pe}$ line (ie. the ideal line),
- the $\log t_{pe}^* = \log t_{pe} \pm 2.5.s_{[A\text{-}RLT]} = \log t_{pe} \pm \log Z$ boundary lines[3,4],

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2 The underlying background to the development of the post assessment tests for CSA is given in App. C1

3 $s_{[A\text{-}RLT]}$ is the standard deviation of the residual log times for all the data at all temperatures, ie. $s_{[A\text{-}RLT]} = \sqrt{\{\sum_i (\log t_{pe\ i} - \log t_{pe}^*{}_i)^2/(n_A - 1)\}}$, where i = 1,2, ... n_A, and n_A is the total number of data points

- the $\log t_{p\varepsilon}^* = \log t_{p\varepsilon} \pm \log 2$ boundary lines[5],and
- the linear mean line fit through the $\log t_{p\varepsilon}^*$,$\log t_{p\varepsilon}$ data points.

and highlight the best tested individual casts.

A perfect prediction of $t_{p\varepsilon/s/T}$ by the master-equation is represented by the Z parameter being equal to zero. Ideally Z is ≤2, Z values of >4 are unacceptable, whereas values of ≤3-4 are marginal and may be regarded as practically acceptable.

3. CREEP STRENGTH DATA ASSESSMENT

3.1 Overview

In addition to the need for rupture strength values based on large multi-cast, multi-temperature datasets, there are similar requirements for creep strength values in Product and Design Standards. However, unlike the CRDA situation (Part Ia), there are no standardised procedures specifically for deriving creep strength values.

Existing creep strength data assessment (CSDA) procedures collate the times to accumulate specific strains from individual creep curves determined for a number of casts, at a range of stress levels and temperatures. These data are then used to determine either (i) a set of individual iso-strain model equations defining the relationship between creep strength, temperature and time to accumulate the specified strain (analogous to CRDA), or (ii) a self consistent master equation set relating creep strength, rupture strength, temperature and the times to a range of creep strains and rupture. In (ii), the link between creep and rupture strengths may be based on (a) parametric or (b) constitutive equations. A number of CSDA procedures are reviewed in App. B2, and details of the WG1 evaluation of their effectiveness when applied to a large dataset for N+T 2¼CrMo (App. A2) are contained in App. C2.

The results of the CSDA evaluation show that the level of uncertainty associated with creep strength predictions is potentially greater than that for rupture strength predictions. The adoption of a pre-assessment / repeat main assessment / post assessment test strategy for CSDA is therefore highly recommended.

3.2 Recommendations for the Assessment of Creep Strength Data

The ECCC-WG1 CSDA evaluation exercises highlighted the risk of unacceptable levels of uncertainty in predicted strength values without the implementation of certain precautionary checks during the course of assessment (App. C2). The findings of these investigations have led to the following recommendations.

1) At least two CSDAs should be performed by two independent metallurgical specialists using their favoured proven methodology.

2) At least one of the CSDAs should be performed using a method for which there is an ECCC procedure document detailed in App. D. These are referred to as ECCC-CSDAs[6].

3) Prior to the main-assessment of the CSDA, a pre-assessment should be performed which takes cognisance of the guidance given in Sect. 3.3.

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[4] for a normal error distribution, almost 99% of the data points would be expected to lie within $\log t_{pe}^* = \log t_{pe} \pm 2.5.s_{[A\text{-}RLT]}$ boundary lines

[5] ie. the $t_{pe}^* = 2.t_{pe}$ and $t_{pe}^* = 0.5.t_{pe}$ boundary lines

[6] An ECCC-CSDA is one for which there is a comprehensive procedure document, approved by ECCC-WG1 and included in App. D.

4) The results of the main-assessment of the CSDA should satisfy the requirements of the ECCC post assessment acceptability criteria (Sect. 3.4).

5) The results of the two CDSAs should predict $R_{p\varepsilon/100kh/T}$[7] strength levels to within 20% at $T_{min[10\%]}$, T_{main} and $T_{max[10\%]}$. $R_{p\varepsilon/300kh/T}$ strength levels should be predicted to within 30% at the same temperatures.[8]

If the maximum test duration is less than 100,000h, the predicted strength comparisons should be made for test durations of $t_{p\varepsilon[max]}$ and $3.t_{p\varepsilon[max]}$.

6) If the results of the two CSDAs meet the requirements defined in *5)* and only one is an ECCC-CSDA, the results of the ECCC-CSDA should be adopted. If both assessments have been performed according to ECCC-CSDA procedures, the results of the ECCC-CSDA giving the minimum $R_{p\varepsilon/100kh}$ strength values at T_{main} should be adopted, unless ECCC-WG3x agree otherwise.

An important deliverable from each individual assessment is a master equation defining time as a function of stress and temperature. Consequently, the results from only one ECCC-CSDA should be adopted to construct the final table of strength values.

7) If the results of the two CSDAs do not meet the requirements of *5)*, up to two repeat independent CSDAs should be performed until the defined conditions are satisfied. However, repeat assessment should be unnecessary if the material has been sensibly specified and pre-assessment has confirmed that (i) all casts making up the dataset conform to the specification, (ii) the distribution of the data is not impractical for the purpose, and (iii) there are no sub-populations which may influence the uncertainty of the analysis result. It is therefore strongly recommended that these aspects are considered by ECCC-WG3.x prior to repeat assessment.

8) The results of all assessments should be reported according to the prescribed ECCC format (App. E1, a CRDA check list file is contained on the Volumes CD).

A copy of the reporting package should be sent to the ECCC-WG1 Convenor to provide the working group with essential feedback on the effectiveness of their recommendations.

9) During subsequent use of the master equation derived from the CSDA, strength predictions based on extended time extrapolations and extended stress extrapolations as defined by [3][9] must be identified.

Quantification of the uncertainties associated with extrapolated strength values and those involving extended extrapolations should be a goal for the future.

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7 In the text, only the subscript reference for total plastic strain is used (eg. $R_{p\varepsilon/t/T}$). This is primarily for brevity, but also because the validation work reported in App.C2 was on the results from interrupted strain measurement tests. Analysts working with creep-strain rather than total-plastic-strain data should acknowledge this when reporting their results and use the appropriate terminology to avoid any misunderstandings (eg. $R_{f\varepsilon/t/T}$ rather than $R_{p\varepsilon/t/T}$).

8 $T_{min[10\%]}$ and $T_{max[10\%]}$ refer to the minimum and maximum temperatures at which there are greater than 10% data points. T_{main} is the temperature with the highest number of data points.

9 According to [3], extended time extrapolations are those beyond x3 the test duration exceeded by data points from 5 casts at temperatures within 25°C of that specified. Results from tests in progress may be included when above the -20% scatterband limit at the appropriate duration. Extended time extrapolations are not permitted at temperatures which do not meet this criterion.
Extended stress extrapolations are those in the ranges ($0.9.\sigma_{o[min]}$ - $\sigma_{o[min]}$) and ($1.1.\sigma_{o[max]}$ - $\sigma_{o[max]}$), where $\sigma_{o[min]}$ and $\sigma_{o[max]}$ are the minimum and maximum stress value used in the derivation of the master curve.

10) The reliability of CSDA predictions is dependent on both the quality and quantity of the data available for the analysis. Interim-minimum and target-minimum dataset sizes for the determination of creep rupture strength values for standards are recommended in Table 2.

11) To improve the reliability of CSDA predictions in the future, greater emphasis should be placed on the generation of homogeneously distributed datasets during the planning of creep testing programmes, in particular those activities forming part of large collaborative actions.

12) The use of post service exposure test data for the derivation of design strength values is not recommended.

13) The level of uncertainty in the predicted creep strength values determined from CSDAs will be reduced by using creep test records with an adequate frequency of observations (Table 6, App. 1 [4]).

14) The method of determining $t_{p\varepsilon}$ ($t_{f\varepsilon}$) data should be reported.

15) $R_{u/t/T}$ strength values determined as part of a CSDA should only be used as a means of generating $R_{p\varepsilon/t/T}$ predictions which are consistent with the rupture data. $R_{u/t/T}$ values to be reported outside WG3x should be determined independently of any creep strength data, by CRDA, to minimise uncertainty.

The creep strength data assessment philosophy presented in this section is summarised in Fig. 3.

3.3 Pre-Assessment

Pre-assessment is an important step in the analysis of creep strength data. It involves (a) characterisation of the data in terms of its pedigree, distribution and scatter (random and systematic), and (b) data re-organisation (if deemed necessary by the findings of (a)). In certain CSDAs it includes pre-conditioning/data reduction as routine (eg. App. D1). However, since such steps are method dependent, they are not considered further as part of this section. An important by-product from pre-assessment data distribution analyses is information which could be influential in the planning of future creep testing programmes[10].

The precise boundary between the end of pre-assessment and the start of the main-assessment may be unclear and in certain CSDAs, the final assessment is only performed after a number of iterative steps back into pre-assessment. At least one analysis is usual as part of pre-assessment, in order to characterise the trends and scatter in the data.

Pre-assessment should include:

(i) confirmation that the data meet the material pedigree and testing information requirements recommended in ECCC Recommendations Volume 3 [4],

(ii) confirmation that the material pedigrees of all casts meet the specification set by the instigator(s) of the assessment,

(iii) an evaluation of the distribution of data points with respect to temperature and time (eg. Table A2.1); identifying $t_{p\varepsilon[max]}$, $s_{o[min]}$, and the temperatures for which there are (a) ≥5% test data ($T_{[5\%]}$) and (b) ≥10% test data ($T_{[10\%]}$),

[10] For example, gaps in the data at critical positions in the dataset.

[The $T_{[5\%]}$ and $T_{[10\%]}$ information is needed for the identification of best-tested casts in (iv) and to perform the post assessment tests (Sect. 3.4). Checks for duplicate entries in the dataset should be made at this stage.]

It is acceptable to consider data for temperatures within ±2°C of principal test temperatures to be part of the dataset for that principal test temperature (e.g. test data available for 566°C may be considered together with data for 565°C).

(iv) an analysis of the distribution of casts at each temperature, specifically identifying (a) the main cast, ie. the cast having the most data points at the most temperatures, and (b) the best-tested casts[11],

[The best-tested cast information is required to perform the post assessment tests (eg. PAT 2.2, Sect. 3.4)]

(v) a visual examination of isothermal log s_o versus log t_{pe} plots (containing broken and unbroken data points) and a first assessment to characterise the trends and scatter in the data,

[The first assessment will indicate the presence of metallurgical instabilities, and thereby allow the analyst to take the necessary steps to account for these in the main-assessment. It will also identify excessive scatter, a useful indicator being the presence of data points outside the isothermal mean ±20% lines. Excessive scatter may be due to individual outliers or sub-populations resulting from systematic variations, eg. chemical composition, product form. The cause(s) of excessive scatter should be identified]

(vi) a re-organisation of the data, if the results of the first assessment identify the need.

[As an example, analysis of variance may indicate that there is a product form related sub-population in the data-set. One solution would be to make the material specification more specific in terms of product form, with the consequence that certain data would have to be removed from the original data set]

The reason(s) for excluding any individual data points which are acceptable in terms of *(i)* and *(ii)* above, should be fully documented. In practice, it should not usually be necessary to remove data meeting the requirements of ECCC Recommendations Volume 3, providing the material specification is realistic.

3.4 Post Assessment Acceptability Criteria

The CSDA post assessment acceptability criteria fall into three main categories, evaluating:

- the physical realism of the predicted isothermal lines,
- the effectiveness of the model prediction within the range of the input data, and
- the repeatability and stability of the extrapolations[12].

These are investigated in the following post assessment tests[13].

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[11] As a guide, best-tested casts are those for which there are ≥5 broken testpiece data points at each of at least three $T_{[5\%]}$ temperatures (with ≥2/temperature having rupture durations >10,000h). A cast which just fails to meet this criterion, may still be regarded as a best-tested cast if there are ≥16 broken testpiece data points total (eg. Tables A2b-5b). For practical reasons, it is recommended that a maximum of 10 best tested casts are selected.

[12] The underlying background to the development of the post assessment tests for CRDA and CSDA is given in Apps. C1,C2

[13] The post assessment tests may be conveniently performed in a spreadsheet such as Excel.

Except where indicated, the PATs are equally applicable to the results of CSDAs (Table 1). Hence, when applying to the output from a CSDA, the user should also perform the tests on the s_o,t_{pe},t_{pe}* data for which specific $R_{pe/t/T}$ strength values are required.

Physical Realism of Predicted Isothermal Lines

PAT-1.1 Visually check the credibility of the fit of the isothermal log s_o versus log t_{pe}* lines to the individual log s_o,log t_{pe} data points over the range of the data (eg. Fig. C1.2.1).

[s_o is the initial applied stress, t_{pe} is the observed time to rupture (specified total plastic strain) and t_{pe} is predicted time to specified total plastic strain[1]]*

PAT-1.2 Produce isothermal curves of log s_o versus log t_{pe}* at 25°C intervals from 25°C below the minimum test temperature, to 25°C above the maximum application temperature[14] (eg. Fig. C1.2.2a).

For times between 10 and 10.$t_{pe[max]}$ for CSDA and stresses ≥0.8.$s_{o[min]}$, predicted isothermal lines must not (a) cross-over, (b) come-together, or (c) turn-back.

[$s_{o[min]}$ is the lowest stress to rupture (or specified total plastic strain) in the assessed data set]

PAT-1.3 Plot the derivative ∂ log t_{pe}*/∂ log s_o as a function of log s_o with respect to temperature to show whether the predicted isothermal lines fall away too quickly at low stresses (ie. σ_o ≥0.8 $s_{o[min]}$) (eg. Fig. C1.2.2b).

The values of -∂ log t_{pe}*/∂ log s_o, ie. $n_{p\varepsilon}$ in $t_{p\varepsilon}^* \propto s_o^{n_{pe}}$, should not be ≤1.5.

It is permissible for n_{pe} to enter the range 1.0-1.5 if the assessor can demonstrate that this trend is due to the material exhibiting either sigmoidal behaviour or a creep mechanism for which n = 1, e.g. diffusional flow.

PAT-1.4 PAT-1.4 relates specifically to creep strength data assessments (CSDAs), the objective being to ensure consistency between specific creep strength and rupture strength predictions.

Plot $R_{pe/t/T}$ versus $R_{u/t/T}$ for each specified $R_{pe/t/T}$ strength level for t_{pe} out to 3.$t_{pe[max]}$, for $T_{max[10\%]}$, T_{main} and $T_{min[10\%]}$. Construct a best fit quadratic line (with intercept equal to zero) through the data for each R_{pe} strength level.

Individual $R_{pe/t/T}$ versus $R_{u/t/T}$ lines should have a correlation coefficient of R^2 ≥0.98 and lie as a consistent family of curves (e.g. Fig. C2.3).

Effectiveness of Model Prediction within Range of Input Data

PAT-2.1 To assess the effectiveness of the model to represent the behaviour of the complete dataset, plot predicted time versus observed time for all input data (eg. Fig. C1.2.4).

The log t_{pe}* versus log t_{pe} diagram should show:

- the log t_{pe}* = log t_{pe} line (ie. the ideal line),
- the log t_{pe}* = log t_{pe} ± 2.5.$s_{[A-RLT]}$ boundary lines[3,4],
- the log t_{pe}* = log t_{pe} ± log 2 boundary lines[5],and

[14] The maximum temperature for which predicted strength values are required

- the linear mean line fit through the log t_{pe}*,log t_{pe} data points between t_{pe} = 100h and t_{pe} = 3.$t_{pe[max]}$.

The model equation should be re-assessed:

(a) if more than 3% of the log t_{pe}*,log t_{pe} data points fall outside one of the ±2.5 $s_{[A\text{-}RLT]}$ boundary lines,[15]

(b) if the slope of the mean line is less than 0.78 or greater than 1.22[16], and

(c) if the mean line is not contained within the ±log 2 boundary lines between t_{pe} = 100h and t_{pe} = 3.$t_{pe[max]}$.[17]

It may also be informative to plot standardised residual log times for all input data (ie. A-SRLTs[18]) as a function of (i) log t_{pe}, (ii) log t_{pe}*, (iii) temperature and (iv) log s_o (eg. Fig. C1.2.3).

PAT-2.2 To assess the effectiveness of the model to represent the behaviour of individual casts, plot at temperatures for which there are ≥10% data points (at least at $T_{min[10\%]}$, T_{main} and $T_{max[10\%]}$):

(i) log s_o versus log t_{pe} with log s_o versus log t_{pe}*, and

(ii) log t_{pe}* versus log t_{pe}, with:

- the log t_{pe}* = log t_{pe} line (ie. the ideal line),
- the log t_{pe}* = log t_{pe} ± 2.5.$s_{[I\text{-}RLT]}$ boundary lines[19]
- the log t_{pe}* = log t_{pe} ± log 2 boundary lines**Error! Bookmark not defined.**,and
- the linear mean line fit through the log t_{pe}*,log t_{pe} data points between $t_{pe[max]/T}$/1000 and $t_{pe[max]/T}$.

and identify the best-tested individual cast(s)[20] (eg. Figs. C1.2.5, C1.2.6).

(a) Log t_{pe}* versus log t_{pe} plots for individual casts should have slopes close to unity and be contained within the ±2.5.$s_{[I\text{-}RLT]}$ boundary lines. The pedigree of casts with ∂(log t_{pe}*)/∂(log t_{pe}) slopes ≤0.5 or ≥1.5 and/or which have a significant

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15 Experience suggests that the ±2.5.$s_{[A\text{-}RLT]}$ boundary lines typically intersect the t_u=100h grid line at t_u*≤1,000h and t_u*≥10h respectively (App. C1 in Part Ia). The explanation for those which do not is either an imbalance in the model fit (and hence the PAT-2.1a criteria) or excessive variability in the dataset (e.g. as in the Type 304 18Cr11Ni working dataset, Fig. C1.4.3 in Part Ia). In the latter case, consideration should be given to the scope of the material specification (in conjunction with the assessment instigator, eg WG3x). It is recommended that the same criterion is adopted for CSDA.

16 If the requirements of PAT-2.1b and PAT-2.2b are not satisified at only 1 of the 3 temperatures, it is permissible to repeat the test, determining the mean line slope through those data points between t_u=$t_{u[max]}$/100 and t_u=$t_{u[max]}$. This option is only potentially useful when $t_{u[max]}$ is of the order of >100,000h. The same practice may also be useful for CSDA.

17 Ideally, the mean line will lie within the ±log 2 boundary lines at t_{pe} = 3.$t_{pe[max]}$.

18 A-SRLT is residual log time (log t_{pe} - log t_{pe}*) divided by the standard deviation for all residuals at all temperatures, ie. A-SRLT = {(log t_{pe} - log t_{pe}*)}/$s_{[A\text{-}RLT]}$

19 $s_{[I\text{-}RLT]}$ is the standard deviation for the n_I residual log times at the temperature of interest, i.e. $s_{[I\text{-}RLT]} = \sqrt{\{\sum_j (\log t_{pe\,j} - \log t_{pe}*_j)^2/(n_I - 1)\}}$, where j = 1,2, ... n_I.

20 The best-tested casts are identified as part of pre-assessment, eg. Tables A2b-A5b (see Sect. 3.3(iv)).

number of $\log t_{pe}^*, \log t_{pe}$ data points outside the $\pm 2.5.s_{[I\text{-}RLT]}$ boundary lines should be re-investigated.

If the material and testing pedigrees of the data satisfy the requirements of reference 4 and the specification set by the assessment instigator (eg. WG3.x) [as recommended in Sects. 3.3(i),(ii)], the assessor should first consider with the instigator whether the scope of the alloy specification is too wide. If there is no metallurgical justification for modifying the alloy specification, the effectiveness of the model to predict individual cast behaviour should be questioned.

The distribution of $\log t_{pe}^*, \log t_{pe}$ data points about the $\log t_{pe}^* = \log t_{pe}$ line reflects the homogeneity of the dataset and the effectiveness of the predictive capability of the model (eg. Figs. C1.2.6). Non-uniform distributions at key temperatures should be taken as a strong indication that the model does not effectively represent the specified material within the range of the data, in particular at longer times.

The model equation should be re-evaluated if at any temperature:

(b) the slope of the mean line through the isothermal $\log t_{pe}^*, \log t_{pe}$ data points is less than 0.78 or greater than 1.22[16], and

(c) the mean line is not contained within the $\pm\log 2$ boundary lines between $t_{pe[max]/T}/1000$ and $t_{pe[max]/T}$[17].

Repeatability and Stability of Extrapolations

PAT-3.1 and PAT-3.2 represent the most practical solution to the problem of evaluating the reliability of assessed strength values predicted by extrapolation. In reality, the only sure way to check extrapolation reliability is to perform long term tests. The culling tests simulate this situation by removing information from the long term data regime and checking extrapolation reliability and stability by re-assessment of the reduced data sets.

PAT-3.1 Randomly cull 50% of data between $t_{pe[max]}/10$ and $t_{pe[max]}$ and repeat the assessment to check the repeatability of the extrapolation to variations in the data set (eg. Fig. C1.2.7).

If the CSDA $R_{pe/300kh}$) strength predictions determined at $T_{min[10\%]}$, T_{main} and $T_{max[10\%]}$ are not reproduced to within 10%, PAT-3.1 may be repeated. However, if the acceptability criterion is not met after the second cull, the main assessment should be repeated using a different model equation or procedure.

If the maximum test duration is less than 100,000h, the predicted strength comparison should be made for a test duration of $3.t_{pe[max]}$, i.e. with $R_{pe/3.t_{pe[max]}}$ strength values.

PAT-3.2 Cull 10% of the data set by removing the lowest stress data points from each of the main test temperatures (ie. 10% from each) and repeat the assessment to check the sensitivity and stability of the extrapolation procedure (eg. Fig. C1.2.7).

If the CSDA $R_{pe/300kh}$ strength predictions determined at $T_{min[10\%]}$, T_{main} and $T_{max[10\%]}$ are not reproduced to within 10%, the main assessment should be repeated using a different model or procedure.

If the maximum test duration is less than 100,000h, the predicted strength comparison should be made for a test duration of $3.t_{pe[max]}$ (ie. with $R_{pe/3.tpe[max]}$ strength values).

Meeting the requirements of PAT-3.2 is not mandatory in circumstances where it can be shown that the material is metallurgically unstable and that the removal of low stress values at temperatures up to 50°C above the maximum application temperature[14] prevent this mechanism change from being represented by the reduced dataset.

The post assessment acceptability criteria to be satisfied for creep rupture and creep strength data assessment are compared in Table 1.

4. SUMMARY

ECCC-WG1 Volume 5 Part IIb provides guidance for the assessment of creep rupture data sets. The principal aim is to minimise the uncertainty associated with strength predictions by recommending pre-assessment, the implementation of post assessment acceptability criteria, the use of well documented CSDA procedures and the performance of duplicate assessments.

Implementation of the ECCC recommendations require significant additional effort on completion of the first main assessment. However, this is regarded as entirely justified by the demonstrated reduction in the level of uncertainty associated with predicted strength values, in particular those involving extrapolation beyond the range of the available experimental data.

Quantification of the uncertainties associated with extrapolated strength values and those involving extended extrapolations should be a goal for the future.

5. REFERENCES

1 ECCC Recommendations Volume 2 Part I, 2001, 'General terms and terminology and items specific to parent material', ECCC Document 5524/MC/23 [Issue 7], eds: Morris, P.F. & Orr, J., May-2001.
2 ECCC Recommendations Volume 5, 2001, 'Guidance for the assessment of creep rupture, creep strain and stress relaxation data', ed. Holdsworth, S.R. & Merckling, G., publ. ERA Technology Ltd, Leatherhead, (a) Part I 'Generic recommendations and guidance for full-size datasets', (b) Part IIa 'Recommendations for the assessment of sub-size creep-rupture data', (c) Part IIb 'Recommendations for the assessment of weld creep-rupture datasets', (d) Part III 'Recommendations for the assessment of post exposure (ex-service) creep data'.
3 PD6525:Part 1:1990; 'Elevated temperature properties for steels for pressure purposes; Part 1 - Stress rupture properties', [Issue 2], Feb-1994.
4 ECCC Recommendations Volume 3 Part I, 2001, 'Data acceptability criteria and data generation: Generic recommendations for creep, creep-rupture, stress-rupture and stress relaxation data', ECCC Document 5524/MC/30 [Issue 5], eds: Granacher, J. & Holdsworth, S.R., May-2001.

Table 1 Summary of Post Assessment Acceptability Criteria to be Satisfied for Creep Strength and Creep Rupture Data Assessment

	CRDA	CSDA
Physical Realism		
PAT-1.1	• visual confirmation of acceptability of isothermal assessed line fits to experimental log s_o vs log t_u data	• visual confirmation of acceptability of isothermal assessed line fits to experimental log s_o vs log t_{pe} data
PAT-1.2	• no (a) cross-over, (b) convergence, (c) turn-back between $10 < t_u < 10^6$h and $s \geq 0.8.s_{o[min]}$	• no (a) cross-over, (b) convergence, (c) turn-back between 10h $< t_{pe} < 10\, t_{pe[max]}$ and $s \geq 0.8.s_{o[min]}$
PAT-1.3	• $-\partial(\log t_u)/\partial(\log s_o) \geq 1.5$	• $-\partial(\log t_{pe})/\partial(\log s_o) \geq 1.5$
PAT-1.4	• not applicable	• confirmation of self consistency of $R_{pe/t/T}$ versus $R_{u/t/T}$ plots
Effectiveness of Model Prediction within Range of Input Data [Total]		
PAT-2.1(a)	• ≤1.5% data points fall outside a log $t_u^* = \log t_u \pm 2.5.s_{[A\text{-}RLT]}$ boundary line in total-data log t_u^* vs log t_u diagram	• ≤3.0% data points fall outside a log $t_{pe}^* = \log t_{pe} \pm 2.5.s_{[A\text{-}RLT]}$ boundary line in total-data log t_{pe}^* vs log t_{pe} diagram
PAT-2.1(b)	• slope of mean log t_u^* vs log t_u line is between 0.78 and 1.22	• slope of mean log t_{pe}^* vs log t_{pe} line is between 0.78 and 1.22
PAT-2.1(c)	• mean log t_u^* vs log t_u line is contained within log $t_u^* = \log t_u \pm \log 2$ lines for $10^2 \leq t_u \leq 10^5$h	• mean log t_{pe}^* vs log t_{pe} line is within log $t_{pe}^* = \log t_{pe} \pm \log 2$ lines for $0.001.t_{pe[max]/T} \leq t \leq t_{pe[max]/T}$
Effectiveness of Model Prediction within Range of Input Data [Isothermal]		
PAT-2.2(a)	• in isothermal log t_u^* vs log t_u diagrams for T_{max}, T_{main} and T_{min}, individual-cast mean lines have slopes close to unity and data points contained within log $t_u^* = \log t_u \pm 2.5.s_{[I\text{-}RLT]}$ boundary lines	• in isothermal log t_{pe}^* vs log t_{pe} diagrams for T_{max}, T_{main} and T_{min}, individual-cast mean lines have slopes close to unity and data points contained within log $t_{pe}^* = \log t_{pe} \pm 2.5.s_{[I\text{-}RLT]}$ boundary lines
PAT-2.2(b)	• slope of isothermal mean log t_u^* vs log t_u line is between 0.78 and 1.22	• slope of isothermal mean log $t_{p\varepsilon}^*$ vs log $t_{p\varepsilon}$ line is between 0.78 and 1.22
PAT-2.2(c)	• mean log t_u^* vs log t_u line is contained within log $t_u^* = \log t_u \pm \log 2$ lines for $10^2 \leq t_u \leq 10^5$h	• mean log t_u^* vs log t_u line is contained within log $t_u^* = \log t_u \pm \log 2$ lines for 0.001 $t_{pe[max]/T} \leq t \leq t_{pe[max]/T}$
Repeatability and Stability of Extrapolations		
PAT-3.1	• $R_{u/300kh/T}$ values for T_{max}, T_{main} and T_{min}, before and after random cull of 50% data points between $0.1.t_{u[max]}$ and $t_{u[max]}$, are within 10%	• $R_{pe/300kh/T}$ values for T_{max}, T_{main} and T_{min}, before and after random cull of 50% data points between $0.1.t_{u[max]}$ and $t_{u[max]}$, are within 10%
PAT-3.2	• $R_{u/300kh/T}$ values for T_{max}, T_{main} and T_{min}, before and after 10% lowest stress data point cull at all temperatures, are within 10%	• $R_{pe/300kh/T}$ values for T_{max}, T_{main} and T_{min}, before and after 10% lowest stress data point cull at all temperatures, are within 10%

'pe' subscripts (denoting plastic strain) may be substituted by 'fe' subscripts (denoting creep strain) as appropriate

see Sect. 3.4 for details

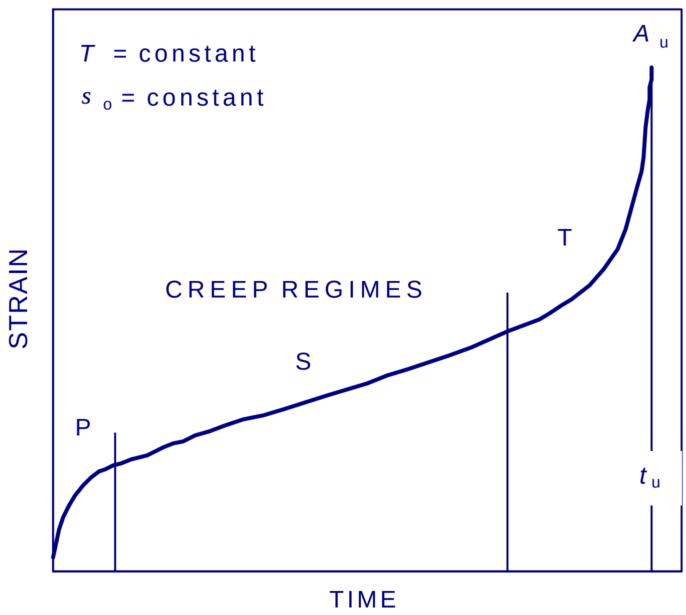


Fig. 1 Schematic diagram showing primary, secondary and tertiary creep regimes

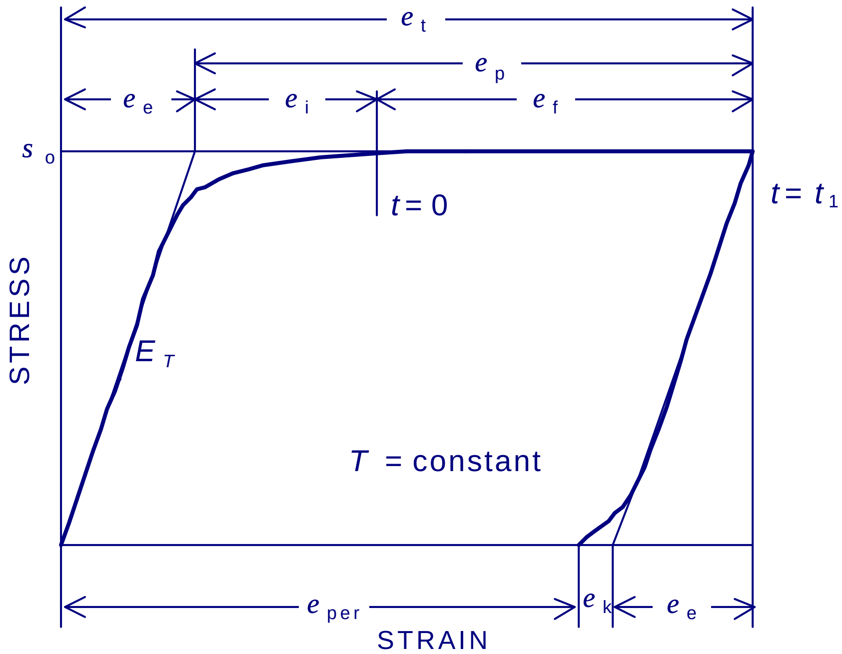
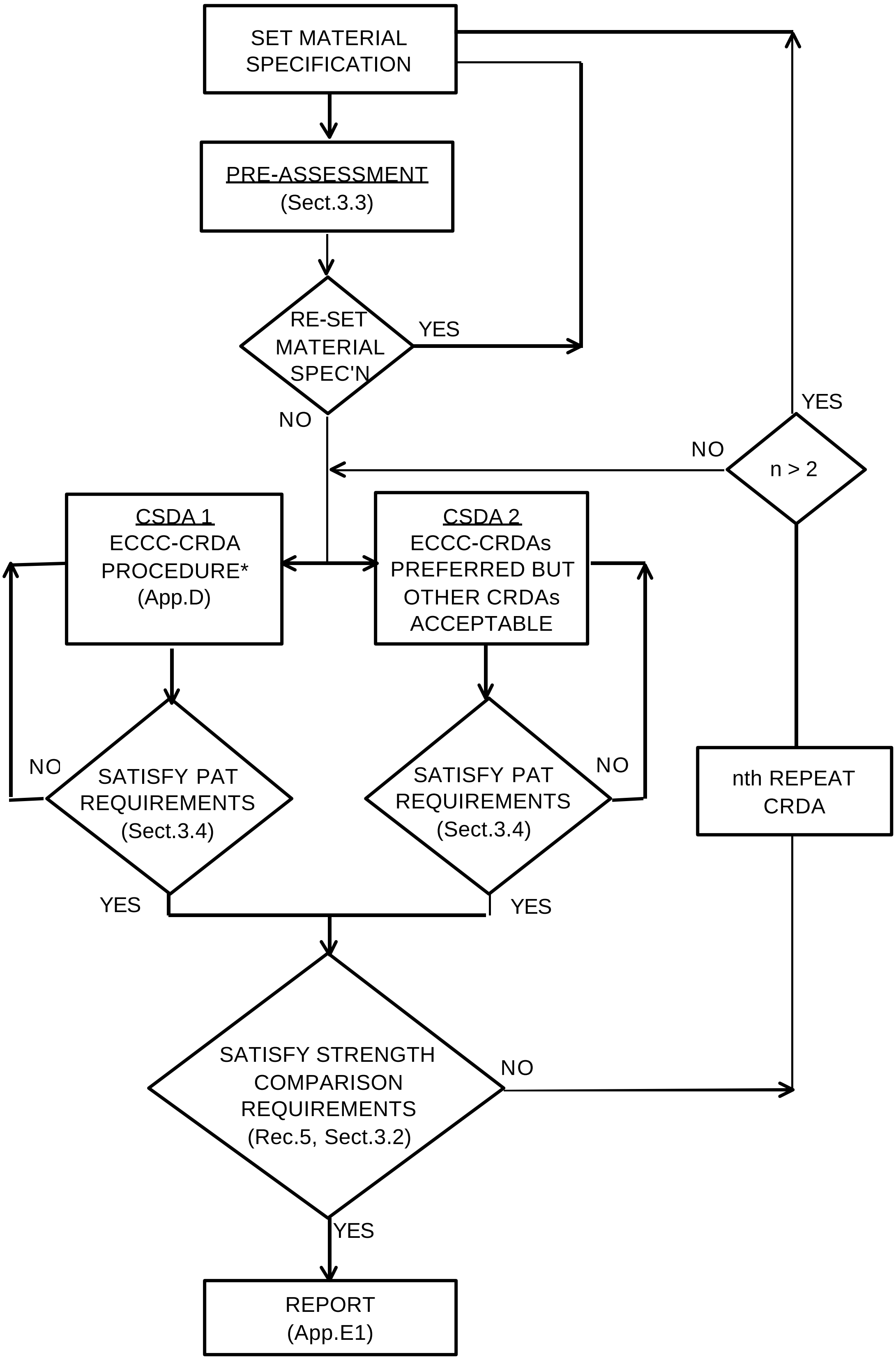


Fig. 2 Schematic diagram showing strains generated during loading of creep test



* an ECCC-CSDA is one for which there is a procedure document (App.D)

Fig. 3 ECCC recommended creep strength data assessment procedure

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APPENDIX A1

WORKING DATA SETS FOR WG1 CREEP STRAIN EVALUATION

S R Holdsworth [ALSTOM Power]

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APPENDIX A1

WORKING DATASET FOR WG1 CREEP STRAIN ASSESSMENT METHOD EVALUATION

S R Holdsworth

The $t_u(T, s_o)$ distribution characteristics of a single cast creep strain dataset for N+T 10CrMo9-10 are shown in Table A1. The constant stress dataset extends to only relatively short rupture durations (<3kh), but is homogeneously distributed as a function of temperature and stress.

There is a full $e_f(t)$ creep strain record for each of the 30 tests identified in Table A1.

Table A1 Distribution of Creep-Rupture Data for N+T 10CrMo9-10 as a function of Temperature and Stress

	IDENTIFICATION (TIME TO RUPTURE, h)				
TEMP, ^{o}C	510	540	565	580	600
STRESS MPa					
280	E34 (137)				
270	E29 (316)				
260	E27 (275)				
250		E33 (56)			
240	E12 (577)	E28 (87)			
220	E17 (2112)	E24 (291)	E1 (37)		
205	E8 (2952)	E13 (495)			
200		E31 (714)	E5 (129)		
190				E35 (69)	
180		E7 (1586)	E2 (301)		
175			E11 (435)	E26 (73)	E36 (69)
160			E10 (824)	E14 (246)	E19 (129)
155				E32 (480)	
145			E4 (1895)	E6 (881)	E18 (367)
140					E15 (319)
135				E20 (2327)	
130					E21 (551)
120					E9 (654)

Constant stress tests

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APPENDIX A2

WORKING DATA SET FOR WG1 CSDA METHOD EVALUATION

S R Holdsworth [ALSTOM Power]

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APPENDIX A2

WORKING DATA SET FOR WG1 CSDA METHOD EVALUATION

S R Holdsworth [ALSTOM Power]

The guidelines given in the main text of ECCC-WG1 Volume 5 for the assessment of creep strength data (CSDA) are based on the comprehensive evaluation of a large multi-cast, multi-temperature working data set for normalised and tempered 2¼CrMo collated by IfW TH Darmstadt. The information supplied had already formed the basis of an extensive assessment activity [A2.1].

The data set comprises interrupted strain measurement (ISM) results from 217 tests performed at temperatures in the range 450 to 600°C. It includes data from 8 casts having compositions consistent with the specification defined for the N+T 2¼CrMo steel in Table A1.1 (App.A1).

The scope of the data is summarised in Tables A2.1. The tests are distributed in a balanced way across the temperature range, with >5% data at each of the six test temperatures and >10% data points at four test temperatures. Maximum rupture times extend out to almost 200,000h, with the majority of tests (74%) having durations of >10,000h. As a consequence, most of the $t_{1\%}$ data are for times of >10,000h and most of the $t_{0.2\%}$ data are for times of >1,000h (Table A2.1a).

The number of tests per cast are summarised in Table A2.2. The dominant cast, D7ZT, has been tested at every temperature with a total of 85 tests.

Reference

A2.1 K H Kloos, J Granacher & M Oehl; "Beschreibung des Zeitdehnverhaltens warmfester Stähle - Teil 1: Kriechgleichungen für Einzelwerkstoffe - Teil 2: Kriechgleichungen für die Stahlsorten 10 CrMo 9 10 und X20(22) CrMoV 12 1", Mat. -wiss. u. Werkstofftech, 1993, 24, 287-295 (Teil 1), 331-338 (Teil 2).

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TABLE A2.1 DISTRIBUTION OF CREEP RUPTURE DATA FOR N+T 2.25CrMo AS A FUNCTION OF TEMPERATURE AND TIME

TEMP °C	TOTAL DATA		TIME TO RUPTURE, h															TOTAL	% OF TOTAL
			<10kh		10-20kh		20-30kh		30-50kh		50-70kh		70-100kh		>100kh		$t_{r[max]}$		
	B	UB	B	UB	B	UB	B	UB	B	UB	B	UB	B	UB	B	UB	A		
450	16	3	12		1	1	2		1			2					37,750	19	9
500	52	11	36		4	1	2	1	5	5		2	2	1	3	1	198,700	63	28
525	11	1	10		1									1			79,970	12	6
550	54	7	38	1	4		2		6	2	1	2			3	2	193,600	61	29
575	27	4	19		1	1	3	2	2	1			1		1		131,700	31	15
600	25	6	21	3	2	1			1	1	1	1					62,960	31	14
TOTALS	185	32	136															217	100

TEMP °C	TOTAL DATA		TIME TO 1% PLASTIC STRAIN[1], h															TOTAL	% OF TOTAL
			<10kh		10-20kh		20-30kh		30-50kh		50-70kh		70-100kh		>100kh		$t_{1\%[max]}$		
	A	NA	A	NA	A	NA	A	NA	A	NA	A	NA	A	NA	A	NA	A		
450	16	2	13	1	1		2					1					26,300	18	8
500	60	1	45		6		2		4	1	1		2				99,280	61	29
525	12	0	11						1								44,400	12	6
550	59	1	49		3		2		4		1	1					59,930	60	29
575	29	1	25		1		2	1	1								30,700	30	14
600	28	1	25		2				1	1							40,500	29	14
TOTALS	204	6	168															210	100

TEMP °C	TOTAL DATA		TIME TO 0.2% PLASTIC STRAIN[1], h															TOTAL	% OF TOTAL
			<1kh		1-2kh		2-3kh		3-5kh		5-7kh		7-10kh		>10kh		$t_{0.2\%[max]}$		
	A	NA	A	NA	A	NA	A	NA	A	NA	A	NA	A	NA	A	NA	A		
450	18	0	13						2				1		2		11,300	18	9
500	60	1	46		3		3	1	3		2		1		2		17,300	61	29
525	12	0	11						1								3,400	12	6
550	58	1	49		5				3		1					1	5,800	59	28
575	28	0	24		2				1		1						5,700	28	14
600	29	0	27				1								1		2,100	29	14
TOTALS	205	2	170															207	100

8 casts

% of points > 10%

[1] times to 0.2 and 1% plastic strains determined by linear interpolation between adjacent [log ε_p,log t] co-ordinates

TABLE A2.2 BEST TESTED CAST ANALYSIS FOR CREEP STRENGTH WORKING DATASET FOR N+T 2.25CrMo

CASTS	TEMPERATURE, °C						TOTALS
	450	**500**	**525**	**550**	**575**	**600**	
D7GA		5		5			10
D7HA		5		5			10
D7ZT	**9**	**19**	**12**	**15**	**14**	**16**	**85**
D7R	5	11		15		9	40
D7U	4	6		6	6		22
D7S		5		6		6	17
D7P		5		3	3		11
D7K		7		7	8		22

APPENDIX B1

REVIEW OF CREEP STRAIN EQUATIONS

S R Holdsworth [ALSTOM Power] and M Schwienheer [IfW TU Darmstadt]

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APPENDIX B1

REVIEW OF CREEP STRAIN EQUATIONS

S R Holdsworth & M Schwienheer

A first WG1 evaluation of creep strain analysis methods involved a review and examination of model equations in common use for representing creep deformation data and an assessment of their effectiveness for various materials and practical applications.

Creep strain $\varepsilon_f(t)$ or $e_{per}(t)$ curves are determined from the results of continuous-measurement or interrupted tests involving the application of a constant load (or stress) to a uniaxial testpiece held at constant temperature (Fig. B 1). In continuous-measurement tests, the creep strain, e_f, is monitored without interruption by means of an extensometer attached to the gauge length of the testpiece. In interrupted tests, the permanent strain, e_{per}, is measured optically at room temperature during planned interruptions ($e_{per} = e_i + e_f - e_k$, Fig. B 2).

It is recognised that many different model equations are used to represent creep strain behaviour, ranging from simple-phenomenological to complex-constitutive. A number of model equations commonly used to represent creep strain development in engineering steels are listed at the end of this appendix. The listing is not exhaustive and simply reflects those expressions most commonly used by organisations currently active in ECCC. Similar creep model equation forms are grouped together in Table1. For example, the Garofalo, BJF and Theta expressions (Eqns. *v)-ix)*) share a similar representation of primary creep.

Certain expressions are likely to be better suited for specific materials and analytical applications. For example, the overall primary (P), secondary (S) and tertiary (T) creep strain characteristics of a particular steel (Fig. B 1) may not be acceptably modelled by certain creep equation forms. Moreover, some practical applications only require a knowledge of primary low strain creep behaviour whereas others need a representation of the full creep curve.

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Table 1 Range of Application of Reviewed Creep Equations

MODEL EQUATION	EQN REF	RANGE OF APPLICATION	
		REGIME	MATERIALS
Norton [1]	*i)*	S	low/high alloy ferritic & austenitic steels, Ni-base alloys, non-ferrous alloys
Mod-Norton	*ii)*	S	Ni-base alloys
Norton-Bailey	*iii)*	P/S	low/high alloy ferritic & austenitc steels
RCC-MR [2]	*iv)*	P/S	low alloy ferritic steels & austentic steels
Bartsch [3]	*v)*	P/S	low/high alloy ferritic, austenitic steels
Garofalo [4]	*vi)*	P/S	low/high alloy ferritic & austenitic steels, Ni-base alloys, non-ferrous alloys
Mod-Garofalo [5]	*vii)*	P/S/T	low/high alloy ferritic steels, Ni-base alloys
BJF [6]	*viii)*	P/S	high alloy ferritic steels
Theta [7]	*ix)*	P/S/T	low/high alloy ferritic & austenitic steels, Ni-base alloys, non-ferrous alloys
Mod-Theta	*x)*	P/S/T	low/high alloy ferritic, austenitic steels, Al-alloys, Al-matrix composites
Graham-Walles [8]	*xi)*	P/S/T	*to be advised*
Classical strain hardening	*xii)*	S/T	*to be advised*
Rabotnov-Kachanov [9]	*xiii)*	P/S/T	low alloy ferritic steels
Baker-Cane [10]	*xiv)*	P/S/T	low alloy ferritic steels
Dyson-McLean [11]	*xv)*	P/S/T	low alloy ferritic steels, Ni-base alloys
I.Mech.E [12]	*xvi)*	P/S	CMn, low/high alloy ferritic & austenitic steels
Bolton [13]	*xvii)*	P/S/T	low/high alloy ferritic & austenitic steels
Omega [14]	*xviii)*	S/T	low/high alloy ferritic steels

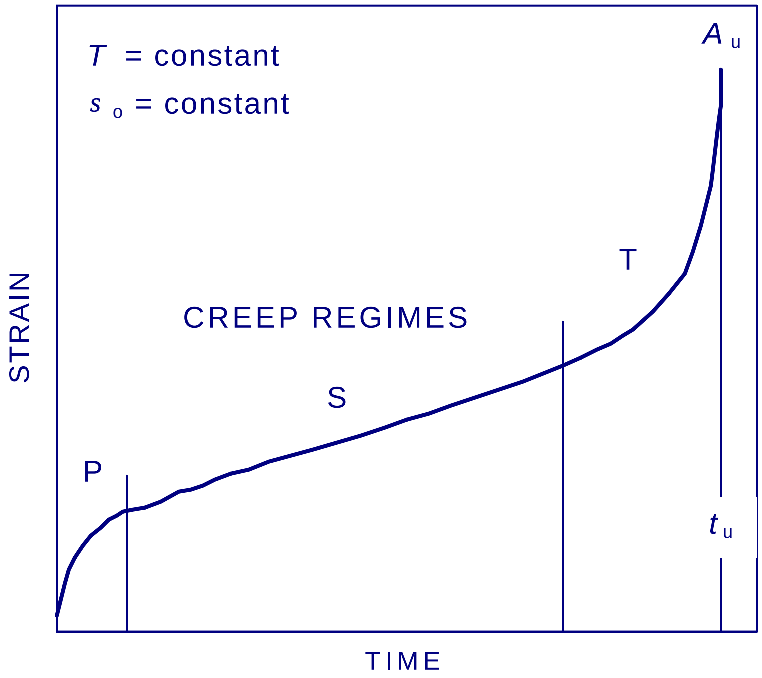

Fig. B 1 Schematic diagram showing primary, secondary and tertiary creep regimes

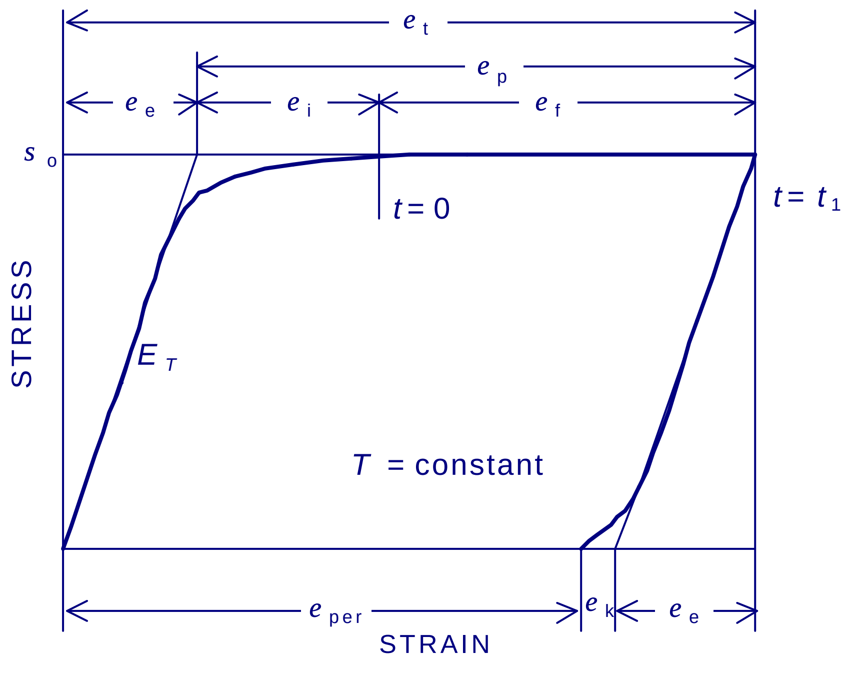

Fig. B 2 Schematic diagram showing strains generated during loading of creep test

CREEP STRAIN EQUATIONS

i) Norton [1] $\dot{e}_{\mathrm{f,min}} = a_1.\exp(Q/R.T).s^{n}$

ii) Modified Norton

$$\dot{e}_{\mathrm{f,min}} = b_1.\exp(Q_{\mathrm{B}}/R.T).s^{n} + c_1.\exp(Q_{\mathrm{C}}/R.T).s^{n}$$

iii) Norton-Bailey $e_{\mathrm{f}} = d_1.s^{n}.t^{p}$

iv) RCC-MR [2]

$$e_{\mathrm{f}} = C_1.s^{n_1}.t^{C_2} \qquad t \le t_{\mathrm{fp}}$$

$$e_{\mathrm{f}} = C_1.s^{n_1}.t_{\mathrm{fp}}^{C_2} + 100.C.s^{n}.(t - t_{\mathrm{fp}}) \qquad t > t_{\mathrm{fp}}$$

where C, C_1, C_2, n, n_1 = f(T) and t_{fp} = f(s,T)

v) Bartsch [3]

$$e_{\mathrm{f}} = e_1.\exp(Q_1/R.T).s.\exp(b_1.s).t^{p} + e_2.\exp(Q_2/R.T).s.\exp(b_2.s).t$$

vi) Garofalo [4] $e_{\mathrm{f}} = e_{t}.[1 - \exp(-b_1.t)] + \dot{e}_{\mathrm{f,min}}.t$

vii) Modified Garofalo [5]

$$e_{\mathrm{f}} = e_{\mathrm{f1,max}}.\left[1 - \exp\left(-D.(t/t_{12})^{u}\right)\right] + \dot{e}_{\mathrm{f,min}}.t + c_{23}.(t/t_{23})^{f}$$

or

$$e_{\mathrm{per}} = e_{i} + e_{\mathrm{f1,max}}.\left[1 - \exp\left(-D.(t/t_{12})^{u}\right)\right] + \dot{e}_{\mathrm{f,min}}.t + c_{23}.(t/t_{23})^{f}$$

viii) BJF [6]

$$e_{\mathrm{f}} = n_1.[1 - \exp(-\underline{t})]^{b} + n_2.\underline{t}$$

where $\underline{t} = (s/A_1)^{n}.\exp(-Q/R.T)$

ix) Theta [7]

$$e_{\mathrm{f}} = q_1.[1 - \exp(-q_2.t)] + q_3.[\exp(q_4.t) - 1]$$

where $\log(q_i) = a_i + b_i.T + c_i.s + d_i.s.T$

x) Modified Theta

$$e_{\mathrm{f}} = q_1.[1 - \exp(-q_2.t)] + q_{\mathrm{m}}.t + q_3.[\exp(q_4.t) - 1]$$

where $q_{\mathrm{m}} = A.s^{n}.\exp(-Q/R.T)$

xi) Graham-Walles [8]

$$e_{\mathrm{f}} = a_1.t^{1/3} + a_2.t + a_3.t^{3}$$

$$\dot{e}_{\mathrm{f}} = \sum_1^3 A_i.\exp(-K_i/T).s^{n_i}.e^{n_i}$$

xii) Classical Strain Hardening

$$\dot{e}_{\mathrm{f}} = A.\exp(-K/T).e^{-s}.\left(\frac{s}{s_{\mathrm{o}}}\right)^{r} \qquad s = s_{\mathrm{o}}.\exp(w.e)$$

where

$$s = a_1 + b_1.T + c_1.s + d_1.s.T$$

$$r = a_2 + b_2.T + c_2.s + d_2.s.T$$

$$w = a_3 + b_3.T + c_3.s + d_3.s.T$$

xiii) Rabotnov-Kachanov [9]

$$\dot{e}_{\mathrm{f}} = \frac{h_1.s^{n}}{(1-w)} \quad \dot{w} = \frac{k_1.s^{n}}{(1-w)^{z}}$$

xiv) Baker-Cane [10]

$$e_{\mathrm{f}} = A.t^{m} + e_{\mathrm{P}} + f.e_{\mathrm{S}} + e_{\mathrm{S}}.(l - f).\left[1 - \left\{\frac{t/t_{\mathrm{u}} - f}{1-f}\right\}\right]^{\frac{1-f}{l-f}}$$

where $l = e_{\mathrm{u}}/e_{\mathrm{S}}$, $e_{\mathrm{S}} = \dot{e}_{\mathrm{m}}.t_{\mathrm{u}}$ and $f = t_{\mathrm{P}}/t_{\mathrm{u}}$

xv) Dyson-McClean [11]

$$\dot{e}_{\mathrm{f}} = \dot{e}'_{\mathrm{o}}.(1+D_{\mathrm{d}}).\exp(Q/R.T).\sinh\left(\frac{s.(1-H)}{s_{\mathrm{o}}.(1-D_{\mathrm{p}}).(1-w)}\right)$$

xvi) IMechE [12]

$$R_{\mathrm{u}/t/T} = \left(a_1 + b_1/e_{\mathrm{f}} - c_1.e_{\mathrm{f}}^{\,2}\right)R_{e/t/T} + d_1 + e_1/e_{\mathrm{f}} + f_1/e_{\mathrm{f}}^{\,2} - g_1.e_{\mathrm{f}}^{\,2}$$

xvii) Bolton [13]

$$e_{\mathrm{f}}(s) = e.\left(R_{\mathrm{u}/t/T}/R_{e/t/\mathrm{T}} - 1\right)/\left(R_{\mathrm{u}/t/T}/s - 1\right)$$

xviii) Omega [14]

$$\dot{e}_{\mathrm{f}} = \dot{e}_{\mathrm{f,min}}/\left(1-\dot{e}_{\mathrm{f,min}}.\Omega.t\right)$$

APPENDIX C1

CREEP STRAIN DATA ASSESSMENT: INTER-COMPARISON OF 10CrMo9-10 DATASET

S R Holdsworth [ALSTOM Power]

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APPENDIX C1

CREEP STRAIN DATA ASSESSMENT: INTER-COMPARISON OF 10CrMo9-10 DATASET

S R Holdsworth

INTRODUCTION

The first WG1 evaluation of creep strain analysis methods involved a review and evaluation of model equations in common use for representing creep deformation data (App. B1). This was followed by an evaluation of the effectiveness of several of the models to represent the deformation characteristics of a small, constant stress dataset for a single cast of N+T 10CrMo9-10 steel (App. A1) in a creep strain assessment inter-comparison. The results of this inter-comparison are summarised in the following appendix.

ASSESSMENT INTER-COMPARISON

The dataset was assessed by 9 analysts [1-9] using 11 model equations (Table C1). Details of the model equations and source references are given in Appendix B1. In all assessments, the selected model equation was first fitted to all of the individual $e_p(t)$ creep strain records (i.e. a total of 30 for this dataset, App.A1). Optimising the curve fitting process was clearly important. For example, the assessment performed by IfWD involved meticulous pre-processing of the test records in the primary, secondary and tertiary regimes prior to final curve fitting [1]. It will be seen below that the modified Garofalo equation employed in the IfWD assessment provided the best overall representation of the creep curves in this 10CrMo9-10 dataset (Table C1). This result should be viewed as not just being a result of the model equation used, but also a consequence of the curve fitting procedure applied. In a similar way, the Innogy assessment involving curve fitting using the Theta equation clearly demonstrated the benefit of independently minimising residual errors during curve fitting the primary/secondary and secondary/tertiary regimes [5].

The results of individual $e_p(t)$ curve-fits were then combined to provide the parameters for the $e_p(t,T,s_o)$ master-equation. The effectiveness of the respective master-equations to represent observed $e_p(t)$ behaviour was examined by graphical comparison (e.g. Fig. C 1 - Fig. C 5), and in the following way. Plastic strains of 0.2 and 1.0% were selected to represent typical low and high strain industry requirements. For each assessment, plots of $\log(t_{pe/s/T}{}^*)$ versus $\log(t_{pe/s/T})$ for the two strain levels were constructed with reference to the following relationships:

$$\log t_{pe/s/T}{}^* = \log t_{pe/s/T} \pm \log 2 \qquad (1)$$

$$\log t_{pe/s/T}{}^* = \log t_{pe/s/T} \pm 2.5.s_{A\text{-}RLT} = \log t_{pe/s/T} \pm \log Z \qquad (2)$$

where for a normal distribution, almost 99% of the observed times to specific strain values would be expected to lie within the boundary lines defined by Eqn. 2.

A perfect prediction of $t_{pe/s/T}$ by the master-equation is represented by the Z parameter being equal to zero. Ideally Z was ≤2, such that the broken lines in Fig. C 6 to Fig. C 13 fell on top of (or within) the dotted lines defined by Eqn. 1. Z values of >4 were regarded as unacceptable, whereas values of ≤3-4 were marginal and regarded as practically acceptable. The Z values determined in the present inter-comparison are summarised in Table C1.

The effectiveness of the evaluated models to predict $t_{pe/S/T}$ by means of the master equation varied with specific strain value for the 10CrMo9-10*(c)* dataset. For example, the Theta expression is most effective at predicting times to 1% strain and less so for times to 0.2% strain (Fig. C 9). The modified-Garofalo model is particularly effective for predicting times to low and high strains, according to this study (Table C1, Fig. C 7), although it should be acknowledged that the adopted analysis approach involved an intensive prior individual $e_p(t)$ curve fitting procedure. It is of little surprise that the *Z* values for the Omega model predictions of times to the selected strains are poor (Table C1) since this expression was developed to represent tertiary creep behaviour, i.e. for e_p>1%.

CONCLUDING REMARKS

There are several model equations available for characterising the primary, secondary and tertiary creep deformation characteristics of engineering materials, ranging in complexity from simple-phenomenological to full-constitutive. The suitability of some of these have been examined with respect to a relatively small dataset for N+T 10CrMo9-10 steel. The following observations are noted.

In those creep strain assessment procedures involving prior individual $e(t)$ curve-fitting, best results are obtained by optimising the procedure adopted to fit specific model equations to the deformation characteristics of the material under investigation.

A method of qualifying the effectiveness of a creep strain equation for specific material types and analytical applications is introduced.

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Table C1 Summary of results of 10CrMo9-10 creep strain data assessment inter-comparison

MODEL EQUATION	EQN. REF. (App. B1)	ANALYST REF.	CREEP RANGE	Z	
				$t_{0.2\%/S/T}$	$t_{1.0\%/S/T}$
Bartsch	*v)*	[3]	P/S	3	4
Mod-Garofalo	*vii)*	[1]	P/S/T	2	2
BJF	*viii)*	[6]	P/S	15	4
Theta	*ix)*	[5]	P/S/T	17	2
Mod-Theta	*x)*	[4]	P/S/T	10	4
Graham -Walles	*xi)*	[9]	P/S/T		
Classical strain hardening	*xii)*	[7]	S/T		
Baker-Cane	*xiv)*	[8]	P/S/T	5	2
Dyson-McLean	*xv)*	[5]	P/S/T	12	3
Bolton	*xvii)*	[3]	P/S/T	4	13
Omega	*xviii)*	[2]	S/T	468	10

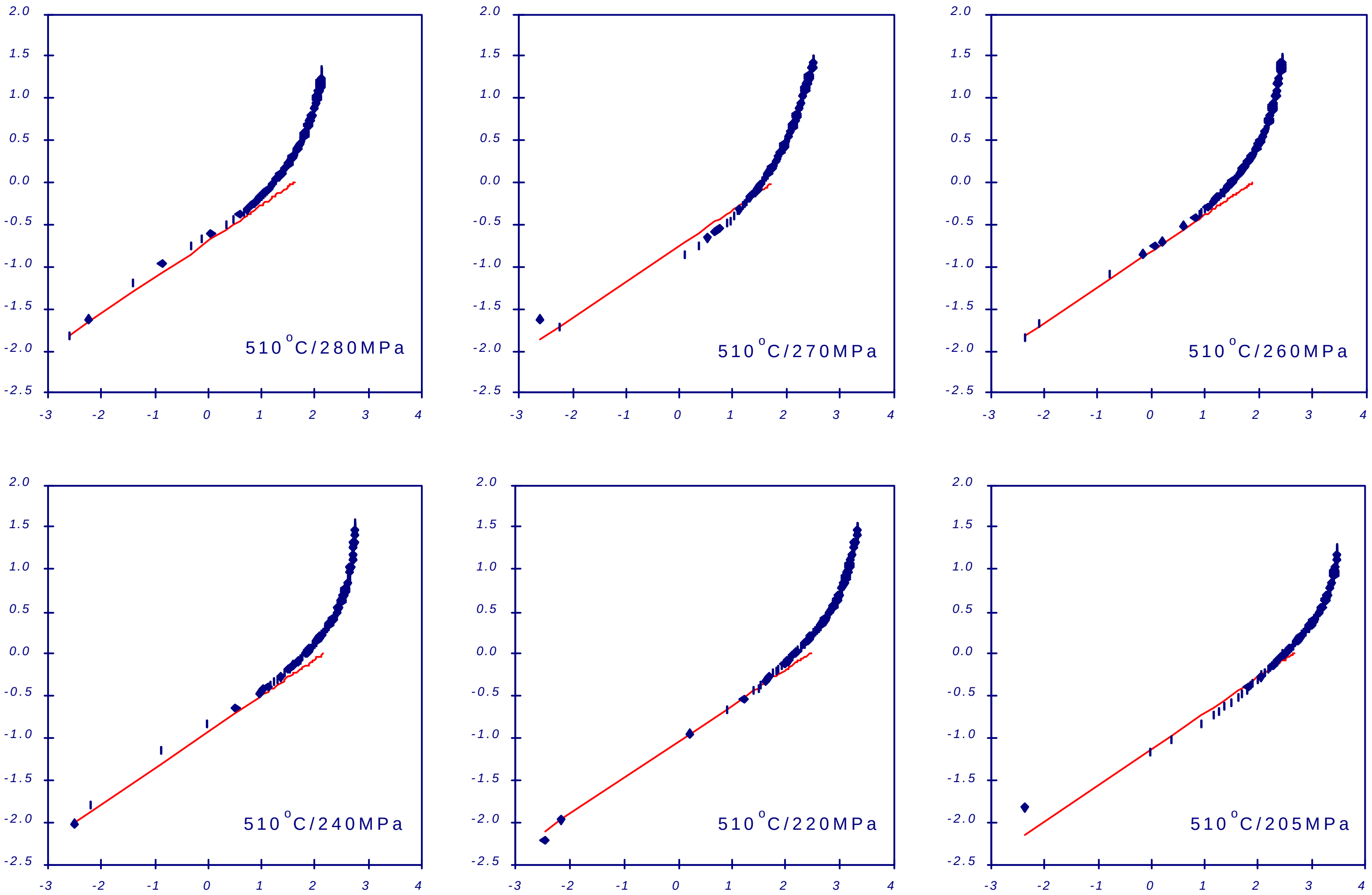

Fig. C 1 Comparison of Bartsch master equation predicted log*e*(log*t*) with observed log*e*(log*t*) creep strain data (points) for the N+T 10CrMo9-10 steel at 510°C

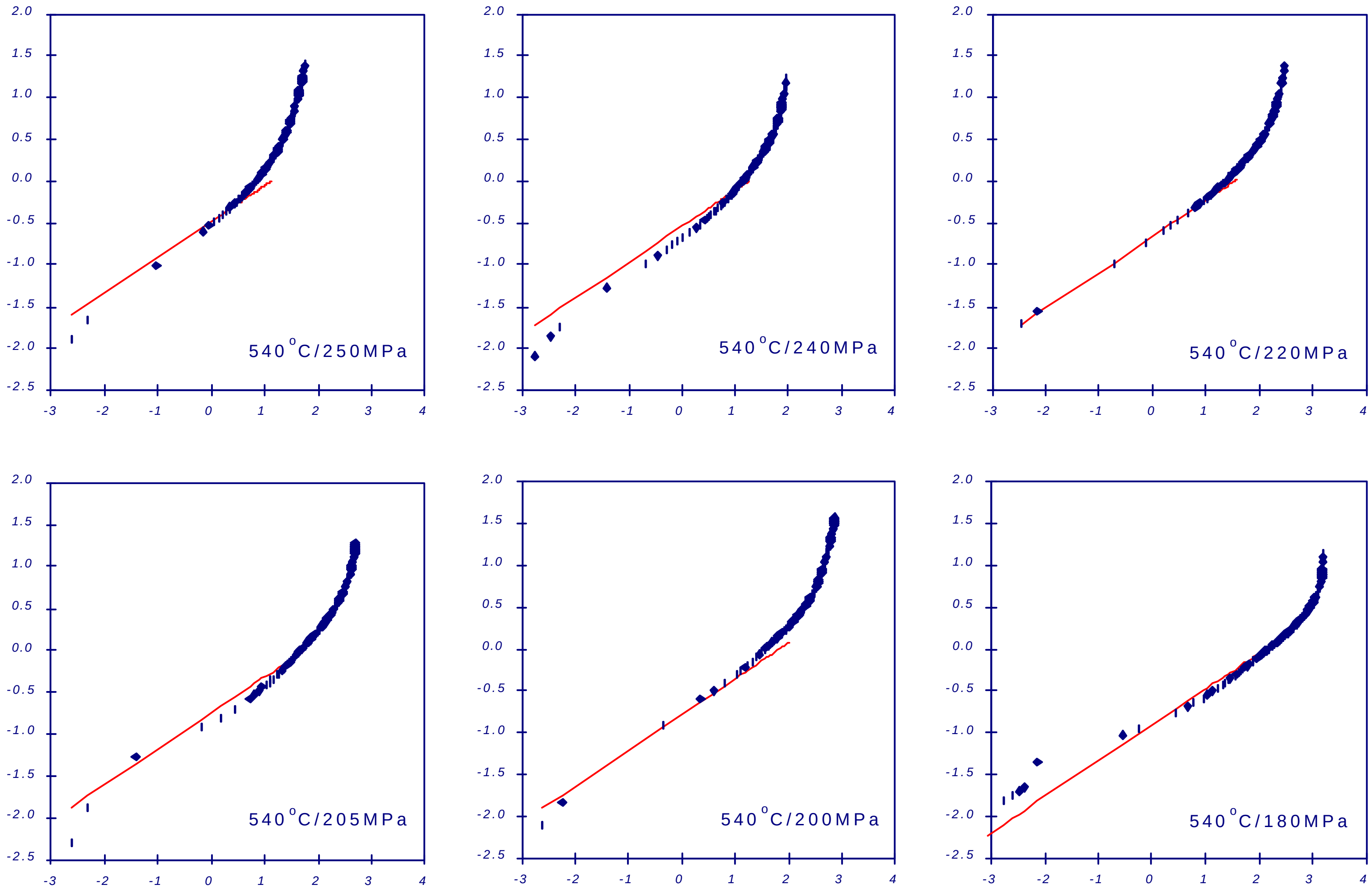

Fig. C 2 Comparison of Bartsch master equation predicted log$e$(log$t$) with observed log$e$(log$t$) creep strain data (points) for the N+T 10CrMo9-10 steel at 540°C

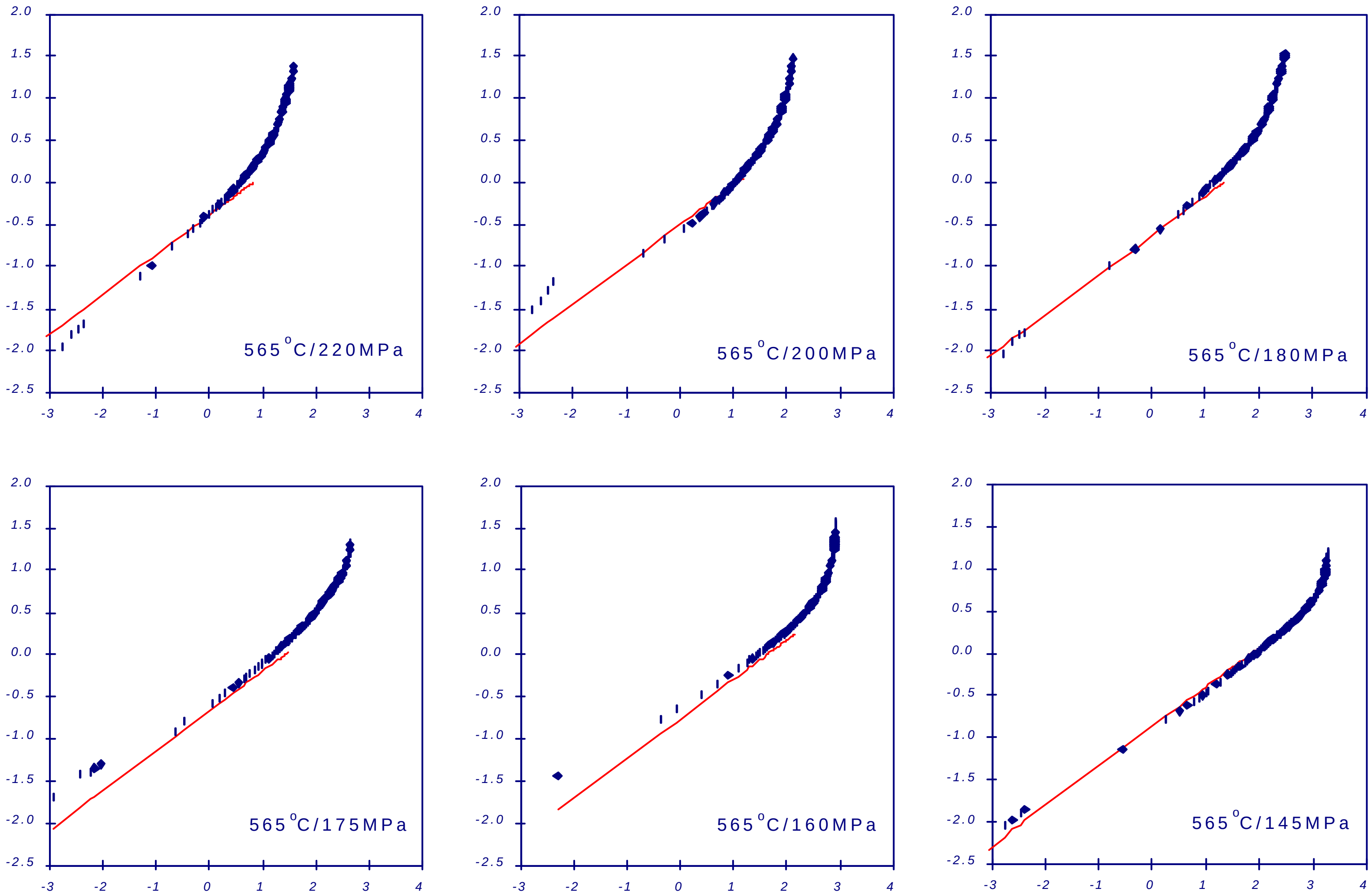

Fig. C 3 Comparison of Bartsch master equation predicted log$e$(log$t$) with observed log$e$(log$t$) creep strain data (points) for the N+T 10CrMo9-10 steel at 565°C

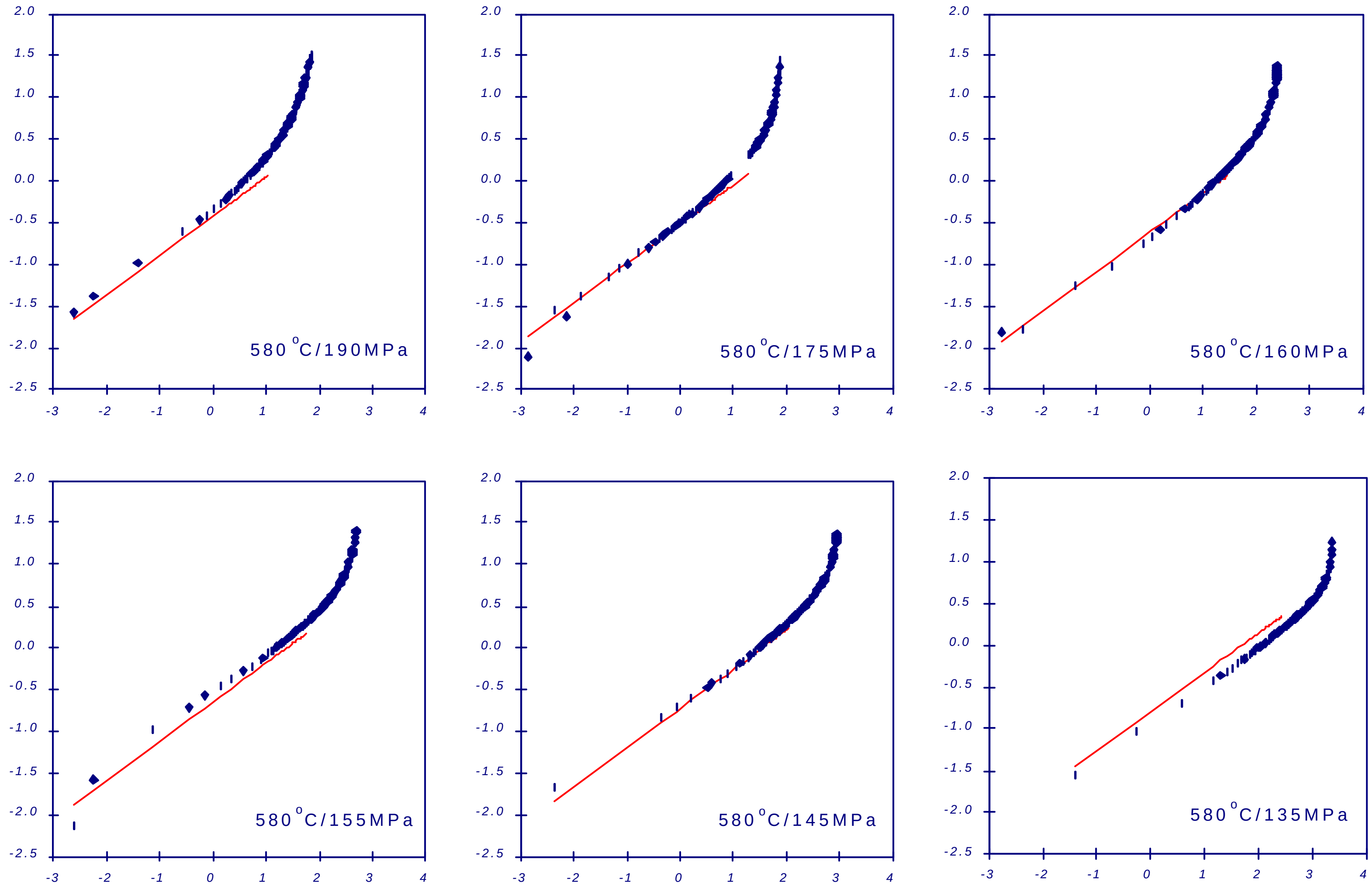

Fig. C 4 Comparison of Bartsch master equation predicted log*e*(log*t*) with observed log*e*(log*t*) creep strain data (points) for the N+T 10CrMo9-10 steel at 580°C

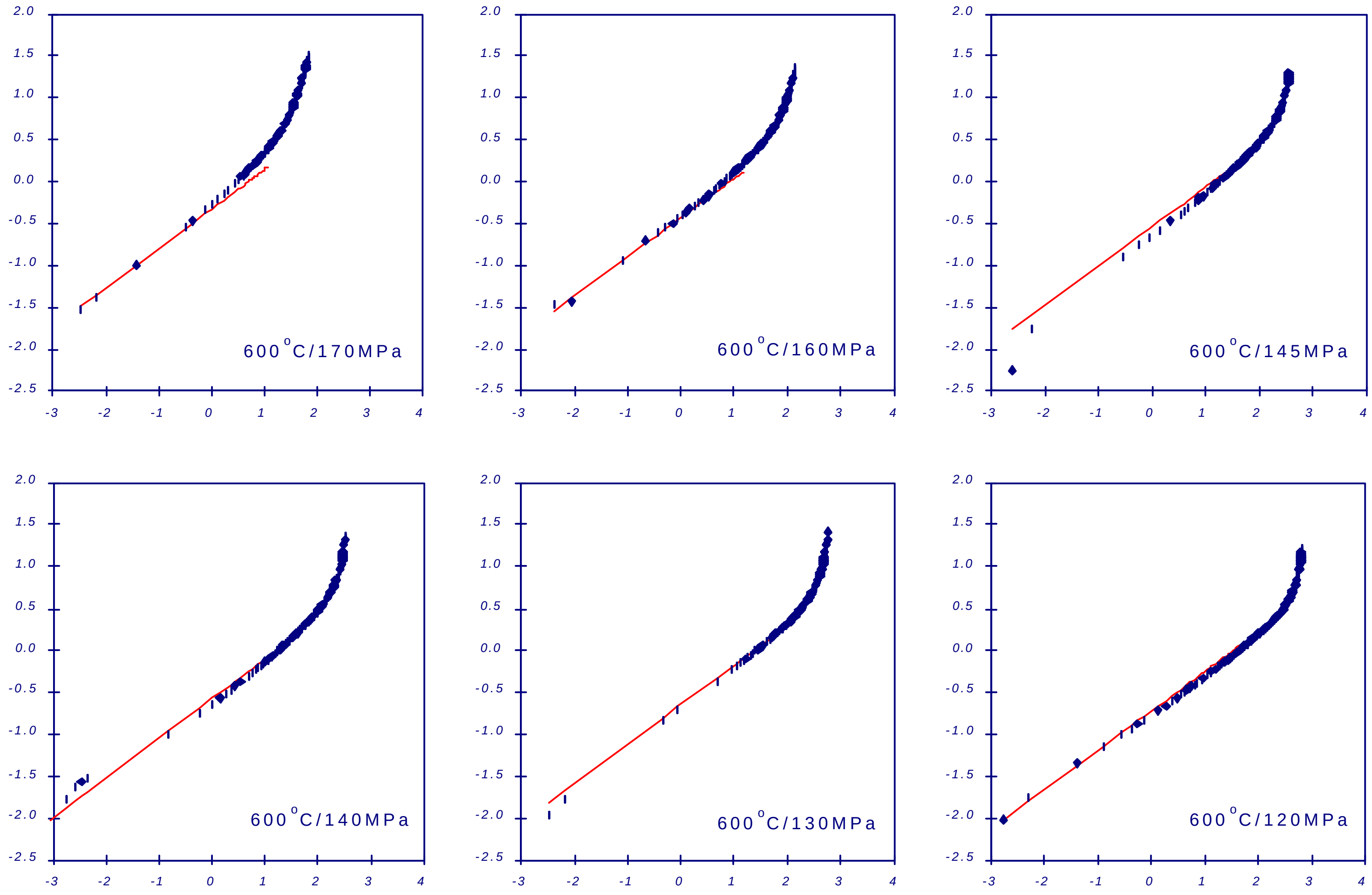

Fig. C 5 Comparison of Bartsch master equation predicted log*e*(log*t*) with observed log*e*(log*t*) creep strain data (points) for the N+T 10CrMo9-10 steel at 600°C

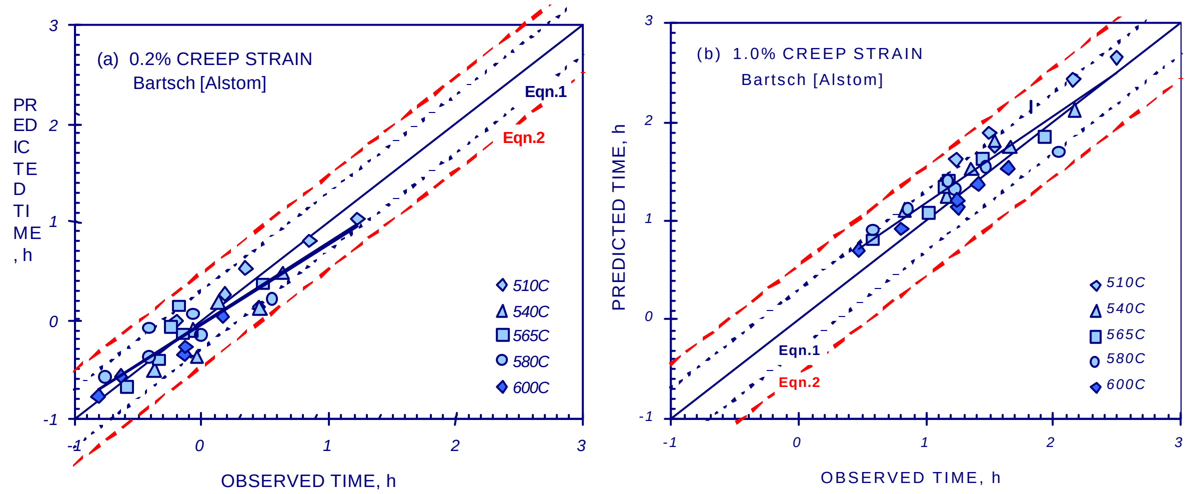

Fig. C 6 Comparison of observed times to 0.2% and 1.0% plastic strain with those predicted using the Bartsch creep equation

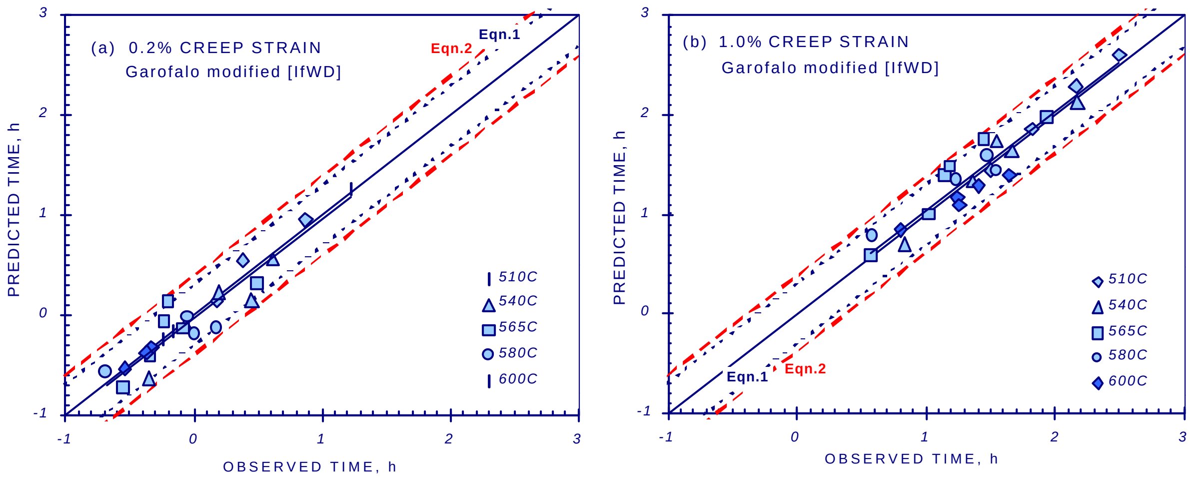

Fig. C 7 Comparison of observed times to 0.2% and 1.0% plastic strain with those predicted using the Modified Garofalo creep equation

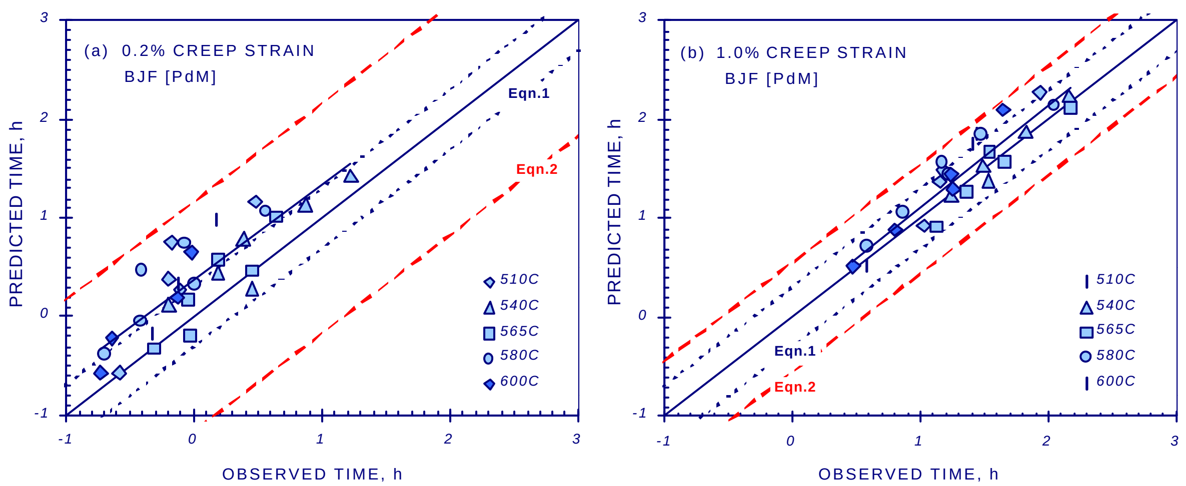

Fig. C 8 Comparison of observed times to 0.2% and 1.0% plastic strain with those predicted using the BJF creep equation

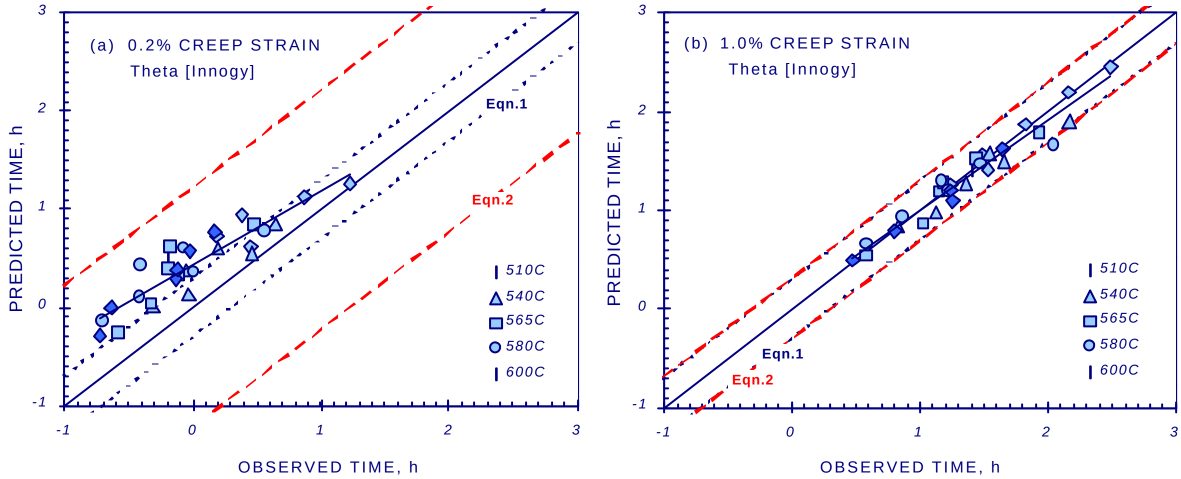

Fig. C 9 Comparison of observed times to 0.2% and 1.0% plastic strain with those predicted using the Theta creep equation

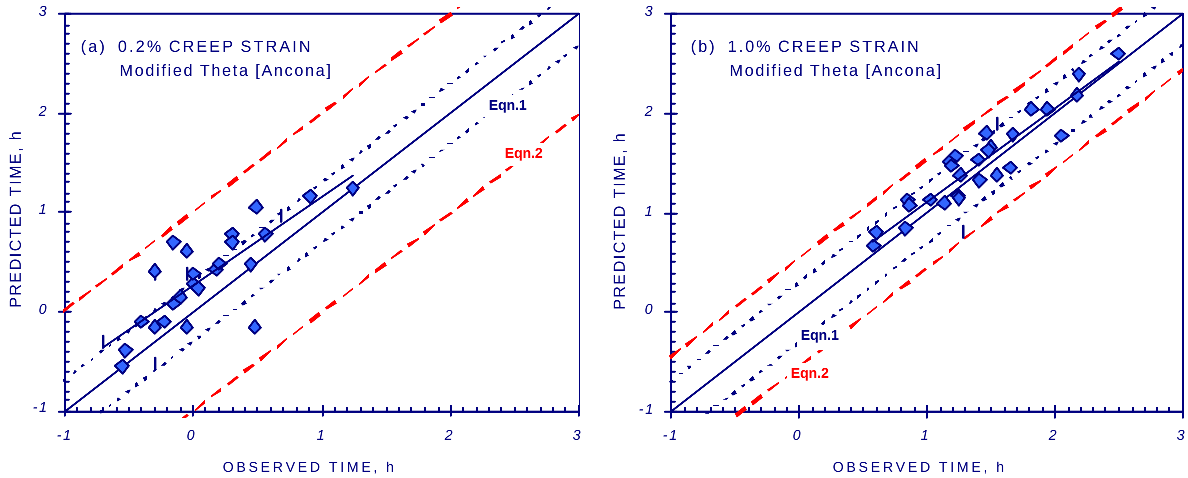

Fig. C 10 Comparison of observed times to 0.2% and 1.0% plastic strain with those predicted using the Modified Theta creep equation

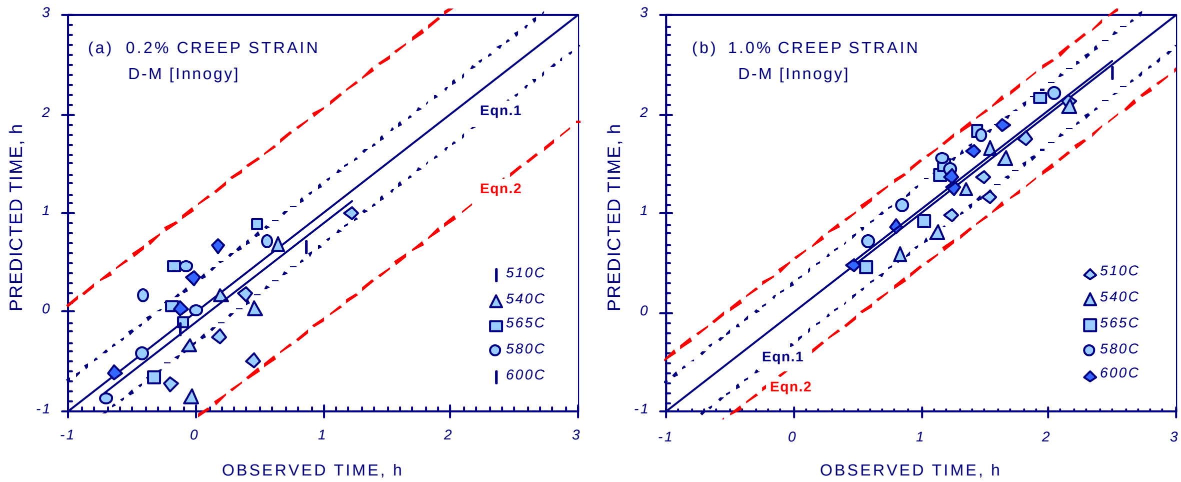

Fig. C 11 Comparison of observed times to 0.2% and 1.0% plastic strain with those predicted using the Dyson-McLean creep equation

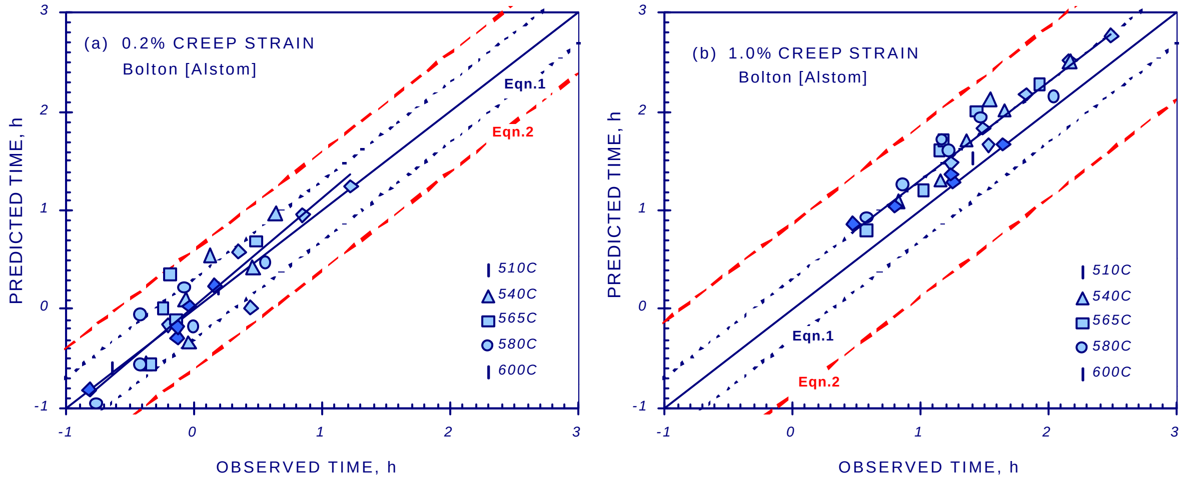

Fig. C 12 Comparison of observed times to 0.2% and 1.0% plastic strain with those predicted using the Bolton creep equation

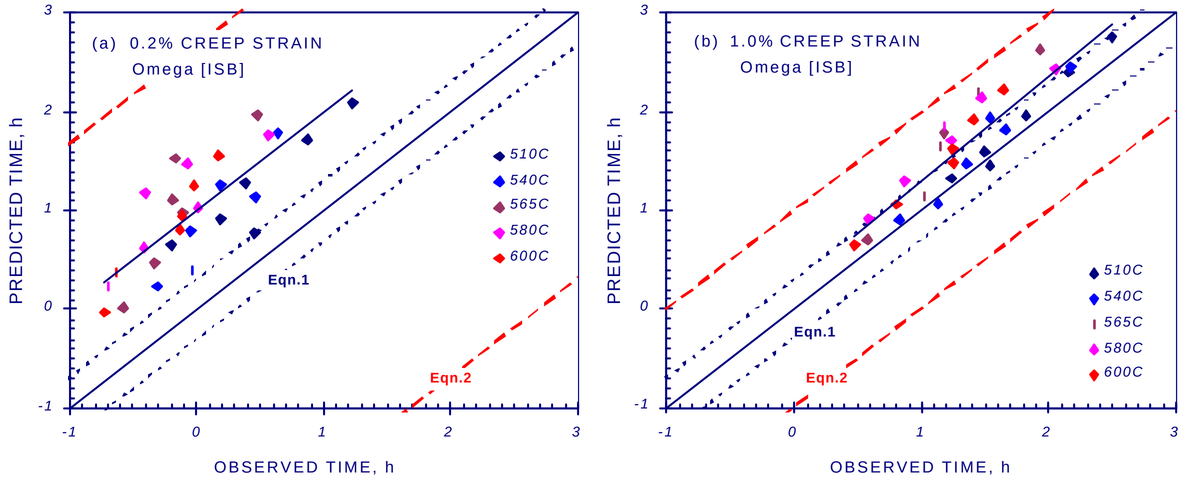

Fig. C 13 Comparison of observed times to 0.2% and 1.0% plastic strain with those predicted using the Omega creep equation

APPENDIX C2

REVIEW OF WG1 EVALUATION OF CREEP STRENGTH DATA ASSESSMENT METHODS RECOMMENDATION VALIDATION

S R Holdsworth [ALSTOM Power]

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APPENDIX C2

REVIEW OF EVALUATION OF CREEP STRENGTH DATA ASSESSMENT METHODS RECOMMENDATION VALIDATION

S R Holdsworth (GEC ALSTHOM LST)

C2.1. INTRODUCTION

ECCC-WG1 guidelines for the derivation of creep strength values are based on feedback from a WG1 evaluation of a large working dataset for normalised and tempered 2¼CrMo which had previously been the subject of a comprehensive assessment conducted in Germany [C2.1]. A summary of the pedigree statistics for this dataset are given in App.A2. To a large extent, the recommendations for CSDA are the same as those for creep rupture data assessment, and consequently make use of the experience gained from the CRDA evaluation exercise reviewed in App.C1.

Existing creep strength data assessment (CSDA) procedures collate the times to accumulate specific strains from individual creep curves determined for a number of casts, at a range of stress levels and temperatures. These data are then used to determine either (i) a set of individual iso-strain model equations defining the relationship between creep strength, temperature and the time to accumulate the specified strain (eg. App.D1b) or (ii) a self consistent master equation set relating creep strength, rupture strength, temperature and the times to a range of creep strains and rupture. In the latter, the link between creep and rupture strengths may be based on constitutive or parametric equations (eg. resp. [C2.2,C2.3]). While a constitutive equation based solution is the most attractive because of the potential flexibility it gives over a wide range of creep strains, the results of the WG1 evaluation demonstrate that there are difficulties when such an approach is applied to large multi-cast, multi-temperature datasets.

Five CSDA approaches were evaluated by WG1 (Table C2.1). The ISO and P* methods independently assess strength values for specific creep strains using the same procedures employed to determine stress rupture strength values (Apps.D1 & [C2.4]). The COSWP approach establishes the appropriate parametric model fit to the stress rupture data (eg. by the ISO method) and uses the expression to form the basis of a functional relationship between creep strain, creep strength and rupture strength [C2.3]. The modified COSWP procedure (MCOSWP) first determines the functional relationship for the dominant cast, before optimising the constants to represent the behaviour of the whole dataset [C2.5]. The DESA procedure for CSDA employs a similar concept [C2.6]. Finally, the Theta projection approach aims to achieve the same objective by establishing the stress and temperature dependent constants in a double exponential constitutive equation representing the shapes of the individual creep curves in the dataset [C2.7].

The results of the assessments and their use to develop and validate the post assessment tests (PATs) for CSDA are reported in the following appendix.

C2.2. CREEP STRENGTH DATA ASSESSMENT

Initially, it had been the objective to evaluate the assessment of datasets comprising results from (i) uninterrupted (continuous) strain measurement and (ii) interrupted strain measurement (ISM) tests, but this was ultimately not possible. The dataset available to WG1 comprised mainly the results of ISM tests.

CSDA procedures were evaluated on the basis of 0.02, 0.2 and 1.0% creep strengths and rupture strength at temperatures of 500, 550 and 600°C. Times to specific strength values were generally determined by linear interpolation between [log ε_p,log t] data points or by curve fitting. In general, the derived times did not vary by a large amount, except when the data point population was low in the critical region of the test record (Table C2.2).

Predicted creep strength curves for (a) 1%, (b) 0.2% and (c) 0.02% plastic strains, determined by six WG1 analysts [C2.5,C2.8-C2.12], are compared graphically as a function of time with the KGO trend lines [C2.1] and the observed data at the $T_{min[10\%]}$, T_{mean} and $T_{max[10\%]}$ temperatures in Figs.C2.1.1-3 respectively. A more direct comparison of WG1 and KGO predicted strength values is given in Figs.C2.2.1-3. Within the range of the experimental data, the results of the two ISO and the DESA assessments are in reasonable agreement. The predicted behaviour determined in the other assessments is less consistent, in particular at longer durations (lower strengths) for lower accumulated plastic strains.

Three analysts based their assessments on the Theta projection concept (Table C2.1). Experience gained with single cast datasets had previously demonstrated this to be an effective method of CSDA (eg. [C2.7]). However, the experience with the multi-cast 2¼CrMo dataset used in this evaluation was not good, and the results from only one of the assessments are referred to in the following text.

Selected strength predictions are also summarised in tabular form in Tables C2.3a-d. Within the range of the experimental data, there is reasonable agreement between the results from certain CSDAs. The variabilities in predicted strength values at times approximating to $t_{p\varepsilon[max]}$, $t_{r[max]}$ and $3.t_{p\varepsilon[max]}$, $3.t_{r[max]}$ are unacceptably large (re. penultimate rows in Tables C2.3a,b,c,d). The requirement for effective post assessment acceptability criteria is therefore even greater for CSDA than it is for CRDA (App.C1). Furthermore, it is clear that potential variability in rupture strength predictions is greatly increased when creep rupture data assessment is performed as part of a CSDA.

C2.3. VALIDATION OF POST ASSESSMENT ACCEPTABILITY CRITERIA

The CRDA post assessment tests are also used to test the results of creep strength data assessment. In the case of CSDA, the three categories of post assessment test are applied to the strength predictions for rupture and the creep strength levels specified by the instigator of the assessment (typically $R_{p1\%/t/T}$ and $R_{p0.2\%/t/T}$, but also $R_{p0.02\%/t/T}$ in this evaluation). The differences in the detail of the PATs applied to CSDAs are considered below.

C2.3.1 Physical Realism of Predicted Isothermal Lines

PAT-1.1, PAT-1.2 and PAT-1.3 are applied to the results of a CSDA in an identical way to the output from a CRDA. However, for creep strength data assessment, a fourth physical realism check is introduced. PAT-1.4 provides a consistency check between the rupture strength and the specified creep strength predictions.

The advice given is to plot $R_{p\varepsilon/t/T}$ versus $R_{r/t/T}$ for each specified $R_{p\varepsilon}$ strength level for $t_{p\varepsilon}$ out to $3.t_{p\varepsilon[max]}$, for $T_{max[10\%]}$, T_{main} and $T_{min[10\%]}$. A best fit quadratic line (with intercept equal to zero) is then constructed through the data for each $R_{p\varepsilon}$ strength level. Individual $R_{p\varepsilon/t/T}$ versus $R_{r/t/T}$ lines should have a correlation coefficient of $R^2 \geq 0.98$ and lie as a consistent family of curves (eg. Fig.C2.4a). An example of a CSDA failing to satisfy PAT-1.4 is shown in Fig.C2.4b.

C2.3.2 Effectiveness of Model Prediction within Range of Input Data

Apart from two amendments to the acceptability criteria adopted, PAT-2.1 and PAT-2.2 are also applied to the results of CSDAs in exactly the same way as they are to CRDAs to assess the effectiveness of the model prediction within the range of the input data.

The results of the CSDA evaluation activity indicated that PAT-2.1a needed to be relaxed (at least for ISM data), such that 'the model equation should be re-assessed if more than 3.0% (rather than 1.5%) of the [log $t_{p\varepsilon}$*,log $t_{p\varepsilon}$] data points fall outside one of the 2.5 $s_{[A\text{-}RLT]}$ boundary lines. The 1.5% criterion adopted for CRDA is clearly too limiting for CSDA (Table C2.4).

The second amendment was to PAT-2.2 with respect to the acceptable position of the best fit line in log $t_{p\varepsilon}$*-log $t_{p\varepsilon}$ space. Instead of constraining the best fit line to fall between the ±log 2 lines and $10h \leq t_{p\varepsilon} \leq 100{,}000h$ (consistent with the requirement for CRDA), more flexible limits (for CSDA) of $t_{p\varepsilon[max]/T}/1000 \leq t_{p\varepsilon} \leq t_{p\varepsilon[max]/T}$ are recommended. This is because $t_{p\varepsilon[max]/T}$ can be significantly less than 100,000h even though $t_{r[max]}$ >100,000h.

C2.3.3 Repeatability and Stability of Extrapolations

The evidence indicates that there is an even greater need for checking the repeatability of extrapolated strength predictions determined from CSDAs. The application of PAT-3.1 (in particular) and PAT-3.2 to CSDAs is therefore recommended.

C2.3.4 PAT Overview

The PATs were applied to the WG1 CSDAs of the 2¼CrMo dataset and the results are summarised in Table C2.4. The variability associated with those predicted CSDAs passing the PATs is significantly reduced, but not as good as the experience gained with the CRDAs (refer to the final rows in Tables C2.3a,b,c,d). The increased variability associated with CSDAs is attributed in part to (i) the uncertainty in determining $t_{p\varepsilon/tT}$, in particular when the data population in the vicinity of the target strain is low, and (ii) to any rationalisation in creep and rupture strengths to ensure self consistency.

C2.4. CONCLUDING REMARKS

The results of a comprehensive CSDA evaluation exercise underpin the ECCC-WG1 recommendations for creep strength data assessment (defined in the main text). The findings highlight the risk of high levels of uncertainty associated with creep rupture strength predictions for durations at the extremes of the observed data and beyond. This risk can be reduced by:

- repeat assessments according to well defined procedures, and
- application of the ECCC-WG1 post assessment tests.

It is also recommended that the level of uncertainty in predicted strength values from CSDAs is minimised by ensuring that only creep test records with an adequate frequency of observations are employed[1].

Finally, $R_{r/t/T}$ strength values determined as part of a CSDA should only be used as a means of generating $R_{p\varepsilon/t/T}$ predictions which are consistent with the rupture data. $R_{r/t/T}$ values to be reported outside WG3.x should be determined independently of any creep strength data, by CRDA, to minimise uncertainty.

[1] For interrupted tests, guidance is given in Table 6, App.1 of [C2.13]. An absolute minimum of 8 observations is recommended for short term tests in [C2.11].

C2.5. REFERENCES

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Table C2.1 ECCC-WG1 Evaluation of CSDA Procedures

PROCEDURE	ANALYST
ISO (App.D1b)	BS [C2.8], ISB [C2.9]
DESA (App.D2b)	IFW [C2.10]
P* [C2.4]	ISB [C2.10]
COSWP [C2.3]	ERA [C2.5]
THETA [C2.2]	GECA [C2.11], ISB [C2.9], TUG [C2.12]

Table C2.2 Comparison of Creep Strength Input Data -1/4

Temp (°C)	Cast	Stress (MPa)	Times to Specific Plastic Strains (h)											
			0.02%				0.20%				1.00%			
			IFW	GECA	BS	ISB	IFW	GECA	BS	ISB	IFW	GECA	BS	ISB
450	D7ZT	385									592	821	624	
	D7ZT	340					459	800	462	459	3,801	3,940	4,216	3,801
	D7ZT	305					4,425	4,440	4,063	4,424	15,335	15,300	16,313	15,336
	D7ZT	270	20	18	18	20	9,185	8,790	9,156	9,186	26,307	26,500	26,462	26,308
	D7ZT	235			70	121	11,333		11,577	11,333	28,539		29,725	28,539
	D7ZT	195			369	474	12,118		12,108	12,118			>60,000	
450	D7R	390					5	2			497	548	514	497
	D7R	360						2			702	724	776	702
	D7R	330					198	250	313	198	1,780	1,790	1,767	1,781
	D7R	300			99	229	3,023	3,140	3,300	3,023	5,412	5,420	6,704	5,413
	D7R	270	50	188	112	50	3,439	3,540	3,514	3,440	8,337	8,350	8,362	8,338
500	D7ZT	348				1				10			40	54
	D7ZT	313				3			31	30	140		138	140
	D7ZT	310					42	55	43	42	194	194	198	194
	D7ZT	275			25	24	230	282	268	268	524	503	482	501
	D7ZT	260	6	6	8	6		231	241	230	501	529	532	524
	D7ZT	245			33	31	294	294	333	294	620	622	689	620
	D7ZT	220	251		50	28	619		400	305	1,032		1,253	1,031
	D7ZT	196			25	30	565	566	569	565	1,526	1,510	1,513	1,526
	D7ZT	175			55	59	667	667	675	667	1,923	1,920	1,911	1,923
	D7ZT	157			79	79	1,963	1,970	1,978	1,964	6,472	6,460	6,291	6,472
	D7ZT	137			101	125	1,262	1,250	1,233	1,262	6,778	6,660	7,100	6,778
	D7ZT	120	142	142	100	142	1,744	1,730	1,746	1,744	17,175	16,900	17,500	17,175
	D7ZT	98			130	118	3,783	3,780	3,814	3,783	36,535	36,500	37,000	36,535
	D7ZT	70	380	331	329	380	16,836	*16,658*	16,425	*16,836*			*107,586*	
	D7ZT	40			424	430			*63,448*				*>300,000*	
500	D7R	320					7		8	7	51		55	51
	D7R	275			4	4			40	39	146	148	143	146
	D7R	245				2			16	17			88	87
	D7R	245			8	7	73	82	72	73	244	245	248	244
	D7R	205	13	30	15	13	236	246	221	236	745	752	763	745
	D7R	196			15	12	219	248	215	219	1,200	1,220	1,252	1,200
	D7R	157			47	47			503	505	2,571	2,570	2,601	2,570
	D7R	123			62	41	986	979	979	986	15,340	15,000	17,094	15,340
	D7R	98			130	158	6,242	6,210	5,552	6,242	29,535	29,700	31,517	29,353
	D7R	79	213		130	213	4,433	4,400	4,705	4,433	42,081	42,400	40,000	42,081

Table C2.2 Comparison of Creep Strength Input Data -2/4

Temp (°C)	Cast	Stress (MPa)	Times to Specific Plastic Strains (h)											
			0.02%				0.20%				1.00%			
			IFW	GECA	BS	ISB	IFW	GECA	BS	ISB	IFW	GECA	BS	ISB
500	D7K	342			1	1			8	8			41	41
	D7K	309			8	9	77	76	74	77	185	184	159	185
	D7K	246			25	25	296	296	287	296	577	576	577	577
	D7K	196			69	70	528	525	530	528	1,357	1,350	1,365	1,357
	D7K	157			109	101	1,037	1,030	1,039	1,039	3,415	3,380	3,449	3,415
	D7K	123			100	192			2,910	2,106	51,860	51,700	53,514	51,860
	D7K	98.1			323	342	11,776	11,600	11,345	11,776			153,600	
525	D7ZT	348							1		2		4	2
	D7ZT	314					1		1	1	24		27	24
	D7ZT	275							1	1			37	6
	D7ZT	245				1			13	12	52		63	52
	D7ZT	220			6	5			52	51	171	171	177	171
	D7ZT	196			6	6			65	63	302	300	300	302
	D7ZT	177			17	12	122	122	122	122	411	410	413	411
	D7ZT	157			17	15	155	153	154	155	747	745	737	747
	D7ZT	137			15	14	275	275	235	276	1,305	1,300	1,292	1,305
	D7ZT	123			32	30	381	378	383	381	2,159	2,120	2,182	2,159
	D7ZT	99			44	58	428	423	441	427	4,250	4,250	4,301	4,250
	D7ZT	71	137	213	115	137	3,428	3,400	3,136	3,427	44,426	44,200	44,236	44,425
550	D7ZT	314									2		3	2
	D7ZT	275					1		1	1	4		6	4
	D7ZT	230	1			1	6		5	6	17		17	17
	D7ZT	219							2	2			11	10
	D7ZT	196				1			12	14			69	70
	D7ZT	190	3	3	2	3	20	19	21	20	83	84	82	83
	D7ZT	176			2	1			15	15			82	75
	D7ZT	157			3	2			26	26	114	113	113	114
	D7ZT	137			5	5			55	54	288	291	283	288
	D7ZT	123			8	8			83	82	454	452	392	454
	D7ZT	98			10	13	157	160	155	137	1,066	105	1,081	1,066
	D7ZT	78			12	22	395	396	385	395	6,454	6,390	5,445	6,454
	D7ZT	62			74	45	972	965	1,190	972	13,888	13,600	12,418	13,888
	D7ZT	49			31	42	1,652	163	1,794	1,653	37,930	3,330	35,343	37,930
	D7ZT	20	55,370			55,370								

Table C2.2 Comparison of Creep Strength Input Data -3/4

Temp (°C)	Cast	Stress (MPa)	Times to Specific Plastic Strains (h)											
			0.02%				0.20%				1.00%			
			IFW	GECA	BS	ISB	IFW	GECA	BS	ISB	IFW	GECA	BS	ISB
550	D7R	196							4	3			13	13
	D7R	185	2	2	1	2	13	13	12	13	65	65	62	65
	D7R	157			4	4			42	41	189	189	191	189
	D7R	132	1	1	1	1	48	47	48	48	485	479	514	485
	D7R	133			6	5			55	55	404	400	420	404
	D7R	133			5	4			48	47	305	303	309	305
	D7R	133			7	7			69	69	553	550	565	553
	D7R	133			7	7			74	74	719	716	729	720
	D7R	123			3	7			66	77	537	538	540	539
	D7R	105	2	1	3	2	151	15	150	151	1,588	1,540	1,670	1,588
550	D7R	98			39	41	234	234	229	234	3,158	3,080	3,211	4,268
	D7R	78			28	26	234	236	306	238	4,302	4,190	4,351	4,302
	D7R	62			43	78	1,299	1,280	916	1,299	12,414	12,300	12,316	12,414
	D7R	49			105	104	1,894	1,870	1,296	1,895	25,000	24,800	21,530	25,000
550	D7K	309			1				13				66	4
	D7K	196			1	1			13	13			73	68
	D7K	157			6	4			48	43	182	181	188	182
	D7K	123			9	9			91	91	681	679	702	681
	D7K	98			21	13	316	315	178	317	2,640	2,620	2,465	2,640
	D7K	78			47	53	485	477	682	485	11,689	11,500	12,935	11,689
	D7K	59			102	82	5,786	5,740	5,229	5,786	50,200	48,200	49,352	48,067
575	D7ZT	275					1				1		1	1
	D7ZT	245					1		1	1	4		4	4
	D7ZT	220					1		2	1	4		5	4
	D7ZT	196					2		2	2	9		11	9
	D7ZT	177					3		2	3	18		18	18
	D7ZT	157				1			8	8			41	41
	D7ZT	137				1			13	13			72	67
	D7ZT	123				2			21	20			106	104
	D7ZT	98			3	5			46	52	439	437	463	439
	D7ZT	78			8	9			89	93	1,281	1,270	1,313	1,281
	D7ZT	62			10	16	248	249	245	248	4,165	4,130	4,211	4,165
	D7ZT	49			20	27	346	343	322	346	7,912	7,740	8,308	7,912
	D7ZT	39			27	32	1,285	1,300	1,266	1,285	23,365	23,100	25,538	23,369
	D7ZT	31			46	53	3,758	3,700	3,832	3,758			107,641	

Table C2.2 Comparison of Creep Strength Input Data -4/4

Temp (°C)	Cast	Stress (MPa)	Times to Specific Plastic Strains (h)											
			0.02%				0.20%				1.00%			
			IFW	GECA	BS	ISB	IFW	GECA	BS	ISB	IFW	GECA	BS	ISB
575	D7K	245							2	2			8	9
	D7K	157				1			6	6			28	28
	D7K	123			2	3			24	33	238	238	240	238
	D7K	98			5	5			52	53	251	252	260	251
	D7K	78			11	12	162	161	151	162	1,966	1,930	2,000	1,966
	D7K	62			19	17	256	258	308	256	5,428	5,410	5,495	5,428
	D7K	49			54	52	1,308	1,290	1,271	1,308	14,609	14,500	14,488	14,609
	D7K	39			79	70	5,695	5,700	5,102	5,695	30,751	30,000	33,549	30,752
600	D7ZT	245											1	
	D7ZT	220									1		1	1
	D7ZT	196									2		2	2
	D7ZT	177					1			1	4		4	4
	D7ZT	145					2	0	1	2	12	0	12	12
	D7ZT	137					2	2	2	2	21	21	25	21
	D7ZT	123							6	3			47	31
	D7ZT	98			2	2			25	23			104	118
	D7ZT	98			2		8	7	7	8	118	119	122	118
	D7ZT	78			2	4			25	44	337	334	330	337
	D7ZT	62			2	6			34	65	1,183	1,180	1,202	1,183
	D7ZT	49			10	12			97	129	1,933	1,920	1,811	1,933
600	D7ZT	39			21	23	421	414	415	420	6,034	6,000	5,408	6,034
	D7ZT	31			26	27	571	562	644	571	11,301	11,300	10,944	11,301
	D7ZT	20			41	43	2,116	2,120	2,407	2,116	40,459	40,500	38,622	40,459
	D7ZT	12			97	90	11,026	11,000	10,211	11,026			>100,000	
600	D7R	138					2	2	3	2	19	18	18	18
	D7R	115					5	5	5	5	60	59	61	59
	D7R	98			1	2			15	17			78	85
	D7R	78			2	6			48	60	406	400	408	406
	D7R	58			5		70	70	70	70	902	900	925	902
	D7R	49			5	7	88	88	90	88	1,785	1,760	1,796	1,785
	D7R	39			19	22	269	268	273	269	4,624	4,560	4,272	4,624
	D7R	29			35	36	739	732	757	739	14,433	14,600	13,837	14,433

Table C2.3 Summary of predicted creep-rupture strength values for N+T 2.25CrMo

(a)	PREDICTED STRENGTH VALUES FOR RUPTURE, MPa					
	500°C		550°C		600°C	
	100kh	300kh	100kh	300kh	100kh	300kh
ISO/BS	111	82	59	38	-	-
ISO/ISB	103	73	54	32	25	13
DESA/IFW	124	104	67	53	32	24
MCOSWP/ERA	106	86	60	45	27	18
P*/ISB	73	35	58	30	18	9
THETA/GECA	118	87	61	39	28	9
KGO/IFW [C2.1]	130	107	66	52	31	22
Variability (all CSDAs), %	78	>100	24	80	78	>100
Variability (PATs passed), %	20	44	24	66	28	85

(b)	PREDICTED STRENGTH VALUES FOR 1% STRAIN, MPa					
	500°C		550°C		600°C	
	100kh	300kh	100kh	300kh	100kh	300kh
ISO/BS	87	63	37	24	-	-
ISO/ISB	80	56	33	20	13	8
DESA/IFW	89	71	41	31	15	10
MCOSWP/ERA	77	55	28	11	-	-
P*/ISB	47	23	38	20	8	5
THETA/GECA	24	-	-	-	15	-
KGO/IFW [C2.1]	80	60	34	23	12	7
Variability (all CSDAs), %	>100	>100	46	>100	88	>100
Variability (PATs passed), %	11	27	24	55	15	25

(c)	PREDICTED STRENGTH VALUES FOR 0.2% STRAIN, MPa					
	500°C		550°C		600°C	
	10kh	30kh	10kh	30kh	10kh	30kh
ISO/BS	80	60	34	24	12	-
ISO/ISB	90	65	32	22	12	8
DESA/IFW	91	70	37	26	11	7
MCOSWP/ERA	90	57	21	-	-	-
P*/ISB	81	54	34	22	13	-
THETA/GECA	44	8	-	-	-	-
KGO/IFW [C2.1]	88	67	36	25	11	-
Variability (all CSDAs), %	>100	>100	76	18	18	14
Variability (PATs passed), %	1	8	16	18	9	14

(d)	PREDICTED STRENGTH VALUES FOR 0.02% STRAIN, MPa					
	500°C		550°C		600°C	
	100h	300h	100h	300h	100h	300h
ISO/BS	142	105	49	29	12	-
ISO/ISB	124	95	50	33	13	-
DESA/IFW	148	110	58	38	17	9
MCOSWP/ERA[1]	182	100	16	-	-	-
P*/ISB	139	92	58	46	12	-
THETA/GECA	120	83	61	31	28	-
KGO/IFW [C2.1]	118	91	47	33	14	-
Variability (all CSDAs), %	54	33	>100	59	>100	
Variability (PATs passed), %	19	16	18	31	31	

[1] Model employs creep strain data in range 0.05% to 7.5%.

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Table C2.4 Summary of PAT results for CSDA assessment of N+T 2.25CrMo

Rupture

CODE	POST ASSESSMENT ACCEPTABILITY TESTS										
	1.1	1.2	1.3	1.4	2.1a	2.1b	2.1c	2.2a	2.2b	2.2c	PASS
ISO/BS		TB	<<0.1	N/A							X
ISO/ISB				N/A							P
DESA/IFW				N/A							P
MCOSWP/ERA				N/A	2.80%			-	-	-	X
P*/ISB	X	X		N/A	-	-	-	-	-	-	X
THETA/GECA			1.1	N/A	-	-	-	-	-	-	X
KGO/IFW [C2.1]				N/A	2.80%					2/3	X

1% Plastic Strain

CODE	POST ASSESSMENT ACCEPTABILITY TESTS										
	1.1	1.2	1.3	1.4	2.1a	2.1b	2.1c	2.2a	2.2b	2.2c	PASS
ISO/BS					3.95%					1/3	X
ISO/ISB					2.98%						P
DESA/IFW					2.00%						P
MCOSWP/ERA			1.3	X	3.95%	0.749	X	-	-	-	X
P*/ISB		X		X	-	-	-	-	-	-	X
THETA/GECA	X	X	0.63	X	-	-	-	-	-	-	X
KGO/IFW [C2.1]					3.95%					1/3	X

0.2% Plastic Strain

CODE	POST ASSESSMENT ACCEPTABILITY TESTS										
	1.1	1.2	1.3	1.4	2.1a	2.1b	2.1c	2.2a	2.2b	2.2c	PASS
ISO/BS					1.83%			2/3	2/3	2/3	X
ISO/ISB					2.75%						P
DESA/IFW					1.79%						P
MCOSWP/ERA			0.95	X	1.80%	0.597	X	-	-	-	X
P*/ISB		X		X	-	-	-	-	-	-	X
THETA/GECA	TB	X	0.67	X	-	-	-	-	-	-	X
KGO/IFW [C2.1]					2.75%				1/3	2/3	X

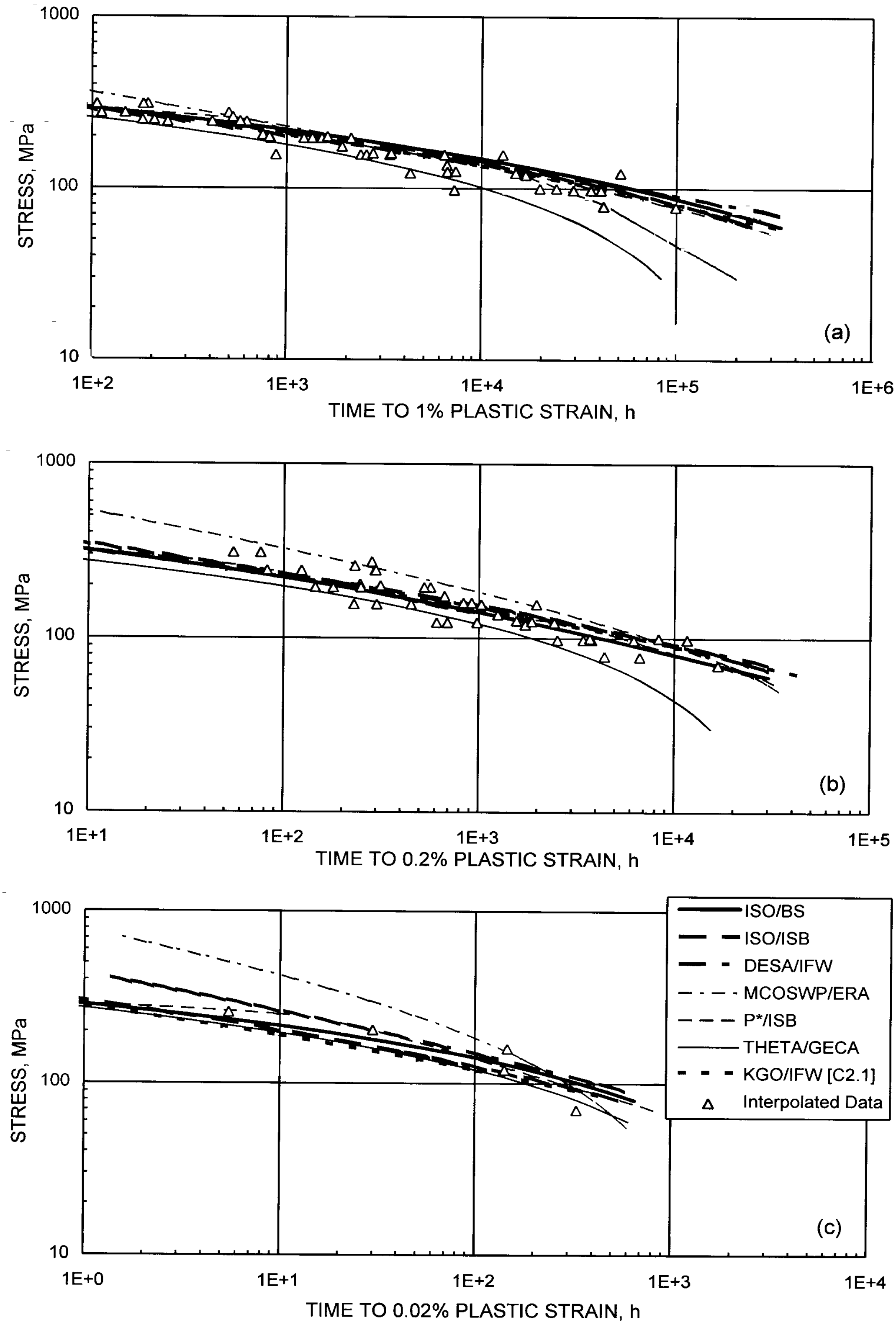
0.02% Plastic Strain

CODE	POST ASSESSMENT ACCEPTABILITY TESTS										
	1.1*	1.2	1.3	1.4	2.1a	2.1b	2.1c	2.2a*	2.2b*	2.2c*	PASS
ISO/BS					7.14%	0.596	X	-	-	-	
ISO/ISB					7.14%			-	-	-	
DESA/IFW								-	-	-	
MCOSWP/ERA			0.4	X	100%	0.589	X	-	-	-	
P*/ISB		X	1.21	X	-	-	-	-	-	-	
THETA/GECA			0.63	X	-	-	-	-	-	-	
KGO/IFW [C2.1]					7.14%		X	-	-	-	

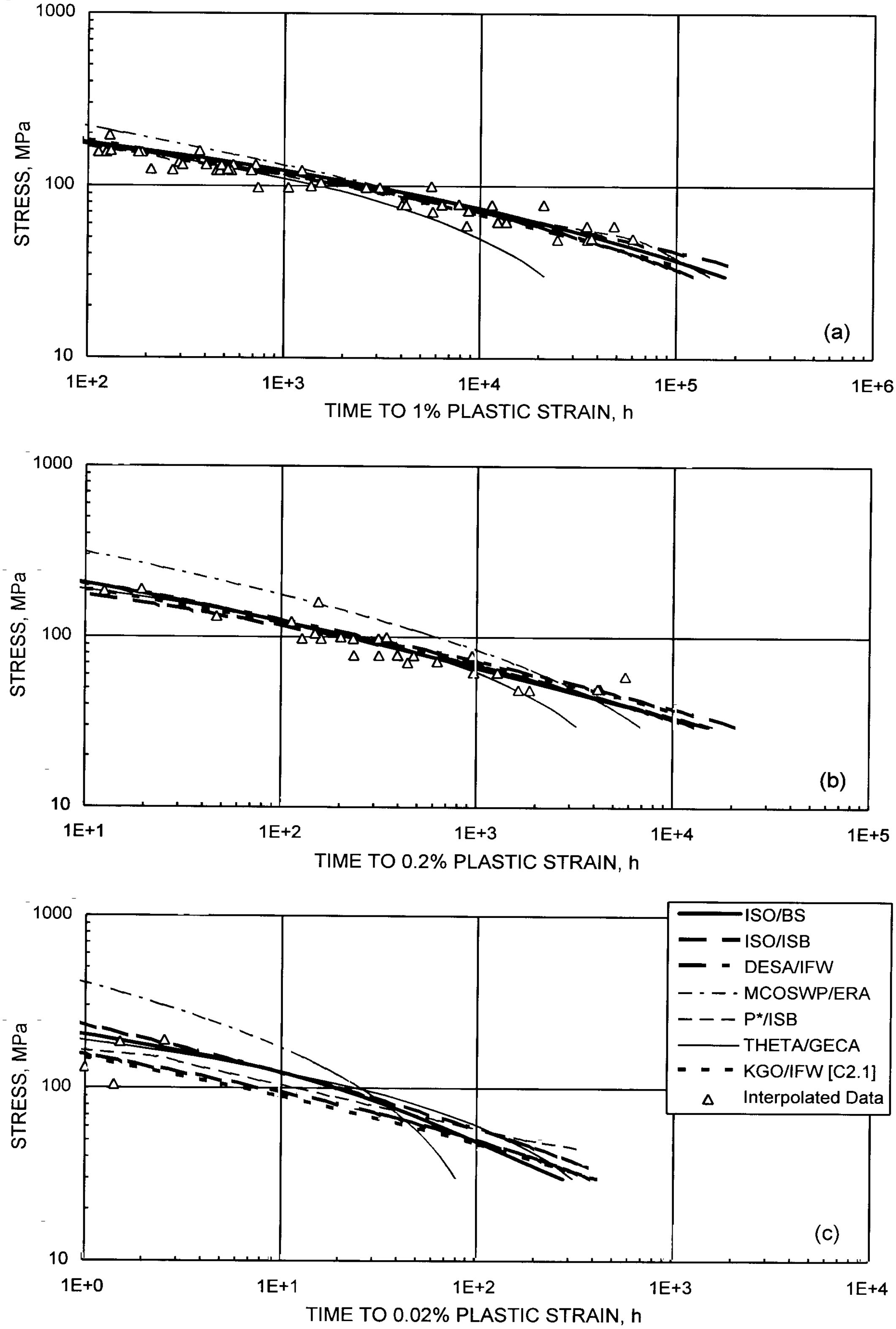
* Measurements too scarce to assess PAT

PAT PASSED   PAT NOT PASSED

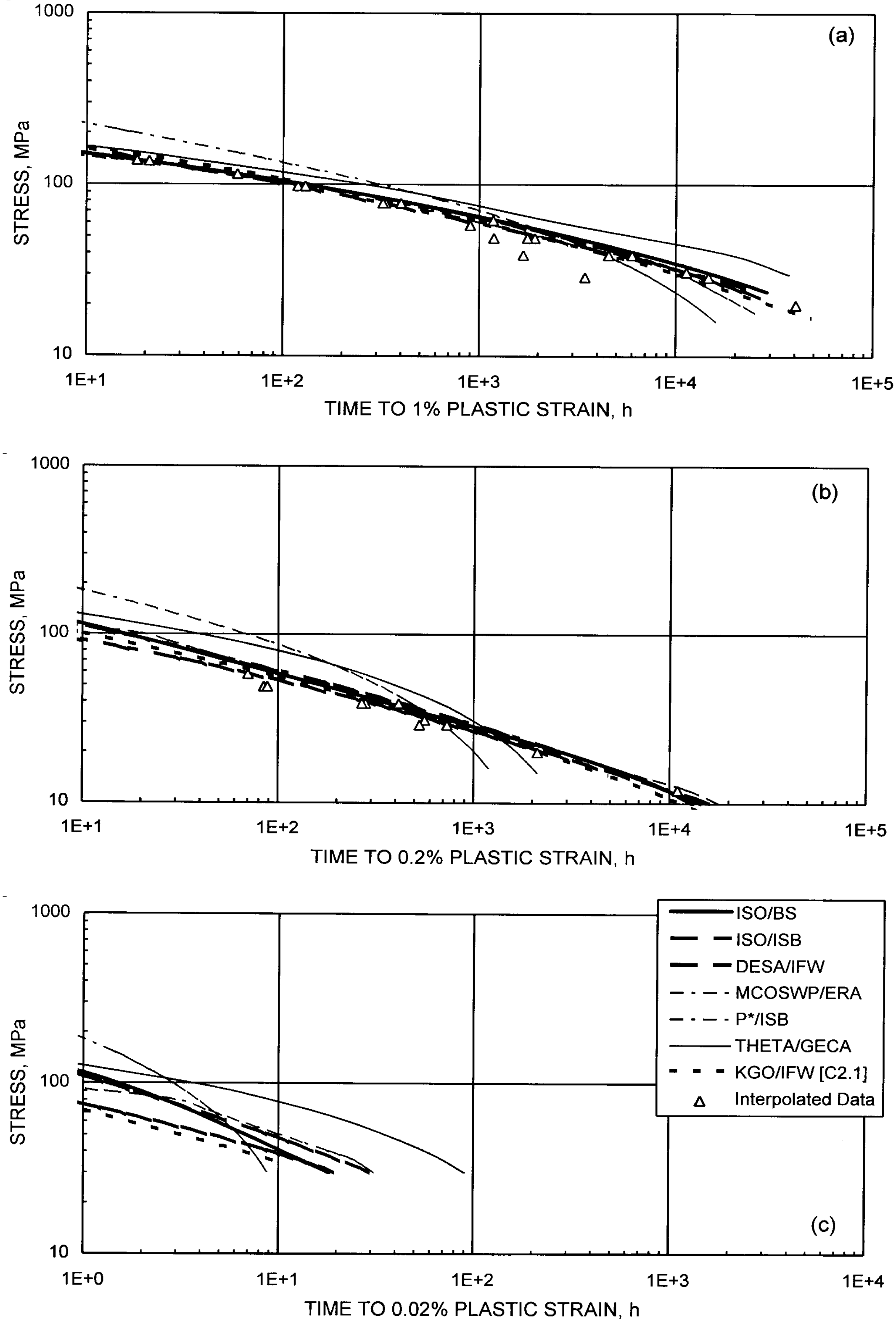
SRH/PATSUM2.XLS



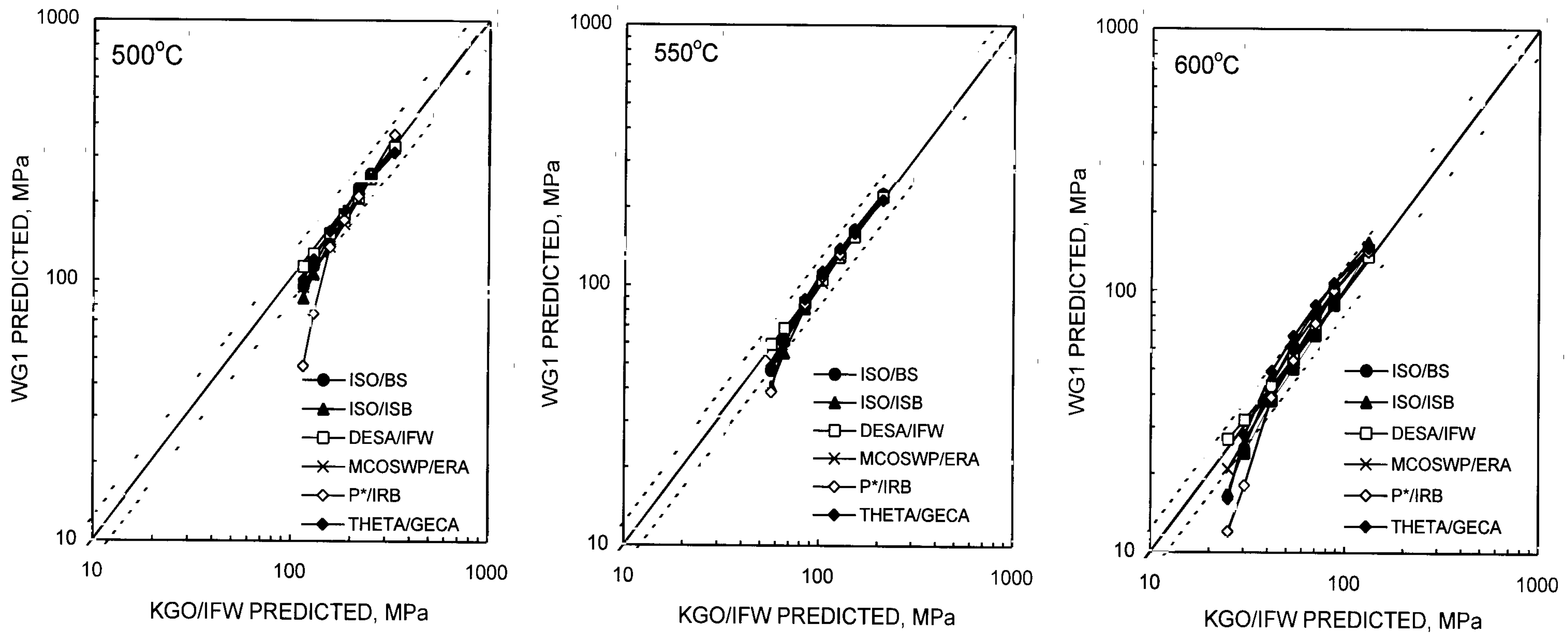
Comparison of creep strength predictions at 500°C for N+T 2.25CrMo
(a) 1% creep strength, (b) 0.2% creep strength, (c) 0.02% creep strength



Comparison of creep strength predictions at 550°C for N+T 2.25CrMo
(a) 1% creep strength, (b) 0.2% creep strength, (c) 0.02% creep strength

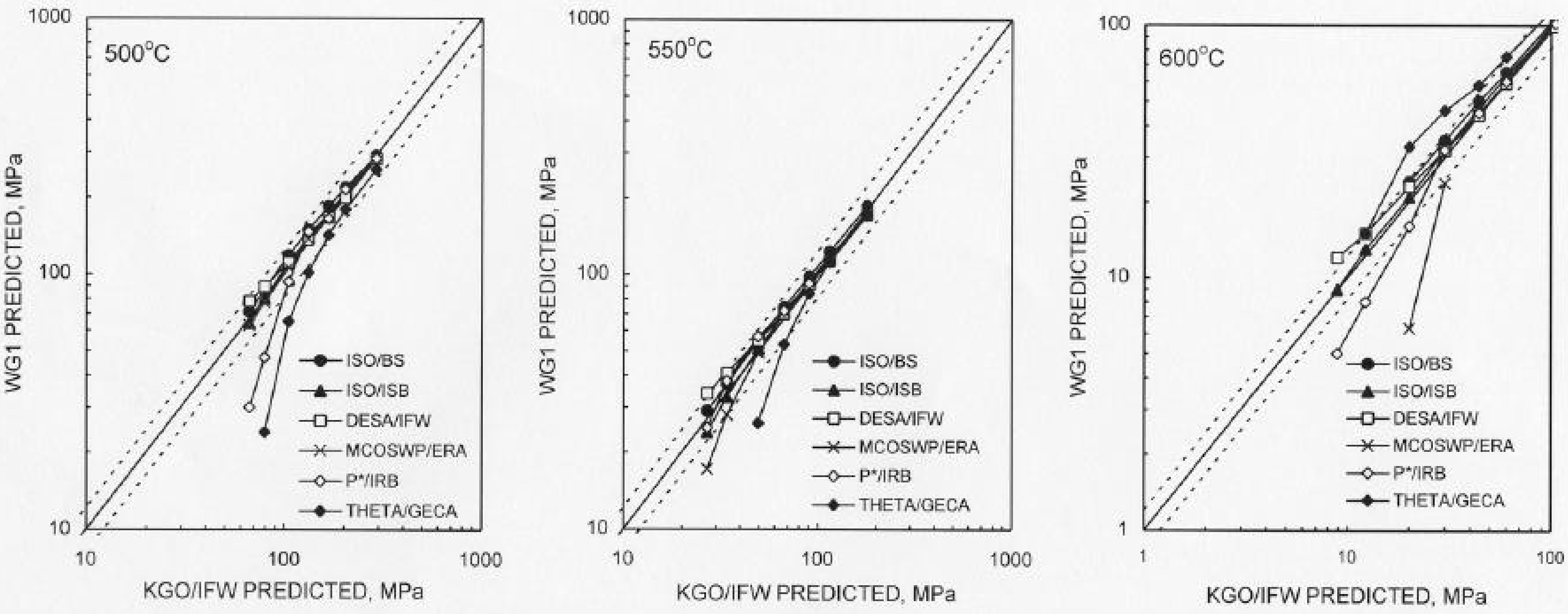


Comparison of creep strength predictions at 600°C for N+T 2.25CrMo
(a) 1% creep strength, (b) 0.2% creep strength, (c) 0.02% creep strength



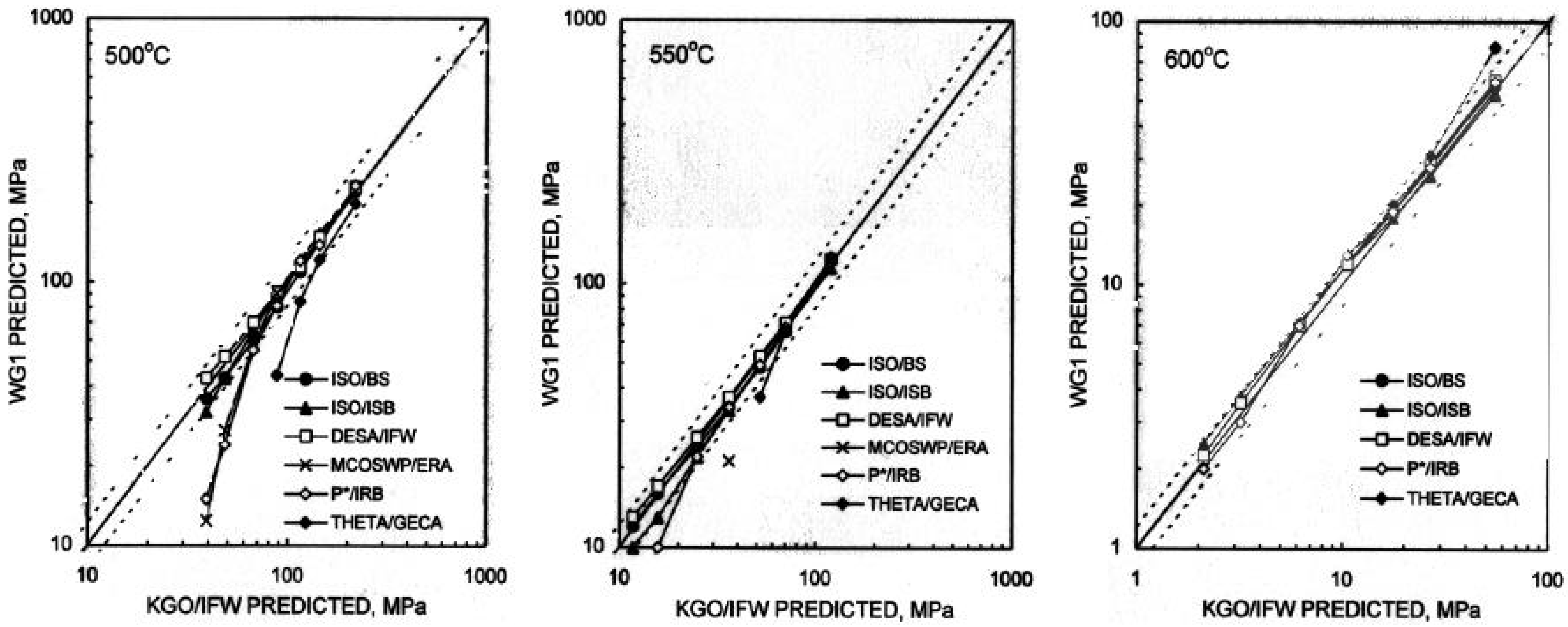
Comparison of WG1 rupture strength predictions with original KGO/IFW assessment of N+T 2.25CrMo [C2.1]

[dashed bounding lines represent 10% variation on strength]



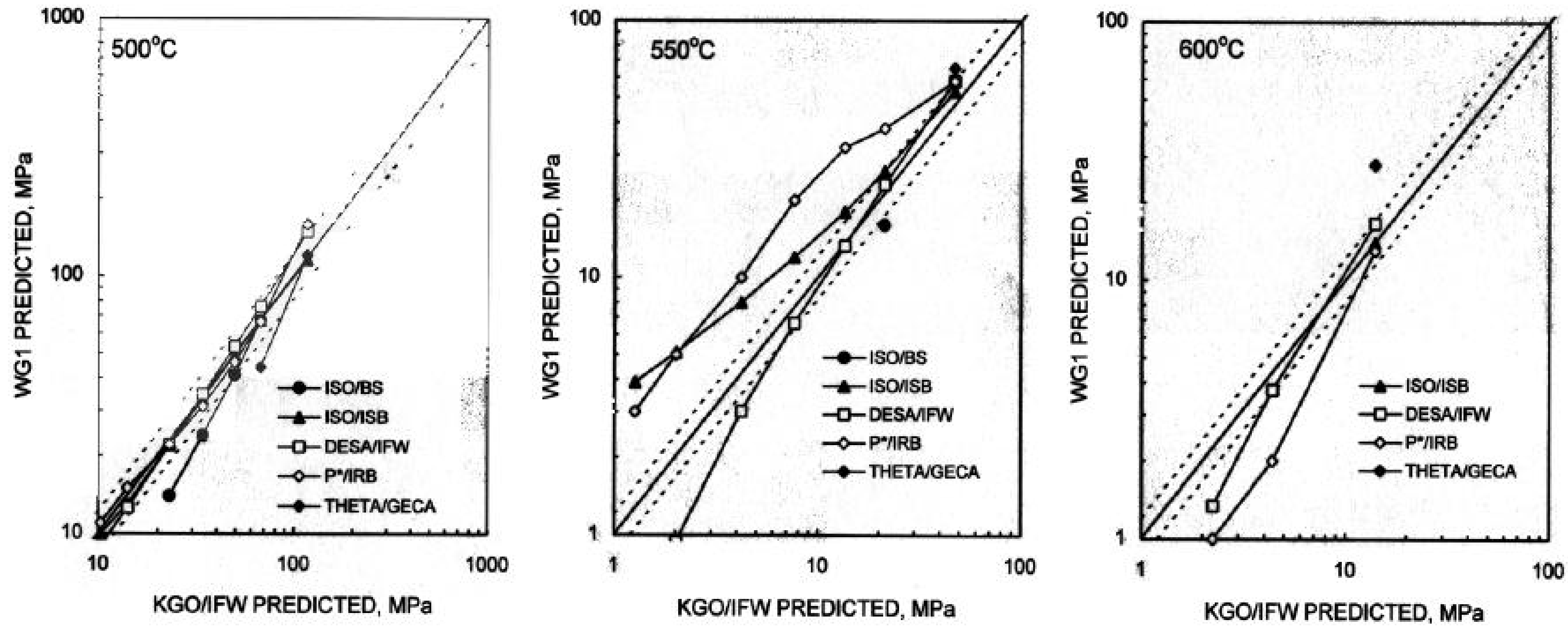
Comparison of WG1 1% creep strength predictions with original KGO/IFW assessment of N+T 2.25CrMo [C2.1]

[dashed bounding lines represent 10% variation on strength]



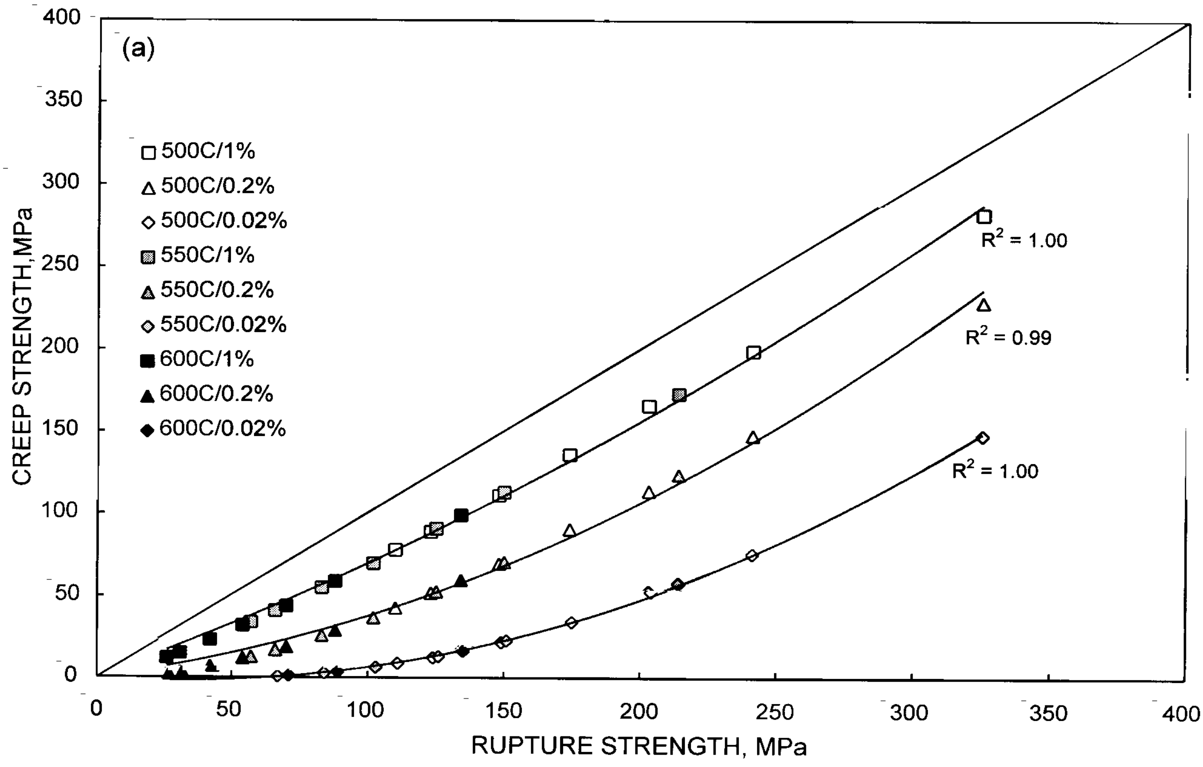
Comparison of WG1 0.2% creep strength predictions with original KGO/IFW assessment of N+T 2.25CrMo [C2.1]

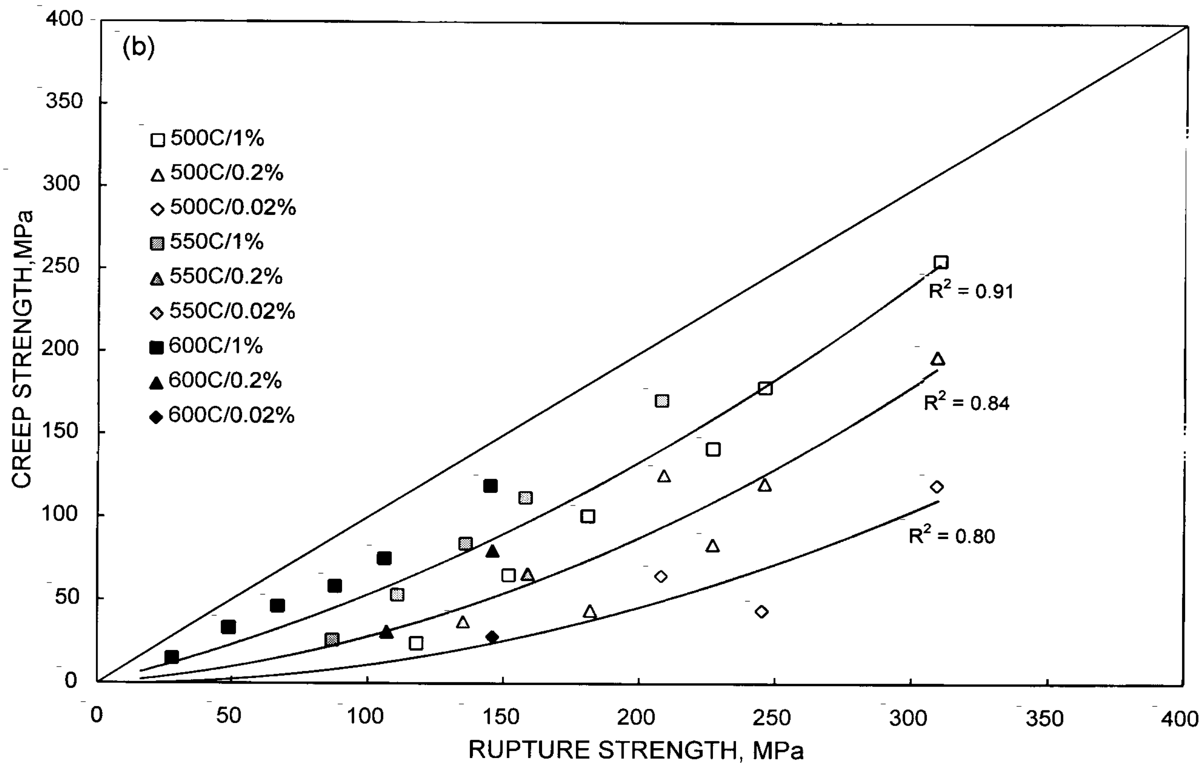
[dashed bounding lines represent 10% variation on strength]



Comparison of WG1 0.02% creep strength predictions with original KGO/IFW assessment of N+T 2.25CrMo [C2.1]

[dashed bounding lines represent 10% variation on strength]





Examples of CSDAs (a) meeting and (b) failing to meet the requirements of PAT-1.4

APPENDIX D1b

ECCC ISO CSDA PROCEDURE DOCUMENT

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British Steel

British Steel plc
Swinden Technology Centre

For ECCC WG1

Procedure for Assessment of Creep Strain Data Used By British Steel

1. <u>Scope</u>

The basis of the method used by British Steel for assessment of creep strain data is based on that used for stress rupture data - see Doc. Ref. 5524/WG1/114.[1] The four major steps in the assessment system are:-

(i) Data input as strain (ε) v time (t) curves for 'n' individual tests at 'X' temperatures.

(ii) From each ε/t curve, determine t_x for selected strain values (x = strain value).

For each strain and temperature, combine all data into an 'isothermal' plot of σ v t.

Data from isothermal curves in Fig. 2 used as input for determinations of master curve, log σ v parameter etc.

2. <u>Procedure Details</u>

Figs. 1-3 show in detail the steps used in the assessment procedure which are particular for creep strain data. However, some preliminary steps are required. The full procedure is:-

2.1 Set/accept/agree specification for material to be assessed.

2.2 Collect creep strain data (ε v t pairs) for material batches conforming with 2.1.

Plot 'raw' strain v time for individual tests and determine from <u>each</u> plot by a curve fit technique (often hand/eye fit is sufficiently acceptable) the test durations for selected strain values, e.g. 0.1, 0.2, 0.5, 1% (Fig. 1). Record time to each strain value from all curves in suitable file(s).

2.4 From file(s) in 2.3, plot for each strain level and temperature, stress v time (Fig. 2). Examine these plots for consistency and determine reasons for any outlying points. Correct any errors derived from Fig. 1.

Determine best curve through data points in Fig. 2 by appropriate means, <u>within</u> the time span range of the data, i.e. no extrapolation beyond longest duration data point.

[1] App. D1a

2.6 Combine curves for selected strain levels from 2.5 for each temperature into one graph, (Fig. 3). Check for consistency of behaviour pattern. Where such curves are not consistent, review data and curve fitting, taking account of cast by cast trends, in Fig. 2. It is often useful to plot similar curve families for each selected strain level for temperatures contributing data to assess consistency of behaviour pattern, e.g. Fig. 4.

2.7 From each consistent sets of curves (Figs. 3 and 4), determine for each strain level, stress/time/temperature combinations at selected times, e.g. 100, 1,000, 3,000, 5,000, 10,000 h etc., always remaining within the duration span of the data, Figs. 2 and 3.

2.8 Use the determined stress/time/temperature combinations from 2.7 as input for master curves determinations (one per strain level) as per 5524/WG1/114.[1]

2.9 From master curves, determine stress values for selected time/temperature pairs and plot on the various Fig. 2s to check the accuracy of positions and trend within the data point distributions. Adjust input data for master curve plots, if required after this examination, and re-run master curve determination(s). A useful check at this stage is to plot all master curves (one/strain level) on one graph to check for consistency of overall behaviour pattern.

2.10 From acceptable master curves, record parametric and master equations and determine table of stress/time/temperature values for each strain level, e.g. Table 1.

[1] App. D1a

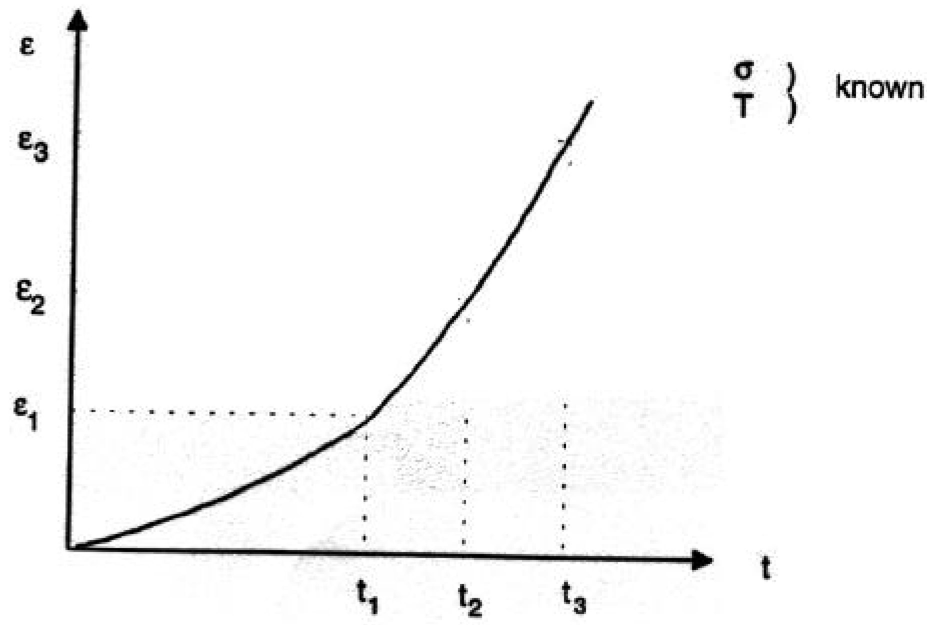

FIG. 1 CREEP STRAIN CURVE AT KNOWN STRESS AND TEMPERATURE

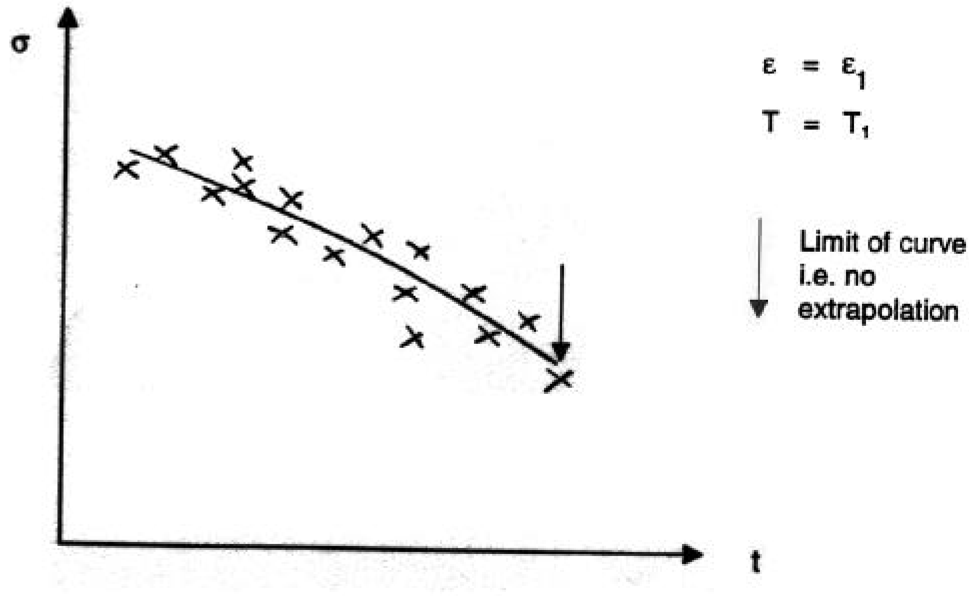

FIG. 2 ISOTHERMAL CURVE FOR EACH STRAIN LEVEL

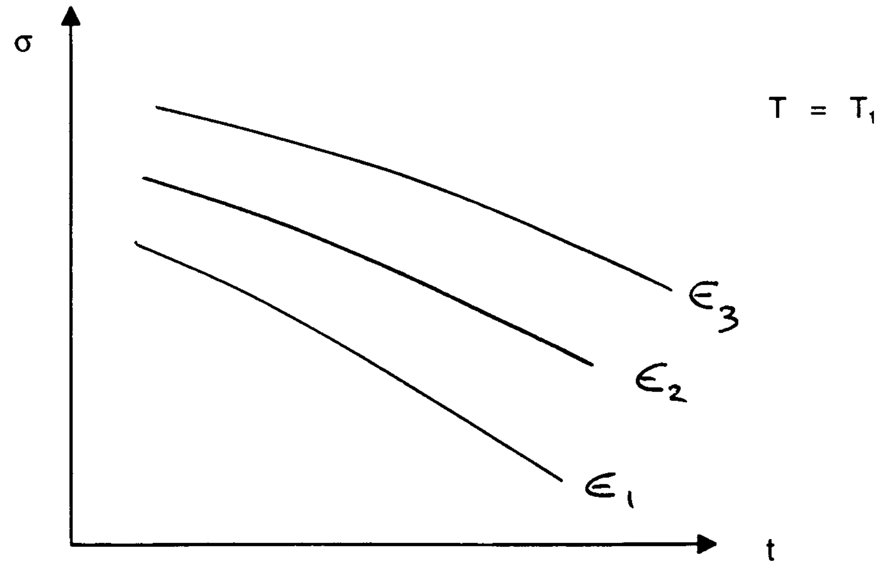

FIG. 3 ISO-STRAIN CURVES FOR GIVEN TEMPERATURE

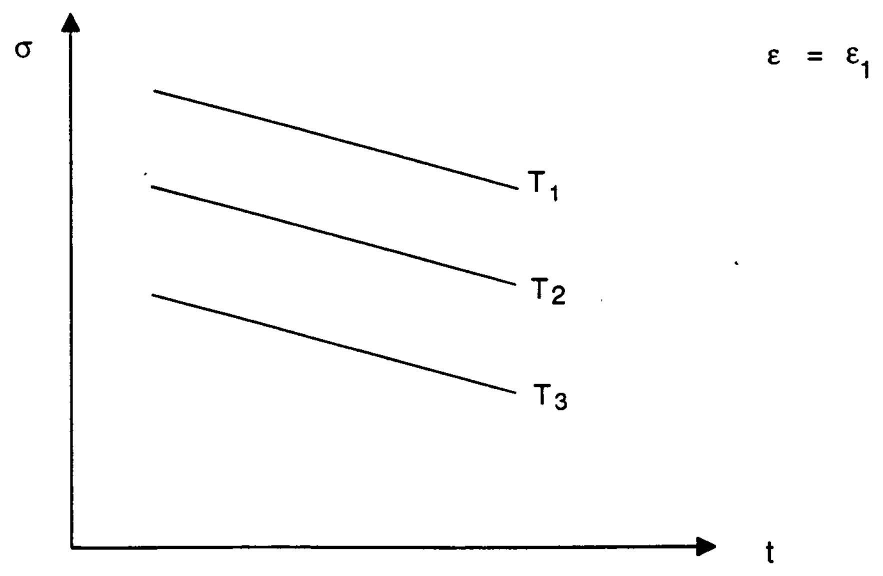

FIG. 4 ISOTHERMAL CURVES FOR GIVEN STRAIN LEVEL

Table 1
ISO 6303 Assessment of Creep Strain Data by British Steel

2¼ CrMo steel

Temp °C	Stress (N/mm^2) at Duration h						
	100	1,000	3,000	10,000	30,000	100,000	200,000
0.02% Strain							
450		169	134	98	66	40	29
500		67	41	24	14	-	-
550		16	-	-	-	-	-
600		-	-	-	-	-	-
0.2% Strain							
450	350	253	212	171	137	105	89
500	220	142	109	80	60	43	36
550	124	66	48	34	24	16	12
600	57	29	20	12	-	-	-
1.0% Strain							
450	-	376	329	280	236	189	164
500	290	218	184	149	118	87	71
550	186	123	98	74	55	37	29
600	107	65	50	35	24	-	-
Rupture							
450	-	408	362	311	264	214	185
500	326	257	220	181	146	111	93
550	220	160	133	104	81	59	46
600	146	100	80	61	44	-	-

APPENDIX D2

ECCC DESA PROCEDURE DOCUMENT

J Granacher & M Monsees [IfW TU Darmstadt]

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Appendix D2

DESA Assessment Procedure Document for DESA, Version 2.2, 20.2.95

J Granacher and M Monsees
Institut für Werkstoffkunde, TH Darmstadt, Germany

Overview

The programme DESA is a highly flexible tool for applying time-temperature parametric equations for the assessment of rupture data and creep strength data. A full range of parametric equations may be assessed, comprising a selectable time temperature parameter in combination with a polynomial of a monotonic function of stress σ_0 in the form σ_0^m, m = 0.1 to 1 or $\log\sigma_0$. The order of polynomial can range from 2 to 5 and DESA has been prepared for all of these functions to be selectable from a menu. The programme has not yet been used to generate strength values for standards, but has been used for homogeneously as well as inhomogeneously distributed, single heat and multi-heat data sets.

All data are fitted simultaneously, with log(time) as the dependent variable, and by applying log-normal statistics. Although statistical measures are available to the analyst following the fitting process, these are provided as a guide only. The analyst is expected to use their metallurgical judgement to decide which function best represents the data. Special methods are applied to overcome non-physical behaviour of 2nd and 3rd order polynomials and certain linear and non-linear coefficients can be adjusted manually. These methods can also be used to fit correlated curve families comprising stress rupture curves as well as stress to specific strain curves. Moreover, a temperature dependent time correction is possible to influence the position and slope of isothermal curves in the range of lower temperatures.

In this paper, information is given in chapter 1 concerning the acquisition of DESA and the which hardware and software components are necessary. Further, a guide for the installation of DESA is given. The DESA time-temperature-parameter evaluation method available in DESA 2.2 is described in chapter 2 with the basic equations and details of the statistical methods applied. In chapter 3 a guideline follows giving advice for the use of DESA for creep rupture assessment or creep strength assessment to be carried out with a comprehensive multi-heat data set.

This paper replaces all earlier publications on DESA* distributed within WG1 of ECCC, ie:

The DESA Time-Temperature-Parameter Evaluation Method (Programme DESA 2.01), Doc. ref. 5524/WG1/52, section B, Pages B1 to B18, June 1993.

Leaflet about Programme DESA 2.01, 15.5.94, Doc. ref. 5524/WG1/74, October 1993.

DESA Input Format, IfW TH Darmstadt, 20.9.1993.

DESA Assessment Procedure Document, Version 1, IfW TH Darmstadt, 31.10.94.

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* The authors express their thanks to Dr.-Ing. T Preußler who prepared the first version of DESA and to Dr.-Ing. M. Oehl who made valuable contributions to the subsequent development of DESA

1 AVAILABILITY, REQUIREMENTS AND INSTALLATION OF PROGRAMME DESA

DESA is available for data assessment in the frame of ECCC with the agreement of the Forschungsvereinigung Verbrennungskraftmaschinen e.V., c/o Mr Dipl-Ing Geisendorf, Lyoner Str 18, Postfach 71 08 64, D 60 498 Frankfurt/M., Fax (49) 69 6603 673. To obtain DESA, please write or fax a short informal letter to Mr Geisendorf, indicating your interest to obtain DESA application within ECCC. After agreement transmitted from Mr Geisendorf to Institut für Werkstoffkunde (IfW), you can order the programme at the Institut für Werkstoffkunde, Grafenstr. 2, D 64 283 Darmstadt, Germany, Fax (49) 6151 16 5659, Phone (49) 6151 16 2451 in the form of executable binary files. Please fill out the questionaire annexed and send it with the order to IfW to enable adaptation of the programme for the hardware configuration of your computer. The delivery of DESA includes a detailed handbook written in the German language. The handbook contains example results from a test data set included in the binary files.

The cost for the adaption of the programme is DM 950,-. Additionally a license of DM 805,- must be purchased for the graphical output library, GKS GRAL 74/Vers.3.3, contained in DESA. In the latter amount a value added tax of DM 105.- is included, which can be refunded in the country of destination. All costs are valid for 1995. The total amount of 1,755.-DM has to be submitted to IfW.

The following requirements are to be considered.

Hardware System Requirements: An IBM compatible PC of type 80 386 or higher, numeric co-processor, hard disc, graphic card, printer or plotter

Memory Requirements:	
Main storage:	8 MByte
Hard disc space:	6 MByte

Programme Requirements:	
Binary files:	DESA, CCGMPL, GO32
Operating system:	PC-DOS 4.0 or MS-DOS Version 3.1 or higher
Graphic:	GKSGRAL 7.4/Ver. 3.3

For the installation of DESA the user should carry out the following actions:

a) Put the disk #1 into the disk drive.

b) Start the installation programme INSTALL.BAT. The installation programme needs two variables. The first variable is the name of your disk drive (eg B:) and the second variable is the name of the target partition on the hard disk (eg E:). The installation command for this example is "INSTALL B: E:".

c) When the installation procedure has been successfully completed, the user has to add the following commands:

E:\GTSGRAL\FONTS\VGAINT.COM
SET_GTS FONTS=E:\GTSGRAL\FONTS
SET DOSX=-SWAPDIR E:\

into the file AUTOEXEC.BAT.
Thereafter, the user has to reboot the system.

Important advice: To get a graphic output from DESA neither a memory manager (eg EMM 386 or QEMM 386) nor the RAMDRIVE or SMARTDRIVE utilities may be loaded into memory. The corresponding commands should be removed from the file CONFIG.SYS.

After the actions a) to c) the programme can be started with the command DESA.

2 THE DESA TIME-TEMPERATURE-PARAMETER EVALUATION METHOD

2.1 Introduction

The programme DESA is a tool for calculating mean stress-time curves with stress to a specific strain or rupture stress. The calculation is carried out by means of a model-function based on a stress function and a time-temperature parameter $P(t,\vartheta)$ (Fig.1). Individual test materials as well as classes of materials can be evaluated.

The program requires the results of creep and creep rupture tests as input data, especially the test temperature ϑ, the stress σ_0 and the time t to specific strain or to rupture. The evaluation of the mean curves is based on a multi-linear or multi-non-linear regression analysis of a polynomial master curve, which describes a time-temperature parameter $P(t,\vartheta)$ in dependence of a polynomial of a monotonic stress function $f(\sigma_0)$ as σ_0^m with $0.1 \leq m < 1$ or $\log \sigma_0$. The number M of the coefficients of the polynomial can be choosen between 5 and 2, starting at the maximum number of 5. The stress function and the time-temperature parameter can be selected from a menu. The exponent m has to be selected. The constants of the time-temperature parameter may be determined within the regression analysis or they may be entered manually. Special criterions can be applied to second and third order polynomials. Subsequent to the fitting, the significance of the mean curves is indicated by statistical test values.

After calculating the mean curves, it is possible to review the results in diagrams $\log \sigma_0$ versus log t as well as in diagrams $\log \sigma_0$ versus $P(t,\vartheta)$. Additionally, the mean curves can be shown in a representation of $\log \sigma_0$ versus ϑ, and of ϑ versus log t (Fig.2).

2.2 Regression analysis

2.2.1 Multi-linear regression analysis

Often, the evaluation of the data (temperature ϑ (°C), stress σ_0 (MPa), time to specific strain or rupture time t (h)) can be based on an multi-linear regression analysis of a polynominal master curve, which describes a time-temperature parameter $P(t, \vartheta)$ in dependence of a polynomial of the stress function $f(\sigma_0)$

$$P(t,\vartheta) = \sum_{j=1}^{M} b_j \cdot f(\sigma_0)^{j-1} \qquad (1)$$

with M = 5, 4, 3 or 2.

Resolving eq.(1) with respect to the logarithm of time log t which is in the following written as lg t and transforming it into notation of regression analysis, one obtains

$$y = B_0 + \sum_{j=1}^{M} B_j \cdot x_j \qquad (2)$$

with the dependent variable y = lg t, the independent variables $x_j = g_j(\vartheta, f(\sigma_0))$ and the coefficients B_j. The determination of the coefficients B_j, j = 1, M is carried out according to the usual methods of multi-linear regression analysis as applied in [1] and as described by example in [2) 3)]. For i = 1, N data points with the observed values y_i and x_{ij}, eq (2) is written in the form

$$Y_i = B_0 + \sum_{j=1}^{M} B_j \cdot x_{ij} \tag{3}$$

with Y_i being the estimate of the observed value y_i. Minimizing the sum of squares

$$S^2 = \sum_{i=1}^{N} \left(y_i - Y_i\right)^2 \tag{4}$$

leads to the following condition for the partial derivatives:

$$\partial S^2 / \partial B_j = 0, j = 0, M \tag{5}$$

Equation (5) results in a linear system of M + 1 equations to obtain the coefficients B_j. Using the transformations

$$\bar{y} = \frac{1}{N} \cdot \sum_{i=1}^{N} y_i \,, \quad \bar{x}_j = \frac{1}{N} \cdot \sum_{i=1}^{N} x_{ij} \,, j = 1, M \tag{6}$$

the coefficient B_0 can be calculated according

$$B_0 = \bar{y} - \sum_{j=1}^{M} B_j \cdot \bar{x}_j \tag{7}$$

The transformations

$$\begin{aligned} \bar{\bar{y}}_k &= \sum_{i=1}^{N} \left(x_{ik} - \bar{x}_k\right) \cdot \left(y_i - \bar{y}\right) \,, \\ \bar{\bar{x}}_{kj} &= \bar{\bar{x}}_{jk} = \sum_{i=1}^{N} \left(x_{ik} - \bar{x}_k\right) \cdot \left(x_{ik} - \bar{x}_j\right) \,, k = 1, M; j = 1, M \end{aligned} \tag{8}$$

lead to a linear system of M equations for the coefficients B_j, j = 1,M

$$\bar{\bar{y}}_k = \sum_{j=1}^{M} B_j \cdot \bar{\bar{x}}_{kj} \,. \tag{9}$$

The inverse matrix

$$\bar{\bar{c}}_{kj} = \bar{\bar{x}}_{kj}^{\,-1} \tag{10}$$

may be determined using the Gauss-algorithm [4)]. Then, the coefficients B_j can easily be calculated by

$$B_j = \sum_{k=1}^{M} \bar{\bar{c}}_{jk} \cdot \bar{\bar{y}}_k \quad \text{with } j = 1, M \,. \tag{11}$$

2.2.2 Statistical data

The quality of the regression analysis may be characterized by statistical data, ie by the standard deviation

$$s = (S^2/(N\text{-}M\text{-}1))^{1/2} \tag{12}$$

which is calculated from the minimum sum of squares according to eq (4), the number of data points N and the number of coefficients M. Furthermore the coefficient of determination

$$r^2 = \sum_{i=1}^{N} (Y_i - \bar{y})^2 / \sum_{i=1}^{N} (y_i - \bar{y})^2 \tag{13}$$

can be calculated. The 90%-confidence limits may be estimated [2) 3) 4)] according to

$$Y_{5\%}, Y_{95\%} = Y \pm 1{,}64 \cdot s \tag{14}$$

which means, that a single, additional data point will be determined between the values $Y_{5\%}$ und $Y_{95\%}$ with an estimated probability of 90%. These estimated values are used for the determination of the upper and lower limitations of the scatterband in the lg σ_0 versus P(t, ϑ) diagram.

The test value

$$t_j = B_j / \left(\bar{\bar{c}}_{jj} \cdot s^2 \right)^{\frac{1}{2}} \tag{15}$$

is calculated to check, if a coefficient is systematically different from zero. If the test value t_j is greater than the value $t_{0,05}$(N-M-1) of the t- or student-distribution[2)], the coefficient B_j is different from zero with a probability of 95%.

2.2.3 Non-linear regression analysis

Non-linear regression analysis presumes the same model function, eq (2), as multi-linear regression analysis, but the independent variables $x_j = g_j(\vartheta, f(\sigma_0))$ additionally contain non-linear coefficients C_l, l = 1, L. These non linear coefficients are optimized by variations between an upper and a lower limit of each coefficient. For each variation a multi-linear fitting is carried out in which the standard deviation

$$s = (S^2/(N\text{-}M\text{-}L\text{-}1))^{1/2} \tag{16}$$

is determined. The combination of non-linear coefficients C_l which represents the lowest sum of squares S^2 is selected as the optimum solution. Generally, the program DESA uses eq (16) to calculate the value s. If linear or non-linear coefficients are set or in other words are manually entered in DESA, the characteristic value of the regression analysis N-M-L-1 is adapted by reduction of L by 1 for each coefficient which is set.

Normally the stress function $f(\sigma_0)$ used in eq (1) is one of the monotonic functions $f(\sigma_0) = \lg \sigma_0$ or $f(\sigma_0) = \sigma_0^m$ with $0.1 \leq m \leq 1$. The second term requires an input of the non linear coefficient m. In this exceptional case, the value L is not changed.

2.3 Model functions

The following time-temperature parameters $P(t, \vartheta)$ can be selected from a menu in the program DESA with $T = \vartheta + 273$:

- Larson-Miller parameter [5]:
  $P_{LM} = T\cdot(C + \lg t)$, (17)
  with the constant C;

- Sherby-Dorn parameter [6]:
  $P_{SD} = \lg t - D/T$ (18)
  with the constant D;

- Manson-Haferd parameter [7]:
  $P_{MH} = (\lg t - \lg t_a)/(T - T_a)$ (19)
  with the constants t_a and T_a;

- Manson-Brown parameter [8]:
  $P_{MB} = (\lg t - \lg t_a)/|T - T_a|^R$ (20)
  with the constants t_a , T_a and R.

If these parameters are combined with the polynomial of the stress function, eq (1), and the resulting equation is transformed according to eq (2) the following model functions result, which may be applied to calculate mean curves of stresses to specific strain or to rupture.

Based on the Larson-Miller parameter P_{LM} one obtains

$$\lg t = B_0 + \frac{1}{\tau} \cdot \sum_{j=1}^{M} B_j \cdot f(\sigma_0)^{j-1} \tag{21}$$

with $\tau = (\vartheta+273)/1000$ and the Larson-Miller constant $-C = B_0$. The coefficients B_j , $j = 0, 5$ can be determined with multi-linear regression analysis. Moreover it is possible to set the coefficient B_0 manually. In this case, the value L is reduced by 1.

Based on the Sherby-Dorn parameter P_{SD} one obtains

$$\lg t = B_0 + \frac{B_1}{\tau} + \sum_{j=2}^{M} B_j \cdot f(\sigma_0)^{j-1} \tag{22}$$

with $\tau = (\vartheta+273)/1000$ and the Sherby-Dorn constant $D = B_1 \cdot 1000$. The coefficients B_j , $j = 0, 5$ result from multi-linear regression analysis. The constant D may be entered manually. In this case, the value L is reduced by 1.

Based on the Manson-Haferd parameter P_{MH} one obtains

$$\lg t = B_0 + \tau_1 \cdot \sum_{j=1}^{M} B_j \cdot f(\sigma_0)^{j-1} \tag{23}$$

with $\tau_1 = (\vartheta+273-T_a)/1000$ and the Manson-Haferd constants T_a and $\lg t_a = B_0$. The non-linear coefficient T_a is optimized for a parabolic polynominal (M = 3), applying stepwise multi-linear regression analysis within the limits $10 \leq T_a \leq T_{min} - 10$ and $T_{max} + 10 \leq T_a \leq 3000$. T_{min} and T_{max} are the minimum and maximum temperatures which are determined by DESA from the data to be assessed. According to chapter 2.2.3 the optimum of the value T_a is characterized by the lowest sum of squares S^2. The constant T_a as well as the constant $\lg t_a$ may be entered manually. In this case, the value L is reduced by 1 or 2 respectively.

Based on the Manson-Brown parameter P_{MB} one obtains

$$\lg t = B_0 + \tau_2 \cdot \sum_{j=1}^{M} B_j \cdot f(\sigma_0)^{j-1} \tag{24}$$

with $\tau_2 = (|\vartheta+273-T_a|/1000)^R$ and the Manson-Brown constants T_a, $\lg t_a = B_0$ and R. The non-linear coefficient T_a is determined as described above for the Manson-Haferd parameter. Additionally the exponent R is optimized within the limits $-1 \leq R \leq 2{,}5$. According to chapter 2.2.3 that combination of the values T_a, $\lg t_a$ and R is taken, which represents the lowest sum of squares S^2. Moreover it is possible to enter the constants T_a , $\lg t_a$ and R manually. According to the number of coefficients entered manually, the value L is reduced by 1, 2 or 3.

As a general guideline for the use of the DESA model functions it is recommended to use quadratic or at the most cubic polynomials and to vary the stress function rather than to use higher polynomial degrees. Further it is recommended to use several different functions (and time-temperature-parameters) and to select the function which gives the best data fit in the long term region of data rather than that presenting the lowest standard deviation. If a perfect fit in the long term region is not to obtain one should attain an optimum long term fit for the mean and higher temperatures and subsequently perform a temperature dependent time correction in the region of lower temperatures (see chapter 2.5). In some cases an optimum fit for a family of correlated curves is of interest, eg for the stress - time to rupture - curves and several stress - time to plastic strain - curves. In these cases special forms of the polynomial of the stress function can help to obtain the optimum solution, see the next chapter. A more detailed guideline for the DESA-assessment of multi-heat data is given in chapter 3.

More detailed information about DESA can be found in the DESA-handbook [9)] which is however written in the German language.

2.4 Special form of polynomials of stress function

Special evaluation methods can be carried out with model functions, eq (21) to (24) with polynomials of third (M = 4) and second (M = 3) order. In a $f(\sigma_0)$ versus P diagram, model functions with a polynomial of third order are characterized by a point of inflection at stress σ_W (Fig.3a). Additionally, they may have two vertices at stresses σ_{E1} and σ_{E2} (Fig.3b). Model functions with a polynomial of second order are always characterized by a vertex at stress σ_E and parameter P_E (Fig.3c). The vertex or vertices of a master curve should normally be situated outside the data points with a sufficient distance. If the regression analysis does not fulfill this condition the model function can be adapted by fixing the σ_0-coordinate of the point of inflection or of the (vertex) vertices and the regression analysis is repeated under this special condition. For a second order polynomial it is also possible to fix simultaneously the σ_0- and the P-coordinate of the vertex.

Supposing a third order polynominal (M = 4, Fig.3a, b), the coordinates of the point of inflection can be calculated according to

$$f(\sigma_W) = - b_3/3 \cdot b_4 \tag{25}$$

and the coordinates of the vertices according to

$$f(\sigma_{E1}) = (-b_3 + D^{0,5}) / 3 \cdot b_4 \tag{26}$$

$$f(\sigma_{E2}) = (-b_3 - D^{0,5}) / 3 \cdot b_4 \tag{27}$$

with $D = 3 \cdot b_2 \cdot b_4 - b_3^2 > 0$. If the coordinate σ_w is fixed, the model function according to eq. (1) results in

$$P(t,\vartheta) = b_1 + b_2 f(\sigma_0) + b_3 f(\sigma_0)^2 \left(1 - \frac{f(\sigma_0)}{3 \cdot f(\sigma_W)}\right) \tag{28}$$

If the coordinates σ_{E1} and σ_{E2} of the vertices are fixed, the model function results in

$$P(t,\vartheta) = b_1 + b_2 \cdot f(\sigma_0) \cdot \left(1 - \frac{S \cdot f(\sigma_0)}{2 \cdot F} + \frac{f(\sigma_0)^2}{3 \cdot F}\right) \tag{29}$$

with $S = f(\sigma_{E1}) + f(\sigma_{E2})$ and $F = f(\sigma_{E1}) \cdot f(\sigma_{E2})$. Third order polynomials may particulary be used for the evaluation of materials, which show S-shaped curves in the $\lg\sigma_0$ versus lg t diagram (example Fig.4) and in this special case the inflection point can be situated inside the data points.

For a second order polynomial (M = 3, Fig.3c), the σ_0-coordinate of the vertex is determined according to

$$f(\sigma_E) = - b_2 / 2 \cdot b_3 \tag{30}$$

If the coordinate σ_E is fixed the model function results in

$$P(t,\vartheta) = b_1 + b_2 \cdot f(\sigma_0) \cdot \left(1 - \frac{f(\sigma_0)}{2 \cdot f(\sigma_E)}\right) \tag{31}$$

For third and second order polynomials, the regression analysis is carried out on the basis of eq (28), (29) or (31), which are combined with a time-temperature parameter according to eq (17), (18), (19) or (20) and transformed into an equation for the value lg t.

Concerning the regression analysis, a second order polynominal with a fixed σ_E-coordinate of its vertex is equivalent to a linear fitting (M=2) and may be interpreted as a master curve with defined "curvature". For test values of inferior quality this kind of defining the curvature can be more suitable than a linear regression analysis (M = 2) with a definition of the curvature by variation of the exponent m of the stress function $f(\sigma_0) = \sigma_0^m$. Details will be given below.

Additionally, it may be of interest for a second order polynominal with a fixed σ_E-coordinate of the vertex to define the "slope" of the master curve. This is possible by an additional fixing of the coordinate P_E of the vertex (Fig.3c).

Placing the value P_E in eq (31), the expression

$$b_2 = 2\,(P_E - b_1)/f(\sigma_E) \tag{32}$$

is obtained. Combining eq (29) and (32), the model function

$$P(t,\vartheta) = b_1 + 2(P_E - b_1)\frac{f(\sigma_0)}{f(\sigma_E)} - (P_E - b_1)\left(\frac{f(\sigma_0)}{f(\sigma_E)}\right)^2 \tag{33}$$

is derived, which has a fixed vertex position (P_E ,$f(\sigma_E)$). If the model function is specified in such a extensive manner, it is convenient, to enter the constants of the time-temperature parameter manually. Then, only the coefficient b_1 of eq (29) had to be determined from the data points. Transforming eq (33) with respect to b_1 , the following expression is obtained:

$$b_1 = P_E + \frac{P - P_E}{(1 - f(\sigma_0)/f(\sigma_E))^2} \quad . \tag{34}$$

In this case, the regression analysis is reduced to a determination of the mean value $\bar{b}_1$ for all data points:

$$\bar{b}_1 = \frac{1}{N}\sum_{i=1}^{N} b_1(\vartheta_i, \sigma_{0i}, t_i) \quad , \tag{35}$$

with b_1 according to eq (34) and the time-temperature parameter according to eq (17), (18), (19) or (20). After the determination of the coefficient $\bar{b}_1$ according to eq (35), eq (33) is transformed into the model function according to eq (21), (22) (23) or (24).

Partial fixing (σ_E) or total fixing (σ_E , P_E) of the vertex of a master curve is convenient, if stresses to several specific strains have to be simultanously interpreted for one material or in other words, if a "curve family" of correlated curves has to be fitted. In most of this cases the number of test values for stresses to reach the lower specific strain values is relatively small. Then the slope of the correspondent mean curves probably does not match well with the mean curves for the higher specific strain values if a normal regression analysis is performed with "free" coefficients b_1 , b_2 and b_3 . An example of such a fixing procedure is shown in [10)], Fig.5. Normally the fixing is accompaigned by fitting the course of σ_E ε_p-curves and if necessary P_E - ε_p-curves (Fig.6). The procedure of fixing the curvature and the slope by fixing the vertex (σ_E , P_E) is comparable with a graphic evaluation method, where it is possible to transfer experiences from curves with sufficient number of test values to curves with an insufficient number of test values. However, a trial should be always given first to fix only the value $f(\sigma_E)$.

Nevertheless, it is possible, that single curves of a set do not run parallel, due to different centres of gravity of the test values, eg Fig.7. In this case it is possible to enter the coefficient b_1 manually, too.

In any case and especially, if fixing of coefficients of a master curve or of a set of master curves is carried out, the interpretation of the test values should be visually checked in the lg σ_0 versus lg t diagram as recommended in DIN 50 118, appendix C and especially the fit of the long term data should be considered in this case.

2.5 Temperature dependent time correction

This correction is developed to overcome a principal disadvantage of time temperature parameters, ie the often too strong slope of isothermals in the range of the lowest test temperatures. This is due to a stress and temperature dependent course of creep exponent n, which cannot considered by the parameter if the temperature and thus stress range ist relatively large and if different creep mechanisms are existing in this range. As an example, for low alloy ferritic or bainitic steels, there is often a change in slope between the 450°C-region and the 500°C-region and higher.

The correction method developed is based on the experience (Fig.8) that the deviation of the measured data points with time t from the calculated DESA points with time t' can be described by

$$t/t' = c \cdot t^d \quad . \tag{36}$$

The constants c and d can be determined in DESA by regression analysis for any test temperature which presents a sufficient number (≥5) of data points. If the constants are plotted against temperature ϑ in the range ϑ_{min} to ϑ_{max} of the data (Fig.9a, b), the value c = 1 and d = 0 should be attained for the higher temperatures until ϑ_{max}. If this is not the case, the model function should be further improved (see guideline for the use of DESA, chapter 3). If finally the conditions c < 1 and d > 0 are fulfilled in the region near ϑ_{min}, a temperature range $\vartheta_{min\,a}$ to $\vartheta_{min\,b}$ has to be selected, between which the temperature correction shall be carried out. In this temperature range the fit of the data by the corrected isotherms is to be checked. To this purpose, eq (36) is modified to

$$t^* = (c \cdot t')^{1/(1-d)} \tag{37}$$

with corrected time t*. As a result of this check, the coefficient $d_{max} = d(\vartheta_{min\,a})$ is adjusted to give an optimum interpretation at least to the slope of the correspondent isotherm and further $d(\vartheta_{min\,b}) = 0$ is set. Now the coefficient $d(\vartheta)$ is interpolated between $\vartheta_{min\,a}$ and $\vartheta_{min\,b}$ by a 3rd degree parabola

$$d = d_0 + d_1 \cdot \vartheta + d_2 \cdot \vartheta^2 + d_3 \cdot \vartheta^3 \tag{38}$$

with the conditions $d(\vartheta_{min\,a}) = d_{max}$, $d(\vartheta_{min\,b}) = 0$, $dd/d\vartheta(\vartheta_{min\,a}) = 0$ and $dd/d\vartheta(\vartheta_{min\,b}) = 0$, ie with horizontal tangents at the ends of range $\vartheta_{min\,a}$ to $\vartheta_{min\,b}$ (Fig.9d). In the next step, the optimum values of coefficient d are calculated with eq (36) and with d from eq (38). For the resulting values of c (Fig.9c) again the fit of data points by the corrected isotherms is checked and if necessary, the coefficient $d(\vartheta_{min\,a}) = d_{min}$ is further adjusted. On this basis the coefficient $d(\vartheta)$ is interpolated between $\vartheta_{min\,a}$ and $\vartheta_{min\,b}$ by

$$c = c_0 + c_1 \cdot \vartheta + c_2 \cdot \vartheta^2 + c_3 \cdot \vartheta^3 \tag{39}$$

with the condition $c(\vartheta_{min\,a}) = c_{min}$, $c(\vartheta_{min\,b}) = 1$, $dc/d\vartheta(\vartheta_{min\,a}) = 0$ and $dc/d\vartheta(\vartheta_{min\,b}) = 0$. Finally the correction with eq (38) (39) and (37) is again applied to the isotherms and if the interpretation of the corrected isotherms is sufficient and no cross over occurs for isotherms in 25°C steps the correction is finished. An example of this correction applied to steel type 2.25Cr-1Mo (Fig.10) demonstrates the usefulness of the method and the improvements on the isothermal rupture curves in the range 450 to 500°C [11].

2.6 DESA input format for ASCII-data

The usual data input of DESA is via the input menu. However, another input facility concerns ASCII-data.

The ASCII-input data set has the following general form

```
Kommentar:    WSKOM
Dehngrenzen: TPE(1) TPE(2) ... TPE(9) Tm
 NR:no NAME:name REC:rec BEM:kom
 DATEN(1,1)DATEN(1,2)DATEN(1,3).........DATEN(1,12)      dataset
     .          .          .          .                  for a unique
     .          .          .          .                  test material
     .          .          .          .
 DATEN(rec,1)DATEN(rec,2)DATEN(rec,3)...DATEN(rec,12)
 NR:no NAME:name REC:rec BEM:kom                         next dataset
 DATEN(1,1)DATEN(1,2)DATEN(1,3).........DATEN(1,12)      for a unique
     .          .          .          .                  test material
     .          .          .          .
     .          .          .          .

 DATEN(rec,1)DATEN(rec,2)DATEN(rec,3)...DATEN(rec,12)
```
and so on.

The number of each time to specific strain or of rupture time may not exceed 2000.

The definition and format of the input variables is described in Table 1. An example is given in Table 2.

2.7 Further development of DESA and associated programmes

The programme DESA is in further development. Some goals are indicated below, they are partly in accordance to proposals in [12]. Some improvements to be realized within the short term concern:

- revised format for the test material identifier (Table 1) to allow longer unique material names,
- input facility for the polynomial degree, from which the regression analysis starts,
- input facility to introduce a user configurable assessment number for the DESA output,

- facility to safe a user configurable sequence of temperatures within the data set of a material for the output of isotherms or for the temperature dependent time correction (see chapter 2.5),

- tabulation of results as isotherms, isostats, isochrones and master curves of the parametric model function,

- facility to allow discrete values of stress, time or temperature to be calculated from the model function.

Some improvements to be realized within the medium term concern:

- facility to fix additionally to the stress value σ_W the parameter value P_W of an inflection point of a cubic polynomial (see chapter 2.4),

- improved charts to include title, axes labels, curve labels or style key, data point style key and comment box into the graphical DESA-output.

Further improvements to be realized within longer time concern:

- reduction in repetitive data input sequences when calculating model functions,

- batch processing facility for calculating model functions,

- introduction of additional pre- and post-assessment facilities into DESA (see [11]) and chapter 3),

- an English version of DESA with an English handbook.

Some of the above mentioned future improvements of DESA are available at present from the programmes ZDESA and PASAC associated to DESA. These programmes have direct access to the DESA input data and to the model functions determined in DESA. ZDESA tabulates isotherms for given temperature and time values. The isotherms are calculated with a model function determined in DESA. PASAC plots isotherms in 25°C-steps from ϑ_{min}- at maximum 25°C until ϑ_{max} + at maximum 25°C. Further, PASAC performs the calculations and graphical presentations of the post-assessment criteria as defined in Vol.5 of ECCC [13]). Examples of PASAC-results are to be seen in [11]). ZDESA and PASAC are available on request from IfW.

3 GUIDELINE FOR THE USE OF DESA FOR MULTI-HEAT DATA ASSESSMENT

3.1 Purpose of the guideline and data pre-assessment

The guideline relates to the assessment of a stress-time-temperature-multi-heat data set which contains at least more than 3 unique test materials (heats). The time is either rupture time or time to a specific plastic or creep strain. For the assessment, DESA contains a practically infinite number of possible model functions, as is shown in chapter 2. The purpose of this guideline is to give help to a user of DESA who is a material expert to come quickly to an optimum creep or rupture data assessment on the basis of a multi-heat data set. For this, the steps in chapter 3.2 are recommended, which are restricted to a single data type, either rupture data or data for a unique specific strain value.

The data set should previously be submitted to a data pre-assessment which assures a sufficient data homogeniety. Three different pre-assessments are of interest.

In a first pre-assessment regarding the pedigree data it should be assured that the data characterizing the manufacturing of the material and the product as well as the chemical composition, heat treatment, structural properties and mechanical short term properties are within the specifications of the material type of interest. This aspect should be addressed without DESA.

In a second pre-assessment regarding the distribution of the test parameters, ie. temperature and stress and the resulting characteristic time, eg rupture time it should be checked whether these data are uniformely distributed for all unique test materials. This ideal goal is only approximated in the normal case. An indication that the data homogeniety is sufficient can be concluded from the observation that the maximum test time is sufficiently long for several temperatures covering a relevant part of the temperature range which is typical for the test material, eg Table 3. To reduce regression pinning, the data can be diluted in regions of relatively high data density. A simple method is being developed by IfW at present. If this method will be successful it will be included into DESA.

In a third pre-assessment the scatter of the test results, i.e. of the characteristic time is to be considered. It is proposed to perform a first assessment with DESA, preferably according to the general guideline described at the end of chapter 3, ie with a simple time-temperature-parameter eg P_{LM} (eq (17)) and a quadratic polynomial of stress function σ_0^m with m = 0.1 or 0.5. On this basis one should consider the data points in the $\log\sigma_0$-parameter-diagram. If a greater part of the data of a unique test material is outside the mastercurve with parameters $P(T_m, \lg t \pm 1.64\ s)$, ie approximately outside the 90%-confidence limits (T_m being the mean temperature of the long term data range and s being taken from eq (12)) all data of that unique material should be removed from the whole data set. If a single data point is outside the range $P(T_m, \lg t \pm 2.58\ s)$, ie approximately outside the 98%-confidence limits, the data point can assumed to be an outlier and can be removed from the data set.

After these pre-assessment steps the DESA assessment can go on as described in the next chapter. Other considerations concerning the scatter of test results are part of the post-assessment [13)] to be performed after the DESA assessment.

3.2 Stepwise DESA assessment

The DESA assessment is recommended to be performed in the following steps which are part of a DESA pre-assessment carried out with selected unique material data sets and a DESA main assessment carried out with the whole data set to be considered.

Step 1. From the whole data set of the steel type, the three best tested unique materials (heats) have to be chosen for the DESA pre-assessment. "Best tested heat" means a heat tested over the usual stress-time-temperature range of the steel type with a uniform data distribution up to the longest time at least at a lower, a mean and a higher temperature and as a recommendation but not mandatory at a high extrapolation temperature down to a stress corresponding to the lowest stress at the highest long term temperature. The easiest way to determine these heats is to examine a listing of the data and to plot the data points of selected heats with DESA in the form of logarithmic stress time diagrams. At the same time, the minimum stress $\sigma_{0\,min}$ and the longest time t_{max} of the data field can be determined.

If sufficient well tested heats are available and if, from a previous data preassessment or by a comparison of the data, small systematic differences between the selected individual heats are known, eg differences in chemical composition, heat treatment or creep rupture strength values, heats with typically different properties should be chosen as the three best tested heats.

Step 2. For each of the three best tested heats, an optimum model function should be determined. For that, one should begin with the Larson-Miller-parameter and the Manson-Haferd-parameter and a quadratic polynomial of the stress functions $f(\sigma_0) = \sigma_0^{0.5}$, $\sigma_0^{0.25}$, $\sigma_0^{0.1}$ and $\log\sigma_0$, ie with 8 different model functions. In the regression analyses performed with DESA and the 8 functions, no parameter constants or polynomial coefficients may be set. For the Manson-Haferd-parameter the case $T_a < T_{min}$ should be selected. As a result of each of the $3 \cdot 8 = 24$ calculations, a stress parameter diagram with the calculated master curve and a stress time diagram with the calculated isothermal (rupture or stress to specific strain) curves should be plotted with DESA. Depending on the experiences of the material expert with eg similar materials, the number of different model functions can be reduced below 8.

Step 3. For each of the three best tested heats, the best of the individual model functions should now be determined. Two conditions are to be fulfilled. The first and in most cases trivial condition is, that there is a good data fit in the whole data range. This condition includes that the stress σ_E of the vertex of the master curve is at least below 80% of the minimum stress $\sigma_{0\,min}$, however a value of 10% or smaller is recommended. Due to the use of a stress function $f(\sigma_0) = \sigma_0^m$ this cannot in all cases be examined in the parameter diagram or in the stress time diagram. However, the stress σ_E is printed out by DESA. If the first condition is fulfilled in both points, one can proceed to examine the second condition described in the next but one paragraph.

In a few cases, a systematic misfit may appear at all log σ_0-log t-isothermals for all functions. Then, the polynomial should be replaced either by a linear function of log σ_0 (if rather linear isothermals appear) or by a cubic polynomial of the stress function $f(\sigma_0)$ (if rather isothermals with an inflection point appear). With the new model functions the calculation should be repeated and the first condition reexamined. After that, one can take over the relatively best model functions and proceed to examine the second condition below. Also in this stage of the assessment, outliers can be detected and removed.

The second condition is, that there is a good data fit in the long term range, ie in the range between the maximum test time t_{max} and the time $t_{max}/10$. This should be examined in the stress time diagram by observing the interpretation of the long term data points. The best fit is a uniform interpretation across the greatest possible temperature range, ideally for all long term isothermals supported by data points. If an optimum fit is not possible for all temperatures the best fit for the mean and higher temperatures should be attempted and the temperature dependent time correction (see chapter 2.5 and step 10) can be applied later. An example of a DESA pre-assessment is demonstrated in Table 4, more examples are to be seen in [11)]. The decision about the best data fit has to be visually made at the moment. A numerical method is being developed by IfW and will be introduced in DESA if it works well.

Step 4. Now the best model function types for the three best tested heats have to be compared to each other. If the parameter type, the polynomial degree and the type of the stress function $f(\sigma_0)$, for which condition 2 of point 2 is at best fulfilled, are the same for three or at least two of the heats, the correspondent type of model function should be carried over for the creep rupture data assessment and one can proceed to step 5. If the latter is not the case or if none of the model functions examined up to now shows an acceptable data fit, the regression analysis can be repeated from step 2 but with the Manson-Brown- and Sherby-Dorn-parameters. If that gives no better solutions or if the expert omits this way, the function type used for a similar steel or a similar steel type or the relatively best Larson-Miller-type model function should be carried over. In this way, the DESA-preassessment is finished and one can proceed to step 5.

Step 5. The optimum model function type resulting from step 4 can be applied now to the whole steel type data set. Again no parameter constants or polynomial coefficients may be set for the regression analysis with DESA. However, to ensure the best model function is selected for the steel type one should again try some variations of the model function. It is recommended to keep at first the parameter type and to change the stress function by taking the next higher and the next lower stress exponents log σ_0 corresponding in this sense to a lower exponent. That means by example if the start from step 4 was with $\sigma_0^{0.1}$ the stress functions $\sigma_0^{0.25}$ and lg σ_0 should be taken. If this change is only possible in one direction two steps in this direction can be made. For all three cases again stress parameter and stress time diagrams should be plotted.

Step 6. For the results of step 5 it is necessary to reexamine if the first and second conditions of step 3 are fulfilled, ie if the rather trivial fit in the whole data range and the more decisive fit in the long term data range between t_{max} and $t_{max}/10$ are acceptable. If the fit becomes better for a stress function varied, further variations if possible should be examined, ie $\sigma_0^{0.5}$ in the example given above. With the best stress function then a variation of the parameter should be made. Instead of the Larson-Miller-parameter the Manson-Haferd-parameter should be taken, the same is recommended for the Manson-Brown-parameter, whereas instead of the Manson-Haferd-parameter or the Sherby-Dorn-parameter one should take the Larson-Miller-parameter. Select the optimum parameter and make finally slight variations of the parameter constants. At least one variation of this type should be made, if up to here only three variations were made. However, depending on the experiences of the materials expert e.g. with similar steel types, the number of variations can be reduced.

To the first assessment of step 6 a quality index of 1 is attributed. For each further assessment with the first and the second condition of step 3 fulfilled, this index is increased by 1, kept constant or decreased by 1, when the fit becomes better, equal or worse than in the preceeding assessment. To assessments which do not fulfill the first and second condition of step 3 no quality index is given. An example of a DESA main assessment according to steps 5 and 6 is demonstrated in Table 5.

Step 7. To the 1 to at maximum 4 assessment(s) with the highest quality index or indices a temperature dependent time correction may be applied if this seems to be useful (refer to Section 2.5). Finally the best of the 1 to 4 solutions has to be determined according to the second condition of step 3 observing the long term data fit in the whole temperature range. Thereafter, the DESA main assessment usually is finished. An example of the assessment according to step 7 is demonstrated in Table 6, details are described in [11)].

Step 8. The results of the best method can now be submitted to the post assessment acceptability criteria described in [13)]. These criteria can be applied by example via the programme PASAC (chapter 2.7). If from there a reassessment is recommended, one should begin at step 6 with a varied stress function. However, for an assessment with culled data one should begin from step 1 [11)].

A short overview on the stepwise DESA procedure is given in Table 7.

3.3 Final remarks on DESA multi-heat assessment

According to the experiences gained up to now with the WG1 creep rupture working data sets of steels 2.25Cr1Mo, 12CrMoVNb, 18Cr11Ni and alloy 31Ni20CrAl, collected within ECCC, WG1 [14)], the recommended stepwise DESA assessment leads to the best possible interpretation of a multi-heat data set. If the results of the 4 best creep rupture data assessments from step 7 on the above mentioned 4 materials are compared to the mean thereof the scatter of the rupture stresses $R_{m\ 100000}$ (for $t_{r\ max}$ 100,000 h) was always below 7% [11)], if the temperatures for long term use of the material were considered.

Depending on the experience of the DESA user some steps can be abreviated. As an example it can be recommended to take the same type of model function if another steel type is assessed which is similar in composition or in structure. If difficulties with DESA are experienced or if improvements for this guideline are found please do not hesitate to contact IfW via the address given in chapter 1.

To give a better support to the decision about the best fit of long term data, a post-assessment procedure is being in development in IfW. The procedure considers the deviation of predicted and measured time values in the long term range, evaluates the level and the trend of prediction for different temperature ranges and determines a number for the quality of prediction in the long term range.

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Table 1. DESA input variables

Input variable	Content	Format	Example
WSKOM	comment for the steel type	A40	10 CrMo 9 10, luftvergütet
TPE(1 to 9), Tm	headline characterizing the time to specific strain and to rupture	10 A4	0.02, 0.05,...t_m
no	consecutive no. of a single test material	I3	1
name	test material identifier	A6	7K
rec	no. of records for the current test material	I3	26
com	comment for the current test material	A40	Prüfzeichen TE
DATEN (1 to 1000,1)	test temperature(°C)	F10.2	500.00
DATEN (1 to 1000,2)	applied stress (MPa)	F10.2	196.00
DATEN (1 to 1000, 3 to 12)	time to specific strain, rupture time -1.00 stands for: time is not available	F10.2	-1.00 195.00...

```
Kommentar:    10 CrMo 9 10, luftvergütet
Dehngrenzen: 0.02 0.05 0.1  0.2  0.5  1.0  2.0  5.0  10.  tm
NR:  1 NAME:7K     REC: 26 BEM:Prüfzeichen TE
   500.00    196.00     -1.00    195.00    320.00    520.00    880.00   1300.00   1900.00   2400.00   2600.00   3400.00
   500.00    157.00     -1.00    260.00    530.00   1030.00   1850.00   3500.00   6000.00   9300.00  11500.00  13500.00
   500.00    123.00     -1.00     -1.00    280.00   1600.00  13000.00  52000.00 100000.00 180000.00     -1.00     -1.00
   500.00     98.10     -1.00   2700.00   6000.00  12000.00  50000.00 140000.00     -1.00     -1.00     -1.00     -1.00
   550.00    309.00     -1.00     -1.00     -1.00     -1.00     -1.00     67.00     71.00     73.00     76.00     82.00
   550.00    196.00     -1.00     -1.00     -1.00     -1.00     -1.00     70.00    110.00    185.00    260.00    420.00
   550.00    157.00     -1.00     -1.00     -1.00     40.00    100.00    180.00    310.00    550.00    650.00    950.00
   550.00    123.00     -1.00     -1.00     -1.00     87.00    265.00    680.00   1700.00   3300.00   4200.00   5000.00
   550.00     98.10     -1.00     -1.00     90.00    280.00   1050.00   2650.00   7000.00  13000.00  15500.00  17500.00
   550.00     78.50     -1.00     75.00    290.00    950.00   4100.00  12000.00  23500.00  35000.00  38500.00  42000.00
   550.00     58.90     -1.00    170.00    700.00   3300.00  20000.00  51000.00  65000.00     -1.00     -1.00     -1.00
   575.00    245.00     -1.00     -1.00     -1.00     -1.00     -1.00     -1.00     17.00     19.50     22.00     26.00
   575.00    157.00     -1.00     -1.00     -1.00     -1.00     -1.00     -1.00     53.00    170.00    250.00    350.00
   575.00    123.00     -1.00     -1.00     -1.00     -1.00     75.00    230.00    430.00    850.00   1030.00   1300.00
   575.00     98.10     -1.00     -1.00     -1.00     36.00    133.00    250.00    600.00   1530.00   2300.00   2900.00
   575.00     78.50     -1.00     20.00     63.00    160.00    620.00   2000.00   4300.00  12500.00  22000.00  25000.00
   575.00     61.80     -1.00     -1.00     83.00    250.00   2800.00   5300.00  13500.00  33000.00  39000.00  42000.00
   575.00     49.10     -1.00     75.00    290.00   1300.00   8800.00  14500.00  27000.00     -1.00     -1.00     -1.00
   575.00     39.20     -1.00    105.00    470.00   5900.00  15000.00  30000.00  55000.00     -1.00     -1.00     -1.00
   500.00    342.00     -1.00     -1.00     -1.00     -1.00     58.00     72.00     86.00    106.00    121.00    150.00
   500.00    309.00     -1.00     -1.00     67.00     94.00    150.00    189.00    242.00    315.00    336.00    450.00
   500.00    246.00     -1.00     73.00    170.00    307.00    453.00    581.00    671.00    820.00    930.00   1050.00
   450.00    320.00     37.00    100.00    180.00    330.00    720.00   5000.00   8000.00   8800.00   9200.00  10000.00
   450.00    278.00     50.00    220.00   3500.00     -1.00     -1.00     -1.00     -1.00     -1.00     -1.00     -1.00
   450.00    240.00    220.00   1380.00  13000.00     -1.00     -1.00     -1.00     -1.00     -1.00     -1.00     -1.00
   450.00    220.00    270.00   5000.00     -1.00     -1.00     -1.00     -1.00     -1.00     -1.00     -1.00     -1.00
NR:  2 NAME:7P     REC: 12 BEM:Prüfzeichen UF
   500.00    309.00     -1.00     -1.00     -1.00     -1.00     77.00    115.00    177.00    301.00    320.00    370.00
   500.00    245.00     -1.00     -1.00     -1.00    100.00    259.00    446.00    654.00   1002.00   1401.00   1800.00
   500.00    196.00     -1.00     -1.00     50.00    125.00    800.00   2000.00   5200.00  11000.00  12500.00  14500.00
   500.00    157.00     -1.00     28.00    150.00    870.00   3800.00  12500.00  29000.00  63000.00     -1.00     -1.00
   500.00    123.00     -1.00     73.00    400.00   2500.00  22000.00  58000.00     -1.00     -1.00     -1.00     -1.00
   550.00    196.00     -1.00     -1.00     -1.00     -1.00     36.00    130.00    230.00    280.00    320.00    480.00
   550.00    123.00     -1.00     -1.00     -1.00    115.00    480.00   1000.00   2100.00   5200.00   6300.00   8200.00
   550.00     78.50     -1.00     -1.00    270.00   1400.00   7800.00  21000.00  27000.00  37000.00  42500.00  46000.00
```

Table 2. Example of the first part of a DESA input data set

Table 2a		Steel type : 12 CrMoVNb					Total number of data points
Total No. of individual heats : 33			Type of data : t_r				
Heat No.	Maximum time (1000 h) for a temperature (°C) of						
	425	450	475	500	550	600	
GBCR				94.8	48.8		14
GBCS				55.7	41.5		13
GBGC			50.3		37.0	43.9	17
GBLD			57.3		68.2	52.8	16
GBCJ				21.0	53.2		11
GBCK				128.1	74.7		12
GBLN			59.9		81.2	52.8	16
GBME			83.9		100.5	9.4	15
GBF409		12.7		21.5	13.0		8
GBF629		20.8		16.6	9.7		7
GBB630		16.5		26.5	18.9		9
GBF384					59.0		5
GBF401					36.4		5
GBF404					41.8		5
D320B		28.4		71.1	92.2	36.1	20
D126				112.2	85.5		14
D127				55.9	57.6		8
D128				66.6	129.2		8
D130					15.0		4
D132					4.4		2
D440E					7.8	15.3	7
D440N	0.8			24.9	64.0	24.3	11
D562A					50.1	28.1	8
D562B					23.7	25.0	9
D563					35.3		2
D564					26.5		3
D320I				14.3	17.7	10.2	9
D320G					7.1	15.3	7
D320C		19.3		88.7	66.2	13.5	16
D320D		1.3		90.7	72.0	13.0	14
D320H				3.2	1.2	1.2	6
D320K				1.3	1.7	2.0	6
D51B					66.4		3
all							310

Table 3. Maximum rupture times for the main test temperatures and total number of rupture points of the individual heats of steel 12 CrMoVNb (X 19 CrMoVNbN 11 1), after [11]

Heat	Ass. No.	Parameter *) P	Stress function $\log \sigma_0$ or $\sigma_0^{m\,x)}$	Optim.para. constants	σ_{min}: 31 (MPa) σ_E	Standard deviation s	Good data fit in the *) hole range	long term ra.	Best model function	opt. model function
All data	1	LM	m = 0.5	C = 17,59	1 033	0,137				
	2		0.25	C = 17,56	79 072	0,142				
	3		0.1	C = 17,61	$<10^{-6}$	0,143	X			
	4		log σ	C = 17,65	0,865	0,141	X			
	5	MH	m = 0.5	lgta=11,77 Ta=482	-1 649	0,120	X	X		
	6		0.25	lgta=12,08 Ta=470	0,906	0,119	X	X	X	X
	7		0.1	lgta=12,93 Ta=437	11,2	0,119				
	8		log σ	lgta=13,98 Ta=369	18,2	0,121				

*) LM: Larson-Miller, MH: Manson-Haferd, SD: Sherby-Dorn, MB: Manson-Brown combined with a quadratic polynomial of the stress function

Table 4. Results of a DESA pre-assessment according to step 1 to 4 at one (D7ZT) of the 3 best tested heats of 2.25Cr 1Mo-steel, after [11]

			1	2	3	4	5	6	7	8
All data	Assessment No.		1	2	3	4	5	6	7	8
	Parameter *)		MH	MH	MH	MH	LM	LM		
	Stress function x)		$\sigma^{0,25}$	$\sigma^{0,1}$	$\sigma^{0,5}$	lgσ	$\sigma^{0,1}$	$\sigma^{0,1}$		
	Optim. par. const.		lgta=22,01 Ta =43	lgta=22,18 Ta =32	lgta=22,99 Ta = 1	lgta=23,01 Ta = 1	C = 15,98	C = 18 set		
	$\sigma_{0\,min}$: 22 MPa , σ_E		-0,0009	5,6	29 962	13,0	0,0049	0,027		
	Good da-	hole range	X	X		X	X	X		
	ta fit in	long t.ra.		X			X	X		
	Quality index		1	2	+)	1	2	2		

*) LM: Larson-Miller, MH: Manson-Haferd, SD: Sherby-Dorn, MB: Manson-Brown combined with a quadratic polynomial of the stress function +) first and second condition of step 3 are not fulfilled

Table 5. Results of a DESA main assessment according to steps 5 and 6 at 2.25Cr 1Mo-steel, after [11)]

All data	Assessment No.		1 main	time corr.	2 main	time corr.	5 main	time corr.	6 main	time corr.
	Parameter *)		MH	T 450/500	MH	T 450/500	LM	T 450/500	LM	no time
	Stress function x)		$\sigma^{0,25}$	d 0,06/0	$\sigma^{0,1}$	d 0,07/0	$\sigma^{0,1}$	d 0,03/0	$\sigma^{0,1}$	corr.
	Optim. par. const.		lgta=22,01 Ta =43	T 450/500	lgta=22,38 Ta =322	T 450/500	C = 15,98	T 450/500	C = 18 set	performed
	$\sigma_{0\,min}$: 22 MPa , σ_E		-0,0009	c 0,8/1	5,559	c 0,7/1	0,0049	c 0,9/1	0,027	
	Good da-+)	hole range	X	X		X		X		X
	ta fit in	long t.ra.				X		X		X
	Quality			best-3		best-2		best		best-1

*) LM: Larson-Miller, MH: Manson-Haferd, SD: Sherby-Dorn, MB: Manson-Brown combined with a quadratic polynomial of the stress function +) first and second condition of step 3 are not fulfilled

Table 6. Results of a DESA main assessment according to step 7 at 2.25Cr 1Mo-steel, after [11)]

DESA	Step	Procedure
pre-assess-ment	1	Select the 3 best tested heats
	2	Apply up to 8 model functions to the 3 heats
	3	Select the best *) model function for each heat
	4	Select the best model function type from step 3
main assess-ment	5	Apply the best function to the hole data set and vary twice the stress function
	6	Select the best *) model function from step 5 and attribute a quality index 1, vary once more the stress function and therafter the parameter, vary slightly the constants of the best *) parameter, increase or decrease the quality index for a better *) or worser function +)
	7	Apply a temperature dependent time correction if necessary to the 1 to 4 functions from step 6 with the highest quality indidices, select the function (with or without time correction) presenting the best long term data fit
post-assess-ment	8	Submit the results of the best model function from step 7 to the post-assessment criteria, repeat if necessary from step 6 to improve the model function or from step 1 with culled data

*) best model function (or parameter) is characterized by
- a good fit in the hole data range
- the best fit in the long term data range ($t_{max/10}$ to t_{max})

+) no quality index is given to an insufficient data fit

Table 7. Overview on the recommended DESA procedure for the assessment of a multi-heat data set comprising temperature, stress and resulting time to rupture or to given strain

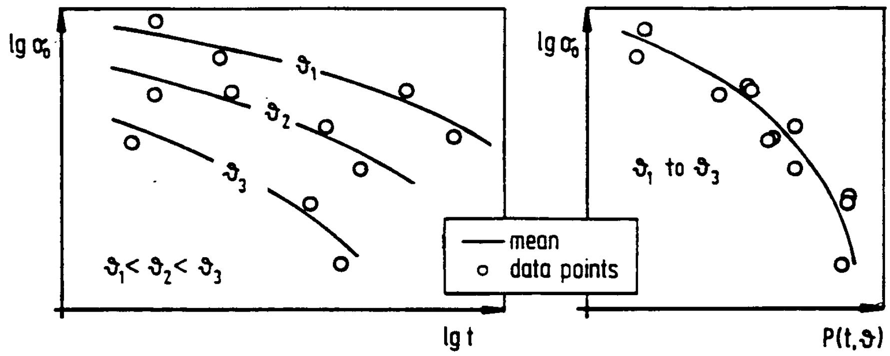

Fig. 1. Time dependency of stresses to reach a specific strain or of rupture stresses in the log σ_0 versus log t-diagram and in the log σ_0 versus P(t,ϑ)-diagram

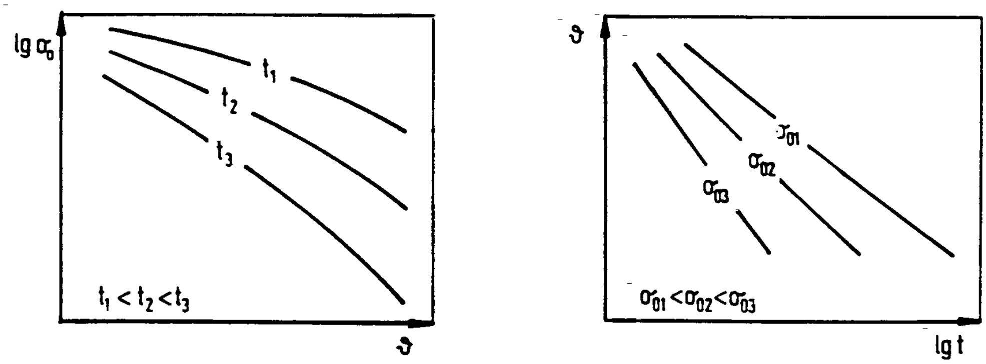

Fig. 2. Representation of mean curves in a log σ_0 versus ϑ-diagram and in a ϑ versus log t-diagram

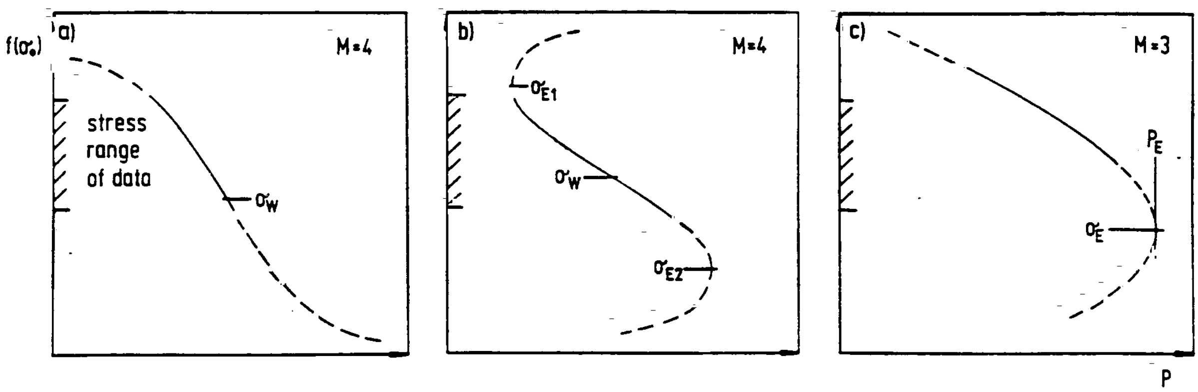

Fig. 3. Model function of a third order polynomial with a point of inflection (a) and additional vertices (b) and model function of a second order polynominal with vertex (c)

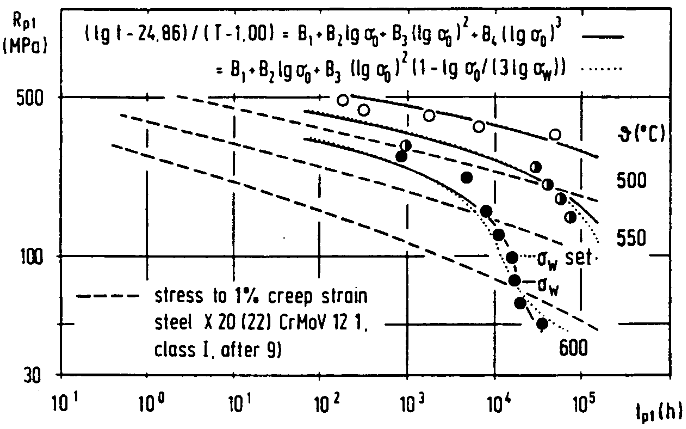

Fig. 4. Evaluation of a material, which shows S-shaped curves in the log σ_0 versus log t-diagram with a third order polynomial, 11Cr-1Mo-0.3V-Nb-N-steel, σ_0 is the stress to 1 % strain

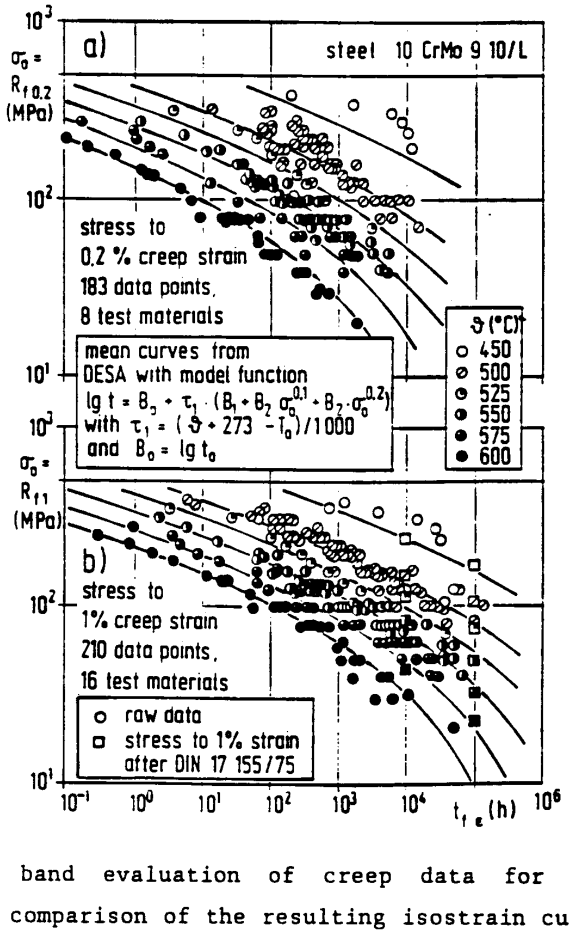

Figure 5. Scatter band evaluation of creep data for 0.2 % strain (a) and 1 % strain (b) and comparison of the resulting isostrain curves with values from DIN 17 155/75, steel 2.25 Cr-1 Mo, austenized, aircooled and tempered, after [9]

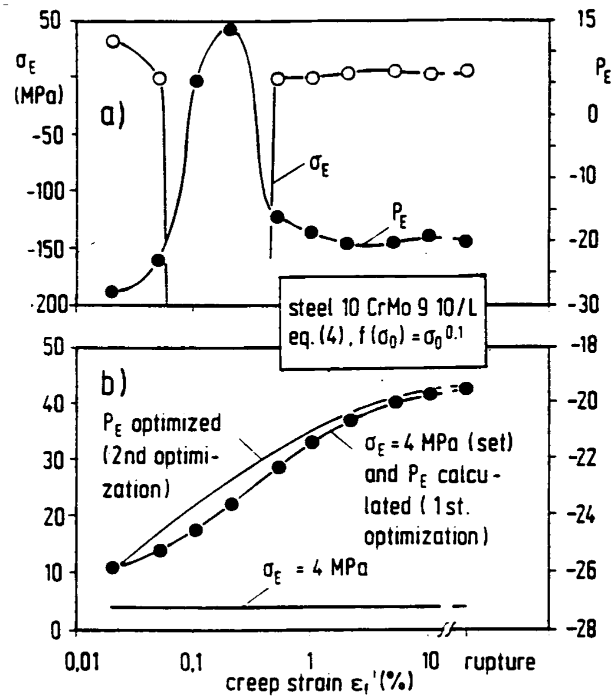

Figure 6. Strain dependency of the coordinates of the vertices of the isostrain master curves (a) resulting from regression analyses and (b) after optimization, steel 2.25 Cr-1 Mo, air cooled

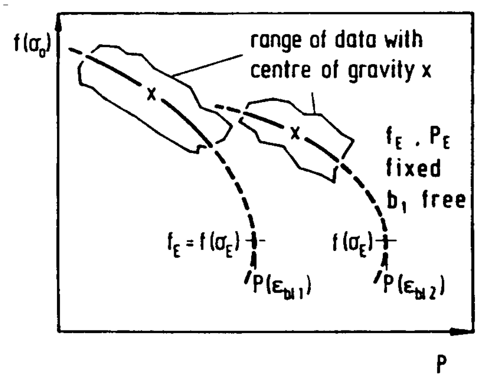

Fig. 7. Example for the influence of different centres of gravity x of test values on adjacent master curves

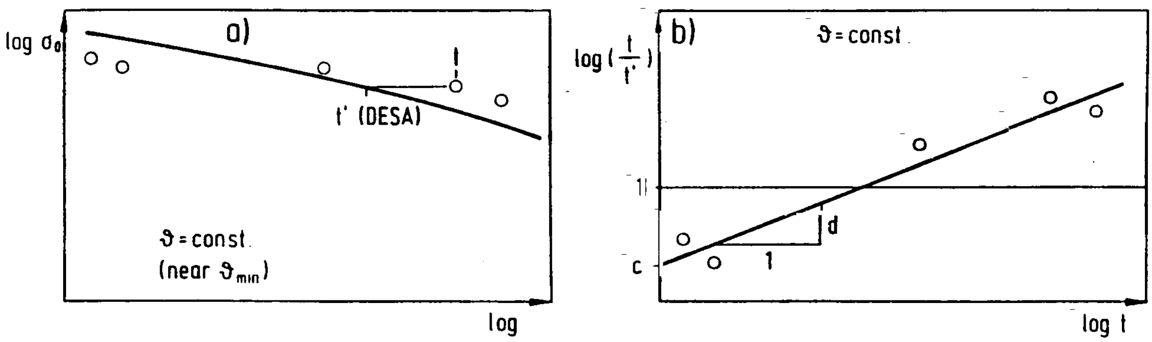

Fig. 8. Principle of the temperature dependent time correction in the log stress-log time-diagram (a) and in a log (t/t')-log t-diagram (b)

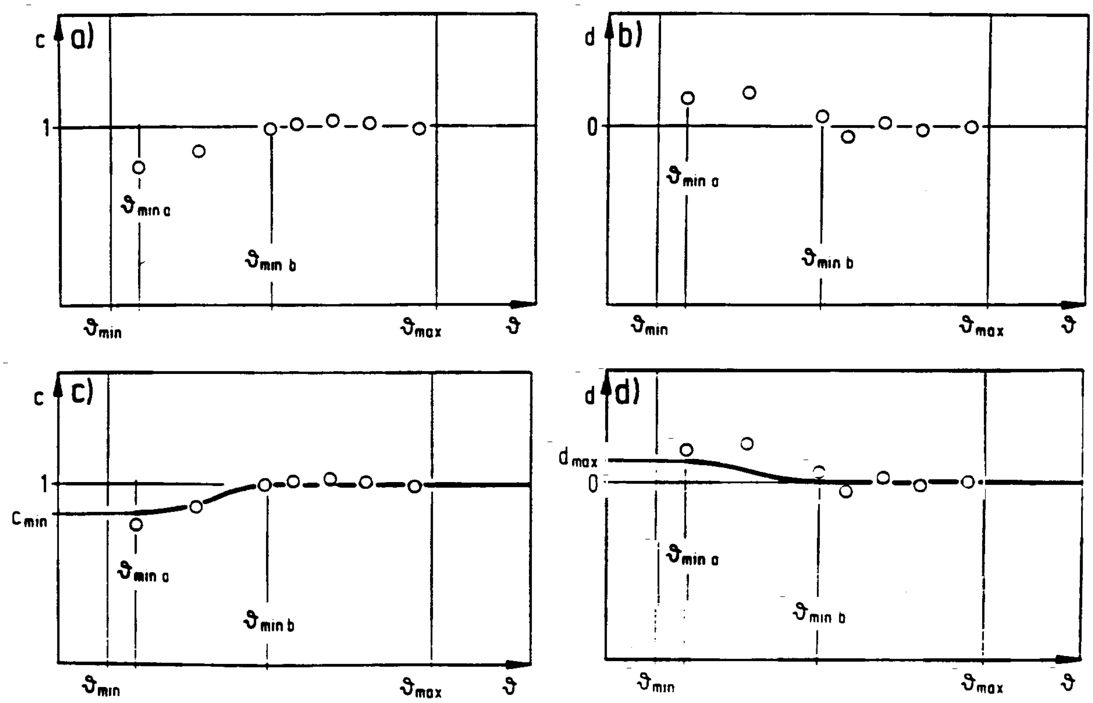

Fig. 9. Scheme of temperature dependent time correction with eq. (36) to (39)

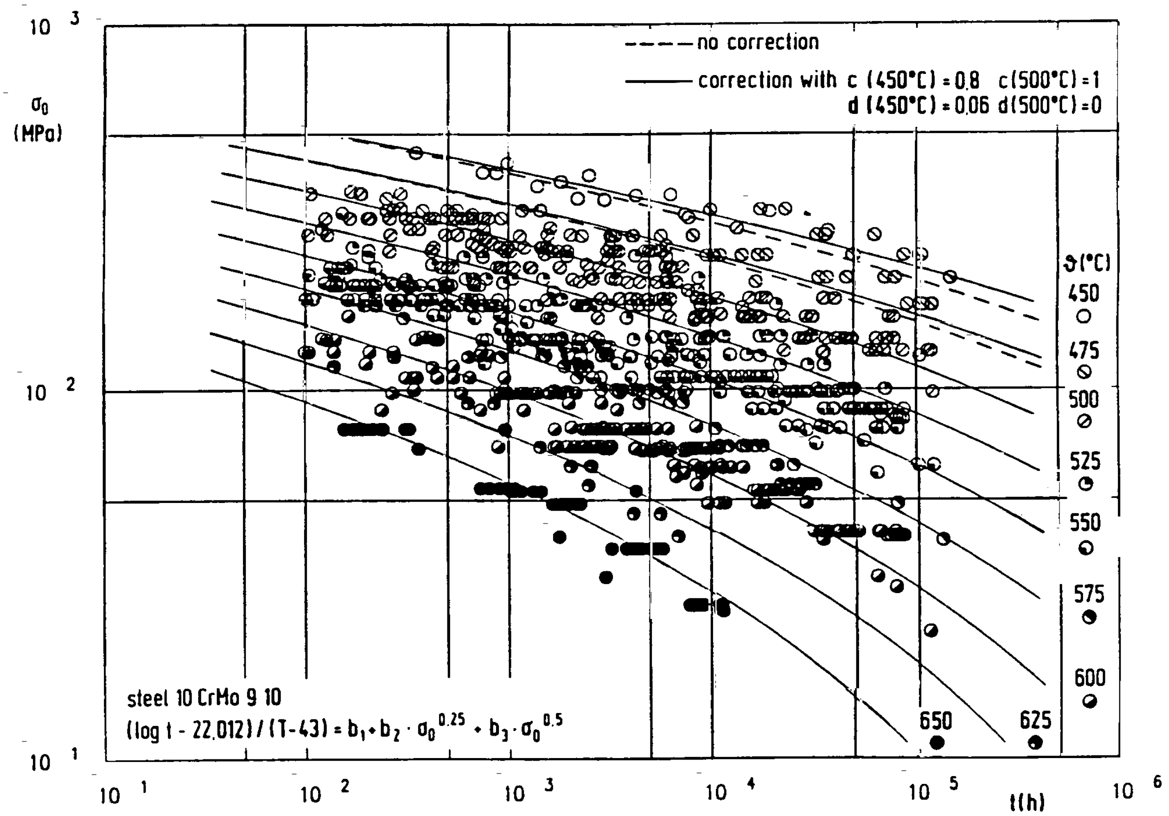

Fig. 10. Example of a temperature dependent time correction of the rupture curves of steel 2.25Cr 1Mo in the temperature range of 450 to 500 °C, after [11)]

6. Annex

Questionaire for the Adaption of the Programme DESA to an existing Hardware configuration *)

IBM-compatible computer, CPU	80 386	80 486		
Main storage	8 MB			
Hard disc space	160 MB			
5 1/4" floppy drive	1,2 MB			
3 1/2" floppy drive	1,44 MB			
Graphic card	Herkules	EGA	VGA	
Numeric Data Processor	available			
Line Printer	Kyocera			
Plotter	Kyocera	HP7550A		
Printer Port	LPT1	LPT2	COM1	COM2
Plotter Port	LPT1	LPT2	COM1	COM2
No. of PC's with DESA				

*) ☐ Standard configuration of the IfW

Please mark or add your configuration and send this form with your address back to

Institut für Werkstoffkunde
Herrn Dr.-Ing. J. Granacher
Grafenstrasse 2

D-64 283 Darmstadt

Fax (49) 6151 165659