ECCC

ECCC RECOMMENDATIONS - VOLUME 5 Part Ic [Issue 2]

RECOMMENDATIONS AND GUIDANCE FOR THE ASSESSMENT OF FULL-SIZE STRESS RELAXATION DATASETS

blank page

ECCC RECOMMENDATIONS - VOLUME 5 Part Ic [Issue 2]

RECOMMENDATIONS AND GUIDANCE FOR THE ASSESSMENT OF FULL-SIZE STRESS RELAXATION DATASETS

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

APPROVED **DATE 08/09/2003**

On behalf of ECCC

blank page

ABSTRACT

ECCC Recommendations Volume 5 Part Ic provides guidance for the assessment of large stress relaxation data sets. It recognises that it is not practical at the present time to recommend a single European stress relaxation data assessment procedure and promotes the innovative use of post assessment acceptability criteria to independently test the effectiveness and credibility of relaxation strength predictions.

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

ECCC Recommendations Volume 5 Part Ic 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

ECCC may from time to time re-issue this document in response to new developments. The user is advised to consult the Document Controller for confirmation that reference is being made to the latest issue.

blank page

CONTENTS

1. INTRODUCTION........ 3
2. RECOMMENDATIONS FOR THE ASSESSMENT OF STRESS RELAXATION DATA......... 3
3. PRE-ASSESSMENT 4
4. SRDA POST ASSESSMENT TESTS 5
Physical Realism of Predicted Isothermal Lines........ 6
Effectiveness of Model Prediction within Range of Input Data........ 6
Repeatability and Stability of Extrapolations........ 8
5. SUMMARY........ 8
6. REFERENCES 8

APPENDIX A - WORKING DATA SETS FOR WG1 ASSESSMENT METHOD EVALUATION
A3 - Working Data Sets for WG1 SRDA Method Evaluation
APPENDIX B - REVIEW OF DATA ASSESSMENT METHODS
B1 -
APPENDIX C - REVIEW OF WG1 EVALUATION OF DATA ASSESSMENT METHODS - RECOMMENDATION VALIDATION
C3 - Stress Relaxation Data Assessment

blank page

1. INTRODUCTION

ECCC Recommendations Volume 5 Part Ic provides guidance for the assessment of stress relaxation data. 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) in characterising material behaviour on the basis of the available data.

There are no standardised procedures for the determination of relaxed strength values. The ECCC recommendations for stress relaxation data assessment (SRDA) are based on the results of a WG1 evaluation exercise performed using methods adopted by four participating organisations (App. C3). These involve adaptations of CRDA procedures (e.g. App. D1a,D2, Part Ia) or the use of parametric equation forms specifically developed for representing stress relaxation behaviour. The evaluation exercise was performed on two multi-source, multi-cast, multi-temperature bolting steel datasets, the first comprising uniaxial results for 1CrMoVTiB (D1055) and the second, model bolt results for 11CrMoVNbN (App. A3). These are typical of the datasets assessed by WG3x.

The variability associated with multi-source datasets involving existing test results can be high relative to that for equivalent collations of creep rupture data (App. C3). The output from stress relaxation tests is particularly sensitive to initial loading conditions and variations in the control-strain/displacement applied, in addition to specimen and laboratory temperature deviations. It is only relatively recently that the influence of such factors has been fully appreciated and steps taken to minimise their effect [1]. Consequently, it is essential that adequate pre-assessment and post assessment checks are adopted to provide assurance that the mean line strength predictions represent the available observations.

2. RECOMMENDATIONS FOR THE ASSESSMENT OF STRESS RELAXATION DATA

The ECCC-WG1 SRDA evaluation exercise highlights the risk of unacceptable levels of uncertainty in predicted strength values without the implementation of precautionary checks during the course of assessment (App. C3). The findings of this investigation have led to the following recommendations.

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

2) At least one of the SRDAa should be performed using a method for which there is an ECCC procedure document. These are referred to as ECCC-SRDAs.

3) Prior to the main-assessment of the SRDA, a pre-assessment should be performed which takes cognisance of the guidance given in Sect. 3[1,2].

4) The results of the main-assessment of the SRDA should satisfy the requirements of the ECCC post assessment acceptability criteria (Table 1b, with reference to Sect. 4).

5) The results of the two SRDAs should predict $R_{R/30kh/T}(e_t)$ strength levels to within 10% at $T_{min[10\%]}$, T_{main} and $T_{max[10\%]}$.[3,4]

---

1 Examples of tables summarising the distribution of available $s_{R/t/T}$ data are given in Tables A3.2,A3.3 [App.A3] (refer Sect. 3*(iii)*).

2 Visual examination is performed on isothermal s_R versus log t plots (refer Sect. 3*(v)*)

3 $T_{min[10\%]}$ 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.

6) If the results of the two SRDAs meet the requirement defined in *5)* and only one is an ECCC-SRDA the results of the ECCC-SRDA should be adopted. If both assessments have been performed according to ECCC-SRDA procedures, the results of the ECCC-SRDA giving the minimum $R_{R/30kh}(e_t)$ strength values at T_{main} should be adopted, unless ECCC-WG3x agree otherwise.

7) If the results of the two SRDA do not meet the requirements of *5)*, up to two repeat independent SRDAs 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 WG3x prior to repeat assessment.

Depending on the range and balance of the dataset, serious consideration should be given to temperature partitioning to ensure that results from one regime do not unduly affect the predicted strength values in another.

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

9) The reliability of SRDA predictions is dependent on both the quality and quantity of the data available for the analysis.

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

11) For the assessment of uniaxial test results, data populations per unit time per test should be approximately the same to avoid unrepresentative weighting within the dataset. As a guide, a population of ≥1 observation per 250h is recommended.

3. PRE-ASSESSMENT

Pre-assessment is an important step in the analysis of stress relaxation 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 procedures it includes pre-conditioning/data reduction as routine. 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[5].

The precise boundary between the end of pre-assessment and the start of the main-assessment may be unclear and in certain procedures, 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:

---

[4] For information on ECCC terms and terminology, the reader is referred to reference 2.

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

(i) confirmation that the data meet the material pedigree and testing information requirements recommended in ECCC Recommendations Volume 3 [1],

(ii) confirmation that the material pedigrees of all casts meet the specification set by the instigator(s) of the assessment (eg. Table A3.1),

(iii) an evaluation of the distribution of data points with respect to temperature and time (eg. Tables A3.2a-3a); identifying t_{max}, $s_{R[min]}$, and the temperatures for which there are (a) ≥5% test data ($T_{[5\%]}$) and (b) ≥10% test data conditions ($T_{[10\%]}$),

[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.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 (eg. 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,

[The best-tested cast information is required to perform the post assessment tests (eg. PAT 2.2, Sect. 4).]

(v) a visual examination of isothermal s_R versus $\log t$ plots 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.

4. SRDA POST ASSESSMENT TESTS

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.

These are investigated in the following post assessment tests[6].

The post assessment tests recommended for SRDA are similar to those for CRDA (Table 1).[7] However, there are essential modifications to cover the fundamental differences between creep rupture and stress relaxation data.

Physical Realism of Predicted Isothermal Lines

PAT-1.1 Visually check the credibility of the fit of the isothermal $R_R(e_t)$ versus log t lines to the individual $s_R(e_t)$,log t data points over the range of the data (eg. Fig. C3.1).[8]

PAT-1.2 Produce isothermal curves of $R_R(e_t)$ versus log t at 25°C intervals from the minimum test temperature to the maximum application temperature[9] (eg. Fig. C3.2).

For times between 10 and 100,000h and stresses $\geq 0.8.s_{R[min]}(e_t)$, predicted isothermal lines must not (a) cross-over, (b) come-together, or (c) turn-back.

PAT-1.3 PAT-1.3 is not applied to SRDA.

PAT-1.4 In circumstances where SRDA involves the assessment of results for more than one control strain, a self consistency check should be performed involving a graphical comparison of $R_{R/t/T}(e_t)$ strength values for all ε_t with respect to $R_{R/t/T}$ for the principle control strain of the test series.

Effectiveness of Model Prediction within Range of Input Data

There are two series of PAT-2 tests (Table 1). Ideally, comparisons should be made between predicted strength and observed relaxed stress values. However, this is not easy to implement when master equations have been determined using a CRDA type approach (e.g. Apps. D1,D2, Part Ia) since time is expressed in terms of a stress polynomial. Consequently, a time based option is also provided (similar to PAT-2 for CRDA, Sect. 2.4 in Part Ia).

PAT-2.1 To assess the effectiveness of the model to represent the behaviour of the complete dataset, plot $R_{R/t/T}(e_t)$ versus $s_{R/t/T}(e_t)$ for all input data (eg. Fig. C3.3).

The $R_{R/t/T}(e_t)$ versus $s_{R/t/T}(e_t)$ diagram should show:

- the $R_{R/t/T}(e_t) = s_{R/t/T}(e_t)$ line (ie. the ideal line),
- the $R_{R/t/T}(e_t) = s_{R/t/T}(e_t) \pm 2.5.s_{[A-RR]}$ boundary lines,[10,11]
- the $R_{R/t/T}(e_t) = s_{R/t/T}(e_t) \pm$ 15MPa boundary lines, and
- the linear mean line fit through the $R_{R/t/T}(e_t), s_{R/t/T}(e_t)$ data points.

The model equation should be re-assessed:

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

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

[8] Stress relaxation diagrams may be plotted as $s_R(e_t)$ versus log t or log $s_R(e_t)$ versus log t.

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

[10] $s_{[A-RR]}$ is the standard deviation of the residual relaxed stresses for all the data at all temperatures, ie. $s_{[A-RR]} = \surd\{\sum_i (\log s_{R\,i} - \log R_{R\,i})^2/(n_A - 1)\}$, where i = 1,2, ... n_A, and n_A is the total number of data points

[11] for a normal error distribution, almost 99% of the data points would be expected to lie within $\log R_{R/t/T}(\varepsilon_t) = \log s_{R/t/T}(e_t) \pm 2.5.s_{[A-RR]}$ boundary lines

(a) if more than 1.5% of the $R_{R/t/T}(e_t), s_{R/t/T}(e_t)$ data points fall outside one of the $\pm 2.5.s_{[A\text{-}RR]}$ boundary lines

(b) if the slope of the mean line is less than 0.85 or greater than 1.15, and

(c) if the mean line is not contained within the ±15MPa boundary lines.

Alternatively, CRDA type log t_R* versus log t_R diagrams may be constructed for $t_R \geq 10$h, and PAT-2.1 followed as defined in Sect. 2.4 of Part Ia.

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 $T_{max[10\%]}$):

- the $R_{R/t/T}(e_t) = s_{R/t/T}(e_t)$ line (ie. the ideal line),
- the $R_{R/t/T}(e_t) = s_{R/t/T}(e_t) \pm 2.5.s_{[I\text{-}RR]}$ boundary lines,[12]
- the $R_{R/t/T}(e_t) = s_{R/t/T}(e_t) \pm$ 15MPa boundary lines,and
- the linear mean line fit through the $R_{R/t/T}(e_t), s_{R/t/T}(e_t)$ data points.

and identify the best-tested individual cast(s)[13] (eg. Fig. C3.4).

(a) $R_{R/t/T}(e_t)$ versus $s_{R/t/T}(e_t)$ plots for individual casts should have slopes close to unity and be contained within the $\pm 2.5.s_{[I\text{-}RR]}$ boundary lines. The pedigree of casts with $\partial(R_R)/\partial(s_R)$ slopes ≤0.75 or ≥1.25 and/or which have a significant number of $[R_R, s_R]$ data points outside the $\pm 2.5.s_{[I\text{-}RR]}$ boundary lines should be re-investigated.

If the material and testing pedigrees of the data satisfy the requirements of reference 1 and the specification set by WG3x [as recommended in Sects. 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 $R_{R/t/T}(e_t), \sigma_{R/t/T}(\varepsilon_t)$ data points about the $R_{R/t/T}(e_t) = s_{R/t/T}(e_t)$ line reflects the homogeneity of the dataset and the effectiveness of the predictive capability of the model (e.g. Fig. C3.4). 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 $R_{R/t/T}(e_t), s_{R/t/T}(e_t)$ data points is less than 0.85 or greater than 1.15, and

(c) the mean line is not contained within the ±15MPa boundary lines.

Alternatively, CRDA type log t_R* versus log t_R diagrams may be constructed for $t_R \geq 10$h, and PAT-2.2 followed as defined in Sect. 2.4 of Part !a.

---

12 $s_{[I\text{-}RR]}$ is the standard deviation of the residual relaxed stresses for the data at the temperatures of interest, ie. $s_{[I\text{-}RR]} = \sqrt{\{\sum_j (\log s_{R\ j} - \log R_{R\ j})^2/(n_I - 1)\}}$, where j = 1,2, ... n_I.

13 The best-tested casts are identified as part of pre-assessment (eg. Tables A3.2b,A3.3b).

Repeatability and Stability of Extrapolations

A practical solution equivalent to PAT-3.1 and PAT-3.2 for CRDA to assess the reliability of assessed relaxed strength values predicted by extrapolation will be recommended in a future issue of Volume 5, following validation.

5. SUMMARY

ECCC Recommendations Volume 5 Part Ic provides guidance for the assessment of stress relaxation 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 SRDA 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.

6. REFERENCES

1 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.

2 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.

Table 1 Comparison of Post Assessment Acceptability Criteria to be Satisfied for Stress Relaxation and Creep Rupture Data Assessment

	CRDA	SRDA	
Physical Realism			
PAT-1.1	• visual confirmation of acceptability of isothermal assessed line fits to experimental log σ_o vs log t_r data	• visual confirmation of acceptability of isothermal assessed line fits to experimental $s_R(e_t)$ vs log t 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 $10 < t < 10^5$h and $\sigma \geq 0.8.s_{R[min]}$	
PAT-1.3	• $-\partial(\log t_u)/\partial(\log s_o) \geq 1.5$	• not applicable	
PAT-1.4	• not applicable	• confirmation of consistency of $R_{R/t/T}(e_t)$ for different e_t, if applicable	
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	• ≤1.5% data points fall outside a $R_{R/t/T}(e_t) = s_R(e_t) \pm 2.5.s_{[A\text{-}RR]}$ boundary line in total-data $R_{R/t/T}(e_t)$ vs $s_R(e_t)$ diagram	• ≤1.5% data points fall outside one $\log t_R^* = \log t_R \pm 2.5.s_{[A\text{-}RLT]}$ boundary line in total-data $\log t_R^*$ vs $\log t_R$ diagram
PAT-2.1(b)	• slope of mean $\log t_u^*$ vs $\log t_r$ line is between 0.78 and 1.22	• slope of mean $R_{R/t/T}$ vs s_R line is between 0.85 and 1.15	• slope of mean $\log t_R^*$ vs $\log t_R$ 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 $R_{R/t/T}(e_t)$ vs $s_R(e_t)$ line is within $R_{R/t/T} = s_R \pm 15$MPa lines	• mean $\log t_R^*$ vs $\log t_R$ line is contained within $\log t_R^* = \log t_R \pm \log 2$ lines for 30 to 30,000h
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 $R_{R/t/T}(e_t)$ vs $s_R(e_t)$ diagrams for T_{max}, T_{main} & T_{min}, individual-cast mean lines have slopes close to unity and data points within $R_{R/t/T}(e_t) = s_R(e_t) \pm 2.5.s_{[I\text{-}RR]}$ lines	• in isothermal $\log t_R^*$ vs $\log t_R$ diagrams for T_{max}, T_{main} and T_{min}, individual-cast mean lines have slopes close to unity and data points contained within $\log t_R^* = \log t_R \pm 2.5.s_{[I\text{-}RLT]}$ 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 $R_{R/t/T}$ vs σ_R line is between 0.85 and 1.15	• slope of isothermal mean $\log t_R^*$ vs $\log t_R$ 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 $R_{R/t/T}(e_t)$ vs $s_R(e_t)$ line is within $R_{R/t/T} = s_R \pm 15$MPa lines	• mean $\log t_R^*$ vs $\log t_R$ line is within $\log t_R^* = \log t_R \pm \log 2$ lines for 30 to 30,000h
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%	to be recommended	
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%		

APPENDIX A3

WORKING DATA SETS FOR WG1 SRDA METHOD EVALUATION

S R Holdsworth [ALSTOM Power]

blank page

APPENDIX A3

WORKING DATA SETS FOR WG1 SRDA METHOD EVALUATION

S R Holdsworth [ALSTOM Power]

The guidelines given in the main text of ECCC-WG1 Volume 5 for the assessment of stress relaxation data are based on the comprehensive evaluation of two multi-cast multi-temperature working data sets, one for 1CrMoVTiB (D1055) and the second for 11CrMoVNbN. The nominal compositions of the two bolting steels are given in Table A3.1.

The data set for the 1CrMoVTiB steel comprises the results of 34 uniaxial tests covering >5 casts and 8 temperatures (Table A3.2). A series of σ_R,t co-ordinates were supplied for each test. The durations of 28 of the tests extend beyond 10,000h with 7 final test times exceeding 30,000h (Table A3.2a).

The 11CrMoVNbN data set includes results from 96 model bolt stress relaxation tests. These describe the stress relaxation behaviour for 12 casts at 4 temperatures (Table A3.3). A total of twenty two 11CrMoNbN tests extend beyond 10,000h, of which 17 were taken to 30,000h before discontinuation (A3.3a). In contrast to uniaxial tests, only a single σ_R,t co-ordinate is determined from a model bolt test.

blank page

TABLE A3.1 SPECIFICATIONS FOR ECCC-WG1 STRESS RELAXATION WORKING DATASETS

1CrMoVTiB (D1055)

	C	Si	Mn	P	S	N	Al	B	Co	Cr	Cu	Mo	Nb	Ni	Ti	V	Harden	Temper	$Rp_{0.2}$	Rm
min	0.15	0.10	0.35	-	-			0.001		0.90		0.85			0.05	0.60	970	660	660	825
max	0.25	0.35	0.75	0.040	0.040			0.005		1.30		1.15			0.20	0.80	1010	730		1050

11CrMoVNb (X 19 CrMoVNbN 11 1)

	C	Si	Mn	P	S	N	Al	B	Co	Cr	Cu	Mo	Nb	Ni	Ti	V	Harden	Temper	$Rp_{0.2}$	Rm
min	0.12	0.20	0.40	-	-	0.03		-		10.00		0.50	0.20	0.30		0.18	1100	680	740	895
max	0.20	0.70	1.00	0.035	0.015	0.08		0.010		11.50		0.90	0.55	0.80		0.35	1170	720		1050

TABLE A3.2a DISTRIBUTION OF STRESS RELAXATION DATA POINTS FOR 1CrMoVTiB AS A FUNCTION OF TIME AND TEMPERATURE

TEMP °C	TOTAL DATA	TEST DURATIONS, h						$\sigma_{R[min]}$ MPa	TOTAL DATA	% OF TOTAL
		<3kh	3-10kh	11-20kh	21-30kh	31-50kh	t_{max}			
375	3	1	1			1	31,852	192	3	9%
425	5	1	2	1	1		27,787	208	5	15%
475	1					1	32,600	171	1	3%
500	2					2	34,115	102	2	6%
525	1				1		28,701	74	1	3%
550	6		1	3	1	1	31,482	44	6	18%
565	13			6	6	1	37,300	8	13	38%
575	3			3			19,260	22	3	9%
TOTALS	34	2	4	13	9	6			34	100%

ε_t = 0.15%

TABLE A3.2b CAST DISTRIBUTION FOR 1CrMoVTiB WORKING DATA SET

CASTS	TEMEPERATURE, °C								TOTALS
	375	425	475	500	525	550	565	575	***34***
LB	2	2							4
LP	1	1							2
LQ		1							1
AFL				1		1			2
ANON[1]		1	1	1	1	5	13	3	25

[1] the information covered by ANON represents >1 cast

TABLE A3.3a DISTRIBUTION OF STRESS RELAXATION DATA POINTS FOR 11CrMoVNbN AS A FUNCTION OF TIME AND TEMPERATURE

TEMP °C	TOTAL DATA	TEST DURATIONS, h						$\sigma_{R[min]}$ MPa	TOTAL DATA	% OF TOTAL
		<3kh	3-10kh	11-20kh	21-30kh	31-50kh	t_{max}			
425	17	8	6	-	3	-	30,150	248	17	18%
480	20	8	7	1	4	-	30,100	158	20	21%
540	51	22	17	2	10	-	30,160	63	51	53%
600	8	4	2	1	1	-	30,000	6	8	8%
TOTALS	96	42	32	4	18	-			96	100%

$\varepsilon_t = 0.18\%$

TABLE A3.3b CAST DISTRIBUTION FOR 11CrMoVNbN WORKING DATA SET

CASTS	TEMEPERATURE, °C				TOTALS
	425	480	540	600	***96***
D/01	5				5
D/02	5	5	5		15
D/03	5	5	5	3	18
D/04	2	5	5		12
D/05			5		5
D/06		5	5		10
D/07			3		3
D/08			4	5	9
D/09			5		5
D/10			5		5
D/11			6		6
D/12			3		3

APPENDIX C3

REVIEW OF WG1 EVALUATION OF STRESS RELAXATION DATA ASSESSMENT METHODS AND RECOMMENDATION VALIDATION

S R Holdsworth [ALSTOM Power]

blank page

APPENDIX C3

REVIEW OF EVALUATION OF STRESS RELAXATION DATA ASSESSMENT METHODS RECOMMENDATION VALIDATION

S R Holdsworth (GEC ALSTHOM LST)

C3.1. INTRODUCTION

ECCC-WG1 guidelines for the derivation of relaxation strength are based on feedback from a WG1 evaluation of large working datasets for two bolting alloys, namely 1CrMoVTiB (D1055) and X19CrMoVNb. A summary of the pedigree statistics for the two datasets are given in App.A3. The evaluation exercise was conducted during the middle part of 1996, and the recommendations provided in Issue 3 for stress relaxation data assessment (SRDA) are therefore still at an evolutionary stage. Aspects requiring further attention are identified in the following text.

It is now recognised that stress relaxation test results are very sensitive to initial loading conditions, variations in the control-strain/displacement applied, and deviations in testpiece and laboratory temperature. However, it is only relatively recently that the influence of such factors has been fully appreciated and steps taken to minimise their effect [C3.1]. Hence, the implications of data scatter due to testing practice should be carefully considered during the pre-assessment of stress relaxation datasets.

There are no known, formally recognised, standardised procedures for assessing stress relaxation data to give tables of relaxed strength values, in particular for large multi-source multi-cast datasets. Individual test record or single cast assessments have traditionally been undertaken using expressions derived from forward creep laws, eg. [C3.2-C3.4]. For multi-cast data, a common practice is to simply fit a polynomial to isothermal σ_R versus log t data. This procedure forms the basis of the ISO method approach adopted in two of the WG1 assessments, in which polynomial fits provide the mean $R_{R/t/T}(\varepsilon_t)$ data for parametric assessment using the CRDA ISO procedure (App.D1) [C3.5,C3.6]. The DESA method applied in [C3.7] similarly uses a CRDA methodology (App.D2) to determine $R_{R/t/T}(\varepsilon_t)$, but in this case the parametric fit is to individual $\sigma_{R/t/T}(\varepsilon_t)$ data points. The final approach considered in the WG1 evaluation exercise was one in which the best set of isothermal curves based on a traditional stress relaxation model (eg. [C3.2,C3.3]) are used to provide $R_{R/t/T}(\varepsilon_t)$ on the basis of cross plot averaging (referred to as CPA-TM [C3.8]).

The results of the four assessments (Table C3.1) and their use to develop and validate the SRDA post assessment tests are reported in the following appendix.

C3.2. STRESS RELAXATION DATA ASSESSMENT

Stress relaxation data are determined from uniaxial tests and model bolt tests [C3.1]. Uniaxial tests provide a 'continuous' record of $\sigma_{R/T}(\varepsilon_t)$,t for a given control strain and temperature, whereas only one $\sigma_{R/t/T}(\varepsilon_t)$ data point is determined from a single model bolt test. An example of each type of dataset was evaluated in the WG1 exercise. Both datasets were multi-temperature collations for a single control strain. The D1055 1CrMoVTiB dataset was the product of thirty four 0.15%ε_t uniaxial tests, while the 11CrMoVNbN dataset contained results from ninety six 0.18%ε_t model bolt tests (Tables A3.2,3, App.A3).

The results of the assessments performed on the 1CrMoVTiB dataset are shown in Figs.C3.1.1(a)-(g) and summarised in Table C3.2. Relaxation strengths were predicted out to

30,000h at seven temperatures in the range 375 to 575°C, although only those between 425 and 575°C are considered further. There appeared to be upper and lower temperature regimes of behaviour in this dataset leading to varying degrees of inconsistency in the assessments. The low temperature 375°C data posed particular problems in this respect. The situation may be due to a mechanism change and/or the non-uniform distribution of casts throughout the temperature range (see Table A3.2b). As a consequence, analysts chose to either restrict the range of applicability of a single model (eg. [C3.5]) or adopt a temperature partitioning strategy to provide strength predictions covering the whole range (eg. [C3.6]).

The observed variability in predicted strength values at 30,000h was up to around 25% for temperatures in the range 500 to 575°C (Table C3.2). A target reproducibility of ≤10% is recommended in the main text, although further experience may indicate that this may have to be modified to within max[10%, 10MPa]. However, before any amendment is made, it is recommended that consideration be given to eliminating the apparently high strength test data at 565°C (Figs.C3.1.1(f),C3.3,C3.4) and repeat assessments performed.

Concerns were raised during the SRDA evaluation relating to data population per unit time per test. In the assessments performed, no limit was set. The influence of individual tests was therefore weighted by the population density supplied by the data supplier, and this varied significantly. A recommendation for the future is that the number of observations per unit time is made to be approximately the same for all tests in the dataset for assessment, typically ≥1 observation per 250h. For model bolt tests, there is no such difficulty, providing the dataset is reasonably homogeneous.

The results of the assessments performed on the 11CrMoVNbN model bolt dataset are shown in Figs.C3.1.1.2(a)-(d) and also summarised in Table C3.2. For this dataset, relaxation strengths were also predicted out to 30,000h at the four test temperatures for which test results were available. For one assessment, temperature partitioning was also necessary to fit this dataset.

C3.3. VALIDATION OF POST ASSESSMENT ACCEPTABILITY CRITERIA

The post assessment tests developed initially for CRDA (App.C1) provide the basis for the SRDA PATs. Modifications have been necessary, not least because of the fundamental difference between stress relaxation and creep rupture tests. Stress relaxation data is acquired under constant strain/displacement control in contrast to the constant load conditions used to control stress rupture and creep tests. Nevertheless, consistency is maintained where possible (Table 3, main text). The differences in the detail of the PATs applied to SRDAs are reviewed below.

C3.3.1 Physical Realism of Predicted Isothermal Lines

PAT-1.1 and PAT-1.2 are applied to the results of a SRDA in the same way as they are to the output from a CRDA (Figs.C3.1,2). The only difference is that PAT-1.2 is applied between 10 and 100,000h since maximum stress relaxation test durations are more typically 30,000h (rather than 100,000h for creep rupture testing). PAT-1.3 is not applied to the results of stress relaxation data assessment.

PAT1.4 is a check to ensure that when the data being assessed have been determined for different control strains, the predicted strength values are self consistent. Hence it is proposed that a graphical comparison is made between $R_{R/t/T}(\varepsilon_t)$ and $R_{R/t/T}(\varepsilon_{t[main]})$, where $\varepsilon_{t[main]}$ is the principle control strain of the dataset.

C3.3.2 Effectiveness of Model Prediction within Range of Input Data

There are two PAT-2 options available to the user. Whenever feasible, the effectiveness of the model prediction within the range of the input data should be based on comparisons of predicted and observed relaxation strength values (eg. Figs.C3.3,C3.4). However, it is recognised that this approach is difficult when assessments are performed using a modified CRDA methodology which outputs time as a complex function of stress (eg. as stress polynomials in the ISO and DESA methods described in Apps.D1,D2). In such circumstances, it is recommended that a time based option similar to that applied to the results of CRDA/CRDAs is adopted.

Three constraints are set in the stress based PAT-2.1 test. These are that:

(a) no more than 1.5% of the $R_{R/t/T}(\varepsilon_t),\sigma_{R/t/T}(\varepsilon_t)$ data points fall outside one of the $\pm 2.5\ s_{[A\text{-}RR]}$ boundary lines,

(b) the slope of the total-data mean line, $\partial(R_R)/\partial(\sigma_R)$, is between 0.85 and 1.15, and

(c) the total-data mean line is contained within the ±15MPa boundary lines.

These criteria have still to be fully validated, but provide reasonable interim working guidelines. The criteria appear to be sensitive to test-to-test differences in data population per unit time, and this aspect should be addressed in the future (see Sect.C3.2).

The guidance for the time based PAT-2.1 test is similar to that for CRDA, except that trials on stress relaxation data have shown that log t_R^* versus log t_R diagrams should be constructed for $t_R \geq 10$h, at least when individual test data populations for uniaxial test results are inconsistent.

The acceptability criteria for PAT-2.2 are that, at T_{min}, T_{main} and T_{max}:

(a) $R_{R/t/T}(\varepsilon_t)$ versus $\sigma_{R/t/T}(\varepsilon_t)$ plots for individual casts should have slopes close to unity and be contained within the $\pm 2.5\ s_{[I\text{-}RR]}$ boundary lines[2]. The pedigree of casts with $\partial(R_R)/\partial(\sigma_R)$ slopes ≤ 0.75 or ≥ 1.25 and/or which have a significant number of R_R,σ_R data points outside the $\pm 2.5\ s_{[I\text{-}RR]}$ boundary lines should be re-investigated,

(b) the slope of the mean line through the isothermal $R_{R/t/T}(\varepsilon_t),\sigma_{R/t/T}(\varepsilon_t)$ data points is between 0.85 and 1.15, and

(c) the isothermal-data mean line is contained within the ±15MPa boundary lines.

As for PAT-2.1, these criteria have still to be fully validated, but provide reasonable interim working guidelines.

The guidance for the time based PAT-2.2 test is similar to that for CRDA, except that trials on stress relaxation data have shown that log t_R^* versus log t_R diagrams should be constructed for $t_R \geq 10$h, at least when individual test data populations for uniaxial test results are inconsistent.

C3.3.3 Repeatability and Stability of Extrapolations

The results of the SRDA evaluation exercise demonstrate that the need for PAT-3 tests to check the repeatability and stability of extrapolated relaxation strength predictions is just as great as for creep rupture strength predictions. The proposal is that PAT-3.1 and PAT-3.2, as

---

[1] $s_{[A\text{-}RR]}$ is the standard deviation of the residual log times for all the data at all temperatures, ie. $s_{[A\text{-}RR]} = \sqrt{\{\Sigma_i (\sigma_{R\,i} - R_{R\,i})^2/(n_A - 1)\}}$, where i = 1,2, ... n_A, and n_A is the total number of data points

[2] $s_{[I\text{-}RR]}$ is the standard deviation for the n_I residual log times at the temperature of interest, ie. $s_{[I\text{-}RR]} = \sqrt{\{\Sigma_j (\sigma_{R\,j} - R_{R\,j})^2/(n_I - 1)\}}$, where j = 1,2, ... n_I.

defined for CRDA/CSDA, should be adopted for SRDA, but with strength comparisons made for $R_{R/100kh}$ at T_{min}, T_{main} and T_{max}.

The practical difficulty associated with this strategy has been that, with no guidance on data population per unit time per test, PAT-3.1 time culls and PAT-3.2 stress culls were likely to remove observations in a non representative way and therefore not be helpful. Now there is a recommendation, validation of PAT-3.1 and PAT-3.2 will be undertaken.

C3.4. CONCLUDING REMARKS

The results of an extensive evaluation exercise form the basis of the ECCC-WG1 recommendations for the assessment of multi-source, multi-cast stress relaxation data (defined in the main text). The findings highlight the potential risk of high levels of uncertainty associated with relaxation strength predictions for durations at the extremes of the observed data and beyond. The level of risk is reduced by:

- careful pre-assessment,
- repeat assessments according to well defined procedures, and
- application of ECCC-WG1 post assessments for stress relaxation data.

It is recommended that, in future, data populations per unit time for all uniaxial test results used in an assessment are approximately the same to avoid unrepresentative weighting during analysis.

C3.5. REFERENCES

C3.1 ECCC-WG1 Recommendations Volume 3; "Acceptability criteria for stress-rupture, creep and stress relaxation data", ECCC Document 5524/MC/30 [Issue 3], Edited: J Granacher & S R Holdsworth, October 1996.

C3.2 P Feltham; J. Inst. Metals, 1960, 89, 210.

C3.3 J B Conway; USAEC Report GEMP-730, 1969.

C3.4 S Osgerby & B F Dyson; "Physically based modelling of stress relaxation in superalloys and ferritic steels", Proc. Conf. Performance of Bolting Materials in High Temperature Plant Applications, Inst. Materials, York, June 1994, Ed: A Strang, Paper 29, 362.

C3.5 N W Frost & J Orr; "Stress relaxation data analysis", British Steel Note, ECCC-WG1 Document 5524/WG1/172, 1995, May.

C3.6 G Merckling; "Preliminary results on stress relaxation data assessment", ISB Note, ECCC-WG1 Document 5524/WG1/188, 1996, May.

C3.7 H Koenig; "Assessment of relaxation muti-cast datasets of 11CrMoVNbN and Durehete 1055", MAN Note, ECCC-WG1 Document 5524/WG1/173, 1995, May.

C3.8 S R Holdsworth; "Stress relaxation assessment of multi-cast dataset of 1CrMoVTiB bolting steel", GECA Note, 1996.

Table C3.1 ECCC-WG1 Evaluation of SRDA Procedures

PROCEDURE	ANALYST
ISO (App.D1)	BS [C3.5], ISB [C3.6]
DESA (App.D2)	GAE [C3.3]
CPA-TM (traditional model fitting, eg. [C3.2,C3.3], with cross plot averaging)	GECA [C3.8]

Table C3.2a Comparison of Predicted Relaxation Strength Values for 1CrMoVTiB (D1055) Bolting Steel

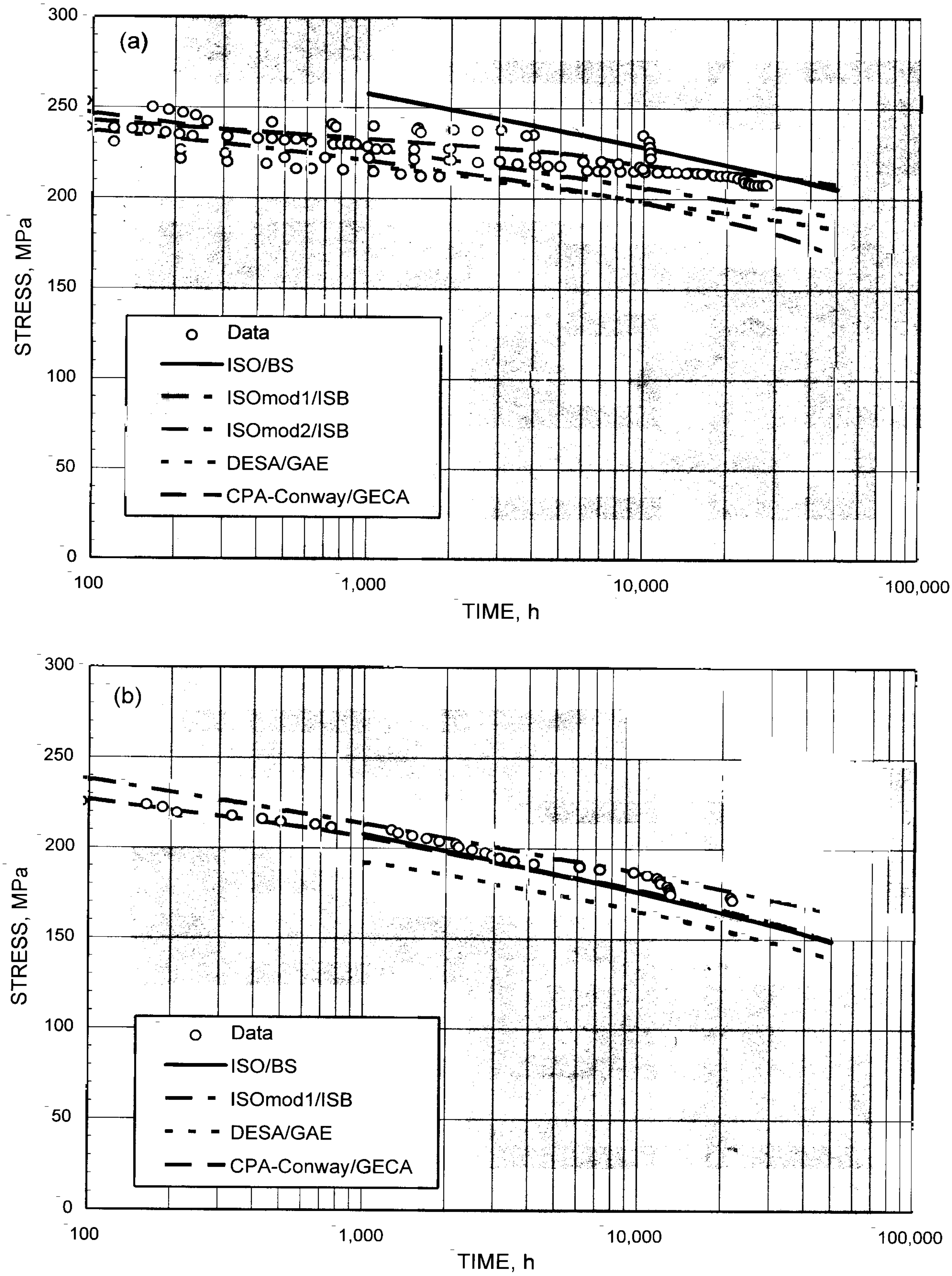
[uniaxial stress relaxation data]

	$R_{R/t/T}(\varepsilon_t\ 0.15\%)$, MPa															
	500°C				550°C				565°C				575°C			
	1kh	3kh	10kh	30kh	1kh	3kh	10kh	30kh	1kh	3kh	10kh	30kh	1kh	3kh	10kh	30kh
ISO/BS	184	168	149	127	133	111	77	47	115	87	52	33	101	69	42	
ISOmod2/ISB	201	188	162	122	136	116	89	54	116	92	56	31	100	70	38	21
DESA/GAE	177	162	141	116	134	104	66	42	114	79	48	31	99	64	39	25
CPA-TM/GECA	186	169	150	129	128	104	76	51	113	89	61	41	99	74	45	25
Variability	*14%*	*16%*	*15%*	*10%*	*6%*	*12%*	*26%*	*22%*	*3%*	*14%*	*21%*	*24%*	*2%*	*14%*	*16%*	*16%*

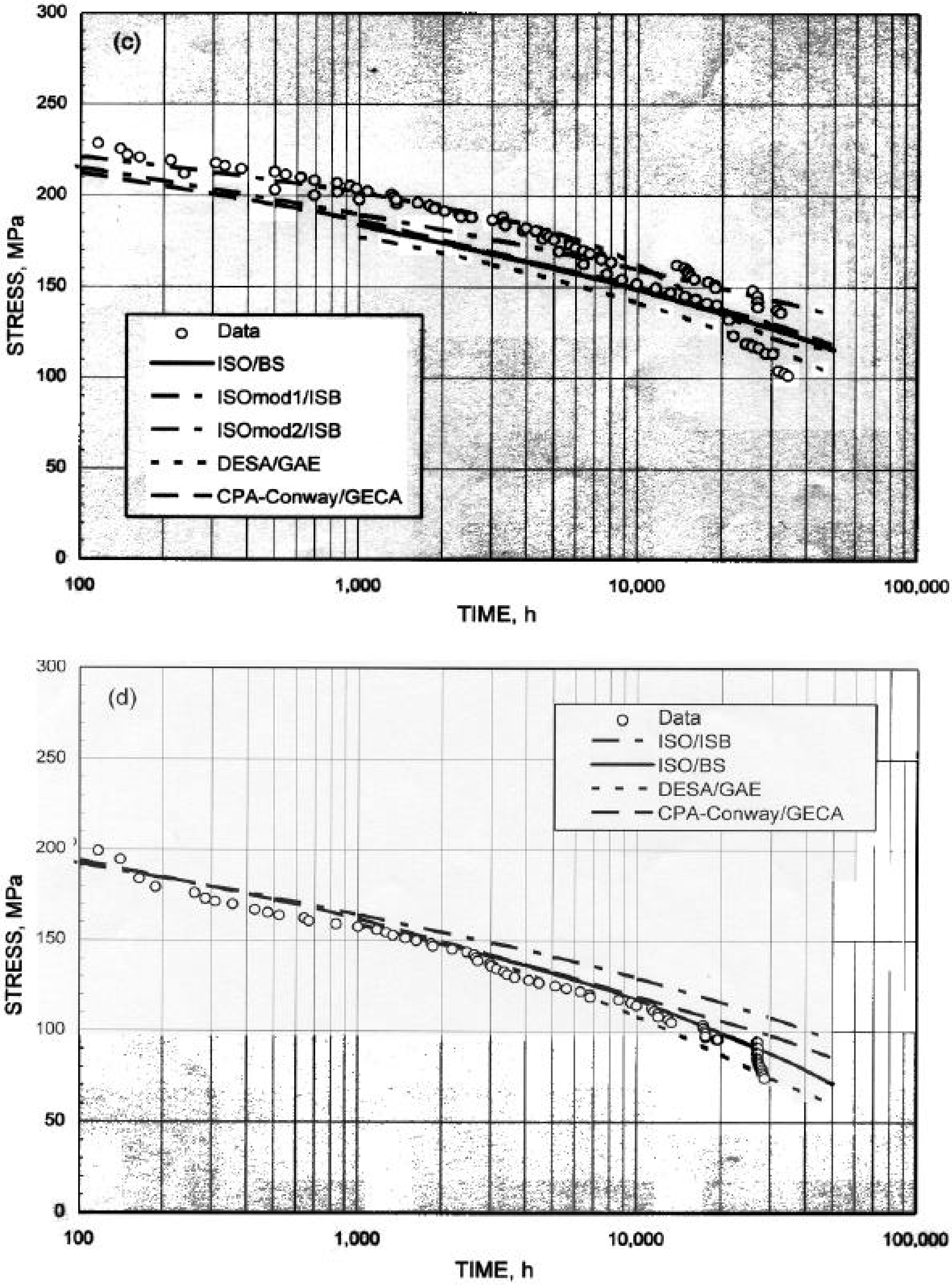
Table C3.2b Comparison of Predicted Relaxation Strength Values for 11CrMoVNbN Bolting Steel

[model bolt stress relaxation data]

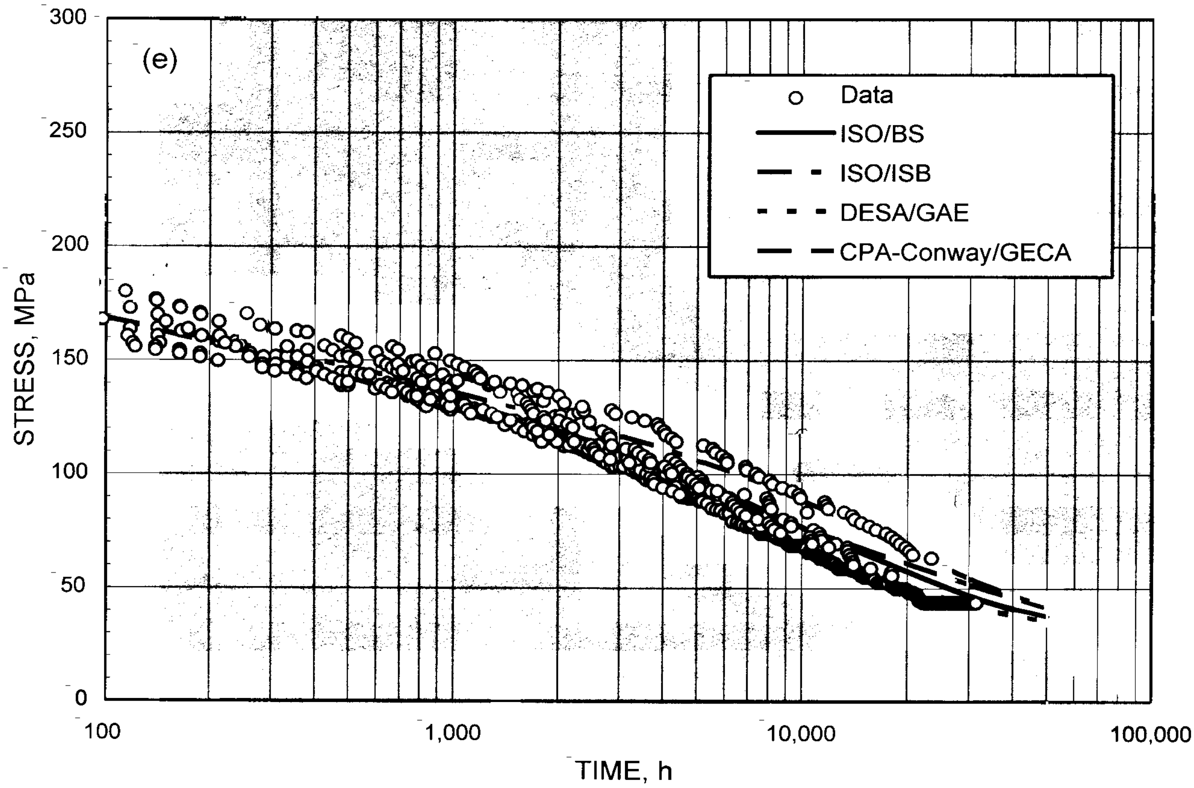
	$R_{R/t/T}(\varepsilon_t\ 0.18\%)$, MPa															
	425°C				480°C				540°C				600°C			
	1kh	3kh	10kh	30kh	1kh	3kh	10kh	30kh	1kh	3kh	10kh	30kh	1kh	3kh	10kh	30kh
Multi-Temperature Model Fits																
ISOMod1/ISB	265	248	229	212	232	213	193	173	152	135	115	95	86	65	36	9
DESA/GAE	262	248	233	217	212	195	175	157	150	130	108	87	84	60	33	
Variability	*1%*	*0%*	*2%*	*2%*	*9%*	*9%*	*10%*	*10%*	*1%*	*4%*	*6%*	*9%*	*2%*	*8%*	*9%*	

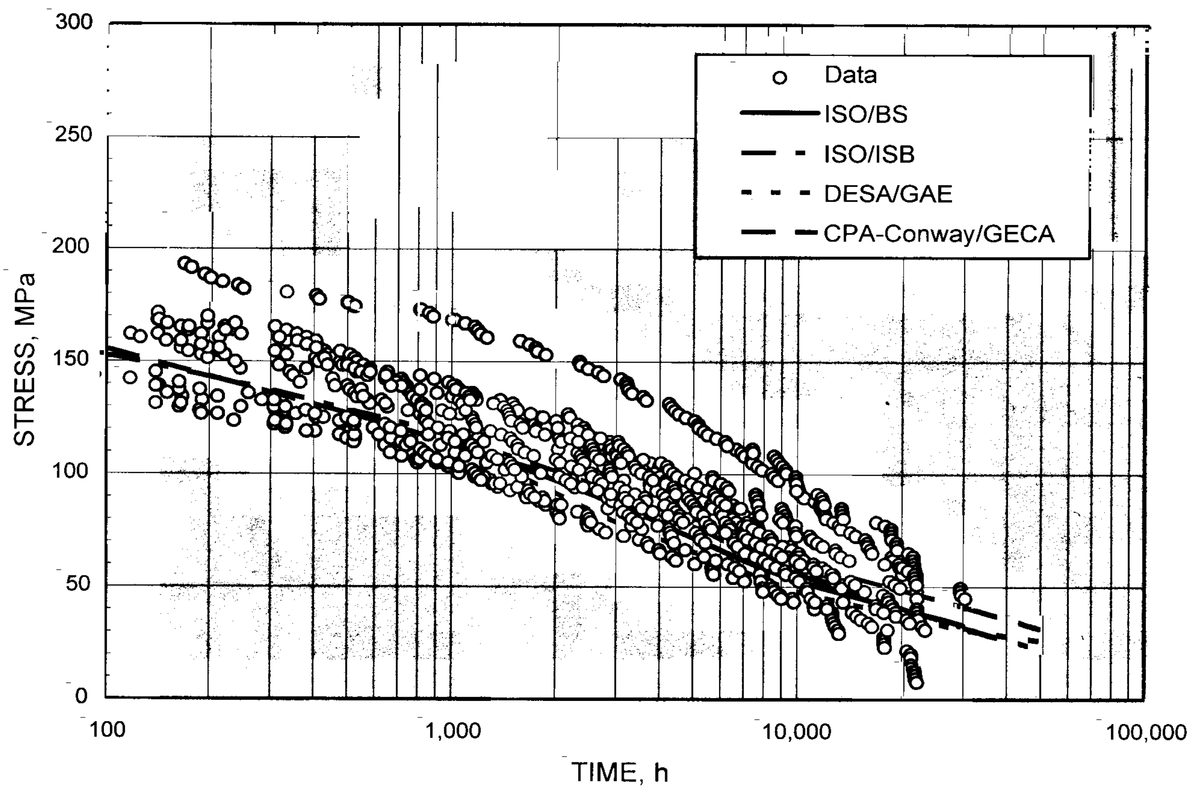


Comparison of observed stress relaxation behaviour for 1CrMoTiB (D1055) bolting steel at (a) 425°C and (b) 475°C [ε_t = 0.15%]

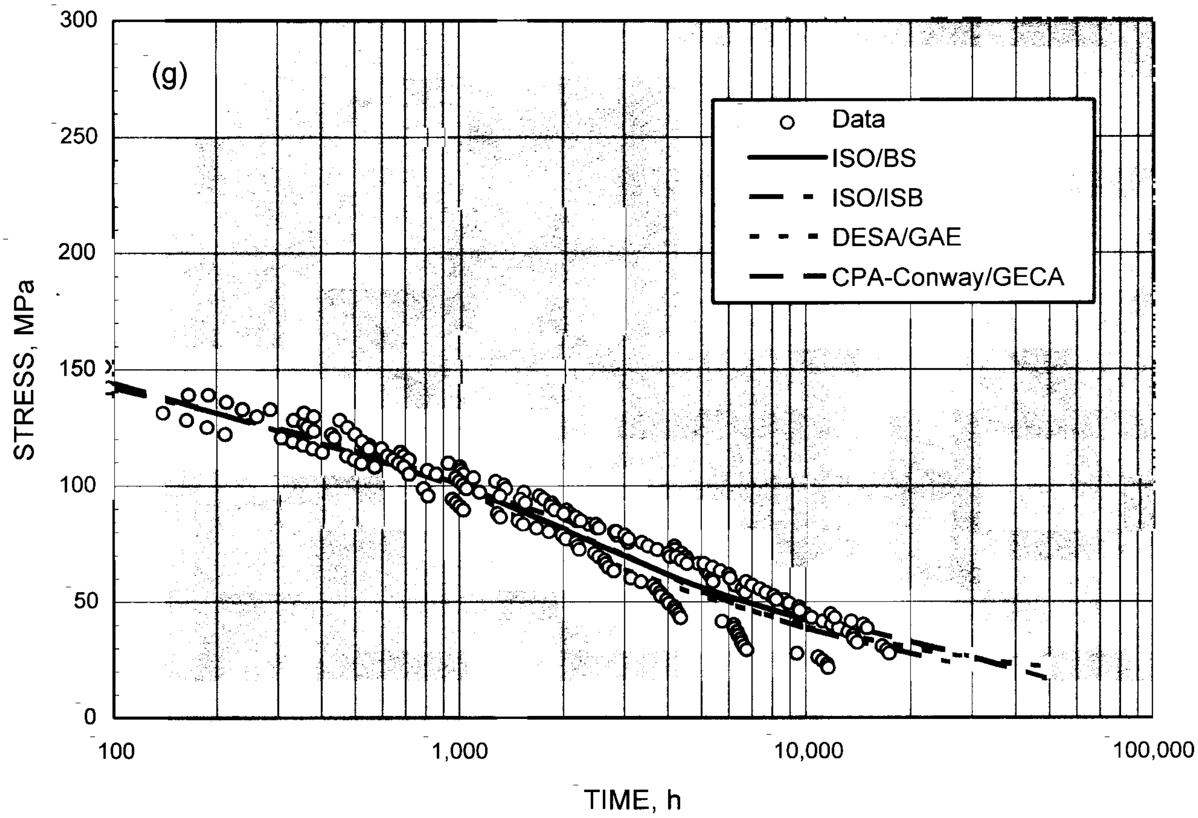


Comparison of observed stress relaxation behaviour for 1CrMoTiB (D1055) bolting steel at (c) 500°C and (d) 525°C [ε_t = 0.15%]

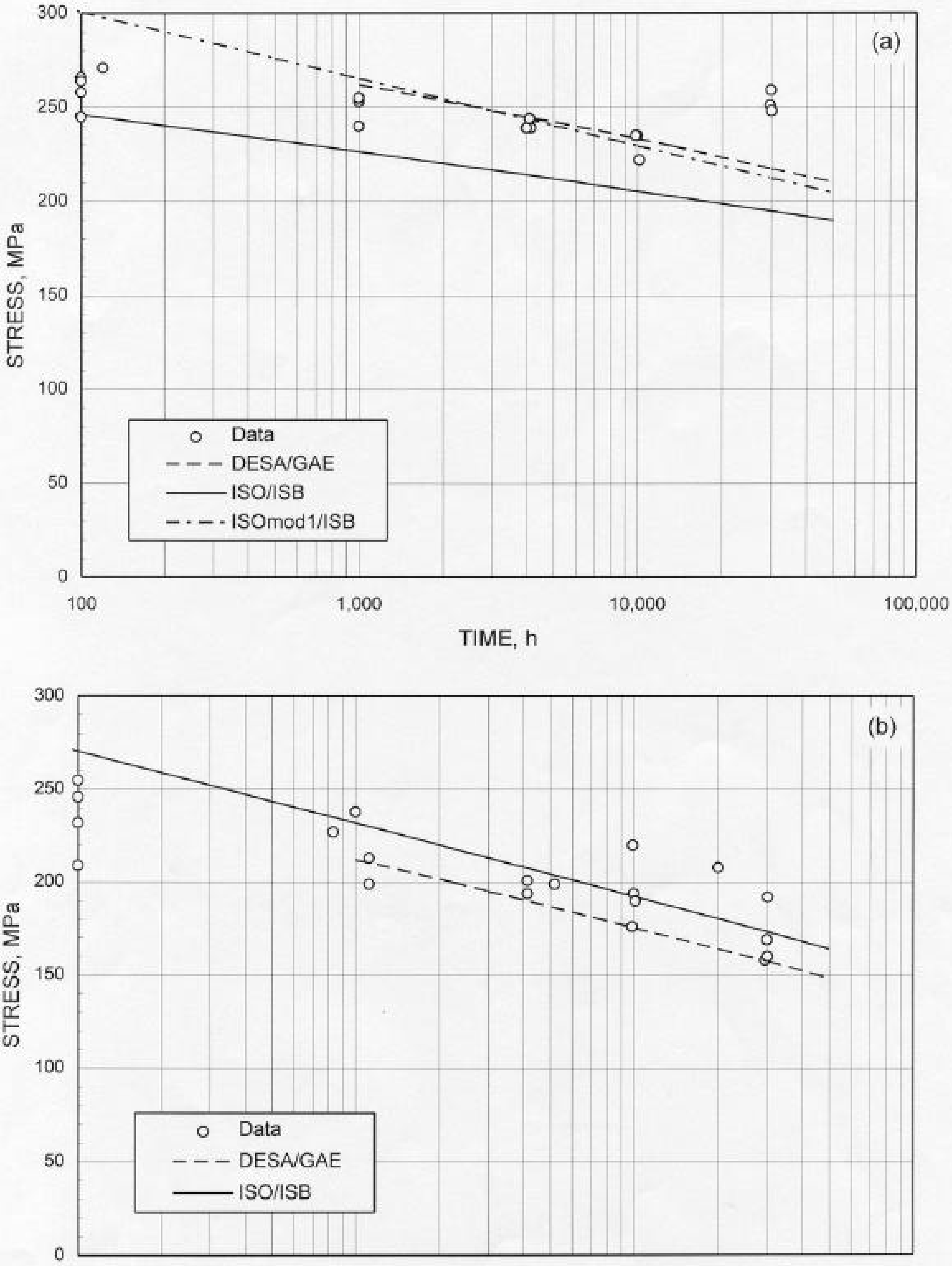




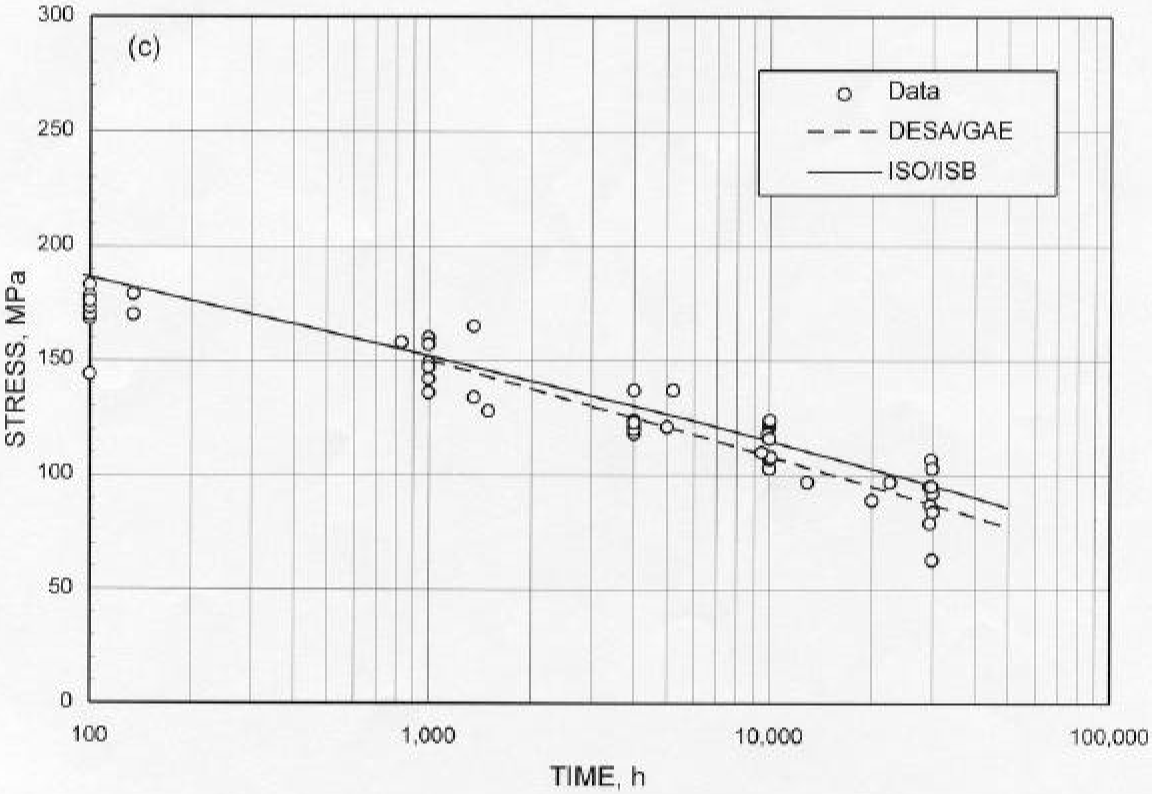
Comparison of observed stress relaxation behaviour for 1CrMoTiB (D1055) bolting steel at (c) 550°C and (d) 565°C [ε_t = 0.15%]

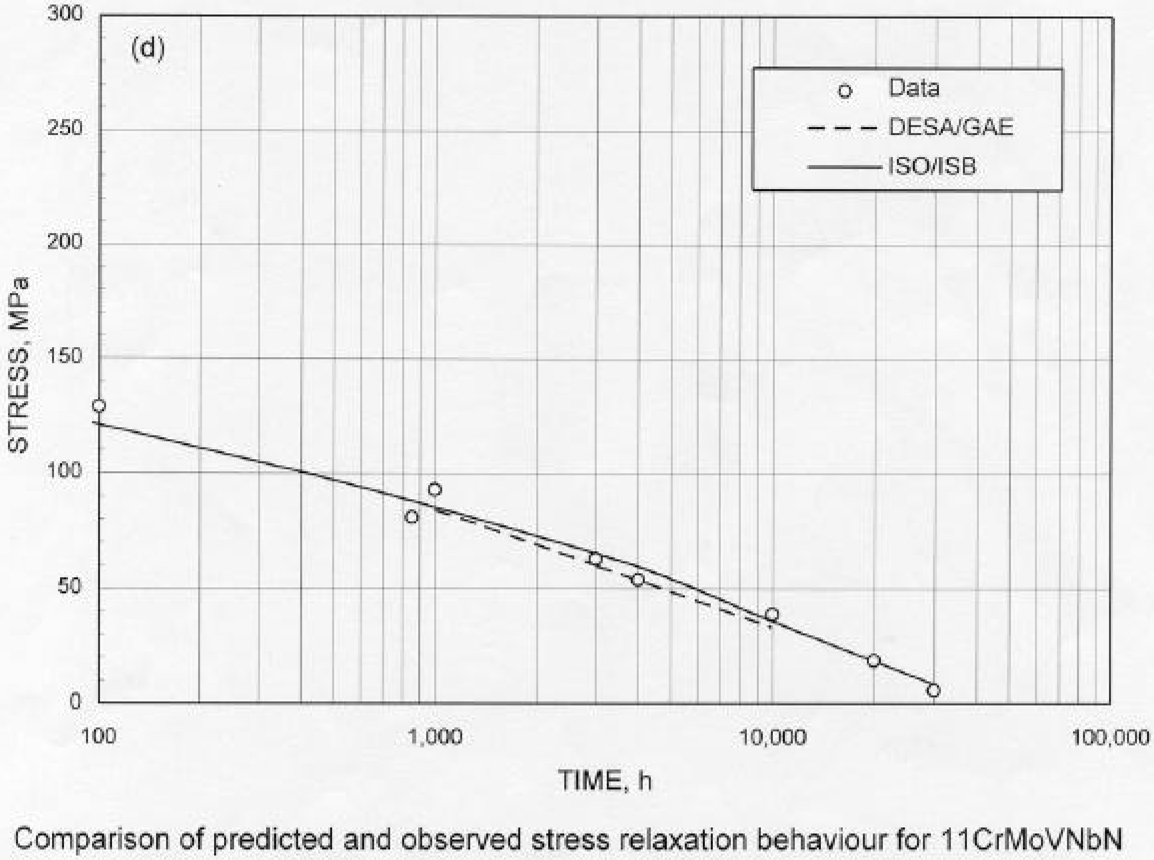


Comparison of observed stress relaxation behaviour for 1CrMoTiB (D1055) bolting steel at (g) 575°C [ε_t = 0.15%]

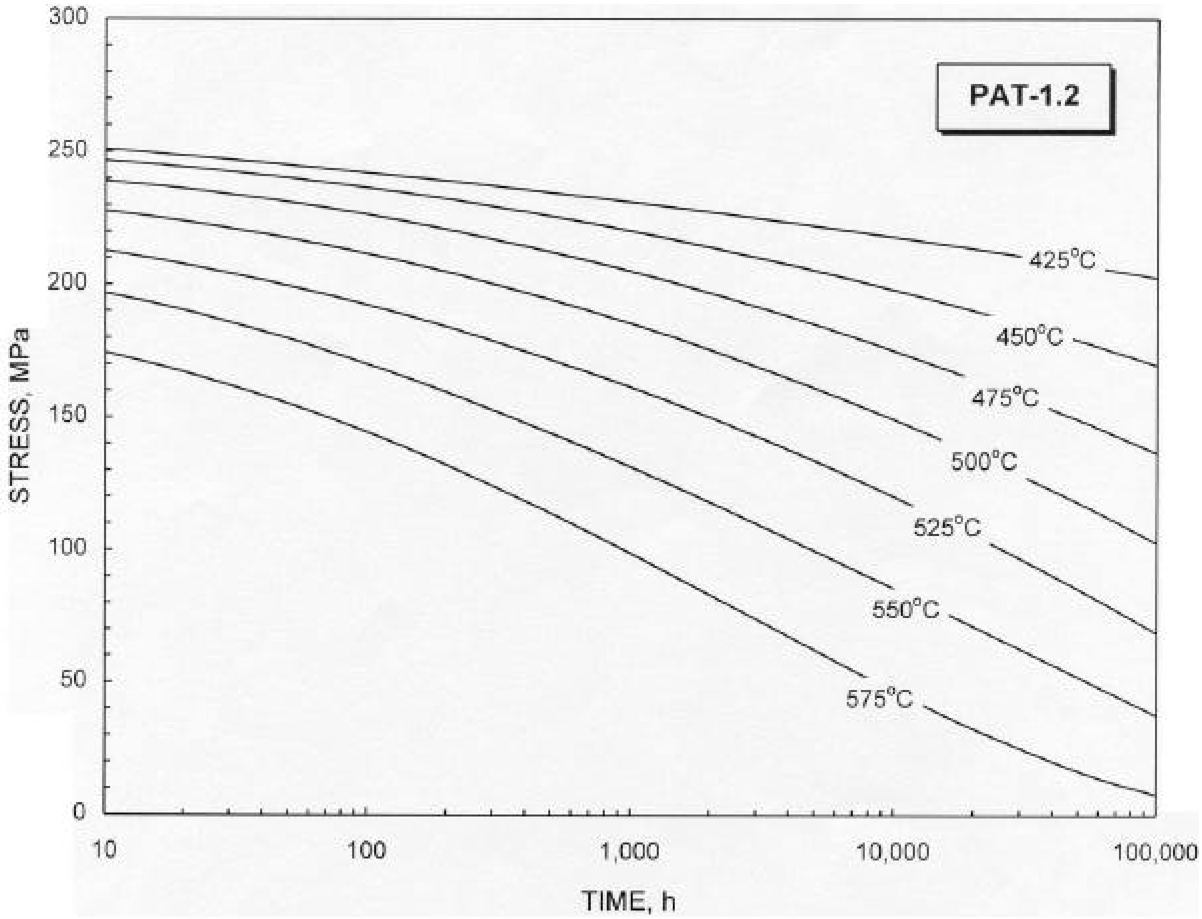


Comparison of predicted and observed stress relaxation behaviour for 11CrMoVNbN bolting steel at (a) 425°C and (b) 480°C [ε_t = 0.18%]

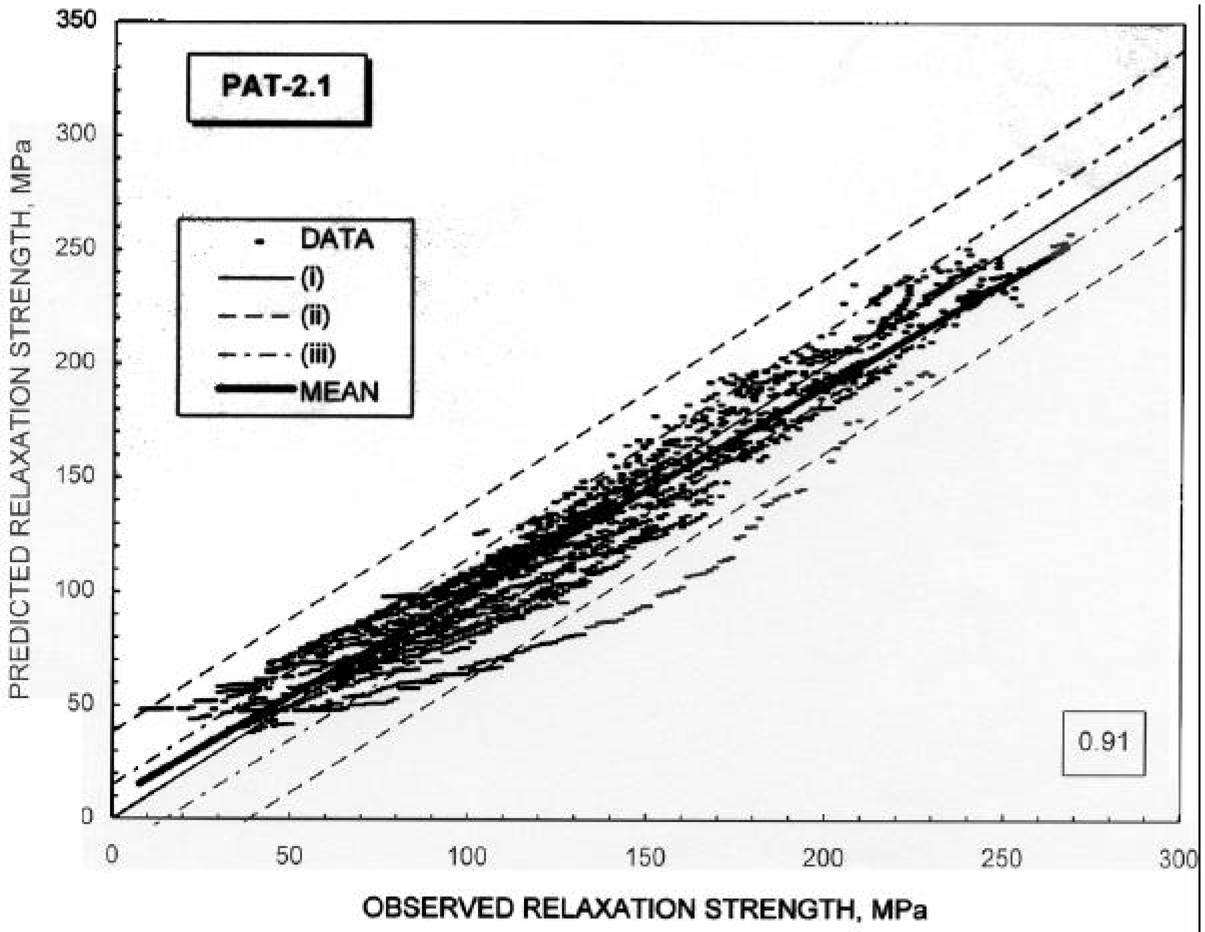




Comparison of predicted and observed stress relaxation behaviour for 11CrMoVNbN bolting steel at (c) 540°C and (d) 600°C [ε_t = 0.18%]



PAT-1.2 for the CPA-Conway predicted $R_{R/t/T}(\varepsilon_t$ 0.15%) strength values for 1CrMoVTiB (D1055) bolting steel



KEY TO REFERENCE/BOUNDARY LINES

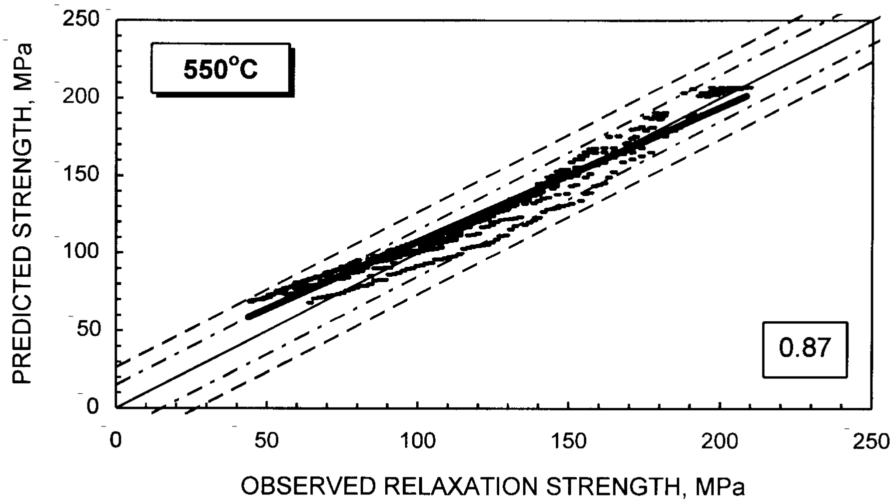
(i) $R_{R/t/T}(\varepsilon_t) = \sigma_{R/t/T}(\varepsilon_t)$ reference line

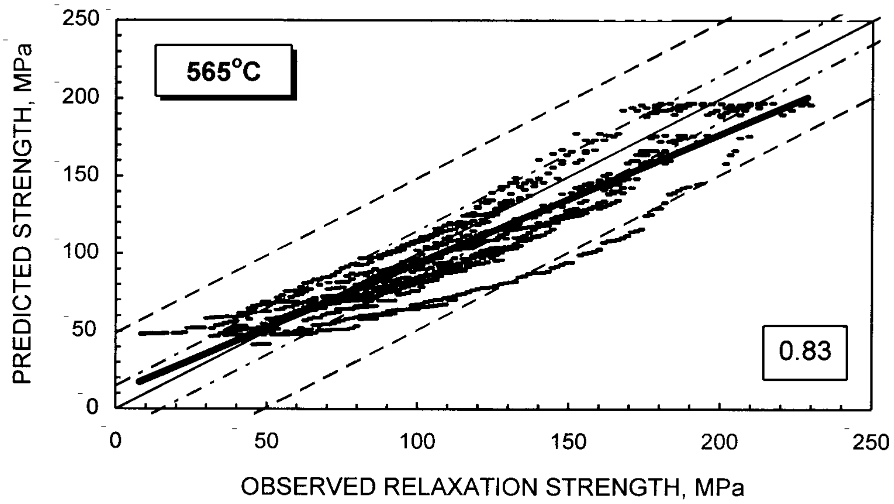
(ii) $R_{R/t/T}(\varepsilon_t) = \sigma_{R/t/T}(\varepsilon_t) \pm 2.5\ s_{[A\text{-}RR]}$ boundary lines

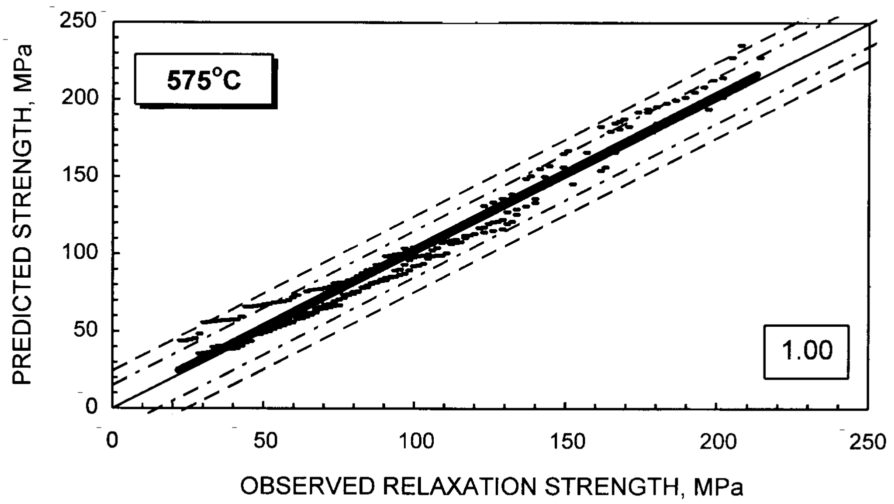
(iii) $R_{R/t/T}(\varepsilon_t) = \sigma_{R/t/T}(\varepsilon_t) \pm$ 15MPa boundary lines

$s_{[A\text{-}RR]}$ is the standard deviation of the residual relaxed stresses for all the data at all temperatures(see text)

PAT-2.1 - Comparison of predicted versus observed relaxation strength values for 1CrMoVTiB (D1055) bolting steel







PAT-2.2 - Isothermal comparisons of predicted versus observed relaxation strength values for 1CrMoVTiB (D1055) bolting steel