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ECCC RECOMMENDATIONS - VOLUME 5 Part IIa [Issue 1]

GUIDANCE FOR THE ASSESSMENT OF CREEP RUPTURE, CREEP STRAIN AND STRESS RELAXATION DATA

RECOMMENDATIONS FOR THE ASSESSMENT OF SUB-SIZE CREEP-RUPTURE DATASETS

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GUIDANCE FOR THE ASSESSMENT OF CREEP RUPTURE, CREEP STRAIN AND STRESS RELAXATION DATA

RECOMMENDATIONS FOR THE ASSESSMENT OF SUB-SIZE CREEP-RUPTURE DATASETS

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ABSTRACT

ECCC Recommendations Volume 5 Part IIa provides guidance for the assessment of small (sub-size) creep-rupture datasets. The post assessment tests established for full-size datasets may be used to define the boundaries on temperature and time within which sub-size dataset predicted strength values can be applied with confidence.

Guidance is based on the outcome of a work programme involving the evaluation of various assessment procedures by a number of analysts using several reduced versions of the four full-size datasets used to prepare the recommendations for Part I. The results of this exercise highlight the risk of unacceptable levels of uncertainty in predicted strength values, in particular those associated with very small datasets. The findings of this work programme are detailed in appendices to the document.

There is no substitute for long-term test data. Creep strength values determined from sub-size datasets should only be regarded as provisional until the appropriate long-term data is available to do a full assessment.

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RECOMMENDATIONS FOR THE ASSESSMENT OF SUB-SIZE CREEP-RUPTURE DATASETS

CONTENTS

1. INTRODUCTION

In ideal circumstances, the creep rupture strength values, $R_{u/t/T}$,[1] are determined from the assessment of a dataset comprising a homogeneous distribution of $t_u(T,s_o)$ data points covering a sufficiently wide range of temperatures and stresses to enable extended time and stress extrapolations to be limited to generally acceptable levels, e.g. [2a,3]. Moreover, these data points represent a sufficient number of casts to fully characterise the variability in creep-rupture properties inherent in the material specified for assessment, in a balanced way. In practice, such circumstances rarely exist, except for certain well established, widely used steels (e.g. [4,5]).

Part IIa is concerned with the assessment of sub-size datasets such as those for i) new alloys ripe for early exploitation, ii) weldments for which strength reduction factors are required or iii) post-service exposed materials.[2] The characteristics of such datasets are a relatively small number of $t_u(T,s_o)$ data points, for a small number of casts, with the maximum test duration(s) at the main application temperature(s) for which strength values are required.

The recommendations for sub-size datasets have been influenced by the results of assessments of a number of data collations prepared specifically for the purpose from the large datasets used to verify the ECCC post assessment tests [2a,6]. The details of these are given in Appendix A.

2. CREEP-RUPTURE DATA ASSESSMENT

2.1 OVERVIEW

Sub-size datasets may be assessed using the same procedures as those available for full-size datasets [2a], but invariably with the help of other techniques. In Part IIa, five strategies are identified to complement these procedures during the assessment of sub-size $t_u(T,s_o)$ datasets, i.e.

- the use of data factors,
- the application of statistical modelling,
- the complementary use of creep strain data,
- the complementary use of reference $t_u^*(T,s_o)$ master-curves, and
- the use of *comparable* $t_u(T,s_o)$ data.

These approaches aim to determine a conservative estimate of mean strength values for the material under evaluation, both within and beyond the range of the $t_u(T,s_o)$ data. Their status is reviewed in the following sections.

2.1.1 Data Factors

An example of the data factors which may be applied to long-time extrapolated strength values determined from relatively short duration test data in a sub-size dataset is given in Eqn. 1, *i.e.*

$$R_{u/t_d/T} = R_{u(s)/t_d/T} \cdot \frac{h_{cast}(n)}{s_{data}(N, t_{u,max}, t_d)} \qquad (1)$$

[1] The terminology used in Part IIa is as defined in [1]

[2] Sub-size dataset types ii) and iii) are considered specifically in Volume 5 Part IIb and Part III respectively [2c,d]

where $h_{cast}(n)$ is a function dependent on the number of casts for which $t_u(T, s_o)$ data points have been collected. The h_{cast} material-variability factor tends to unity as n tends to 6, to be consistent with existing recommendations [2a,3]. The s_{data} data factor is dependent on the number of $t_u(T, s_o)$ data points, N, the maximum test duration at T±25°C and the design life, t_d, *e.g.* [7]. Such data factors are material dependent and can lead to excessively conservative estimates of $R_{u/td/T}$ strength values, Appendix B.

With decreasing N and $t_{u,max}$, and increasing t_d, design life $R_u/R_{u,sub}$ strength ratios are increasingly dependent on material characteristics, analyst, and the extent and distribution of the $t_u(T, s_o)$ data population [8].

There appears to be a practical limitation to the dataset size to which data factors can be applied. For datasets with ~100 data points, the inherent variability revealed by the multiple assessment of different samples of the same population results in a lower bound $R_{u(S)/t/T}$ estimate consistent with that anticipated by the use of a data factor (Appendix B). For smaller datasets, in particular those in which the data points are not distributed in an equi-balanced way (Appendix C), the inherent variability in predicted rupture strength leads to a lower bound $R_{u(S)/t/T}$ estimate significantly below that anticipated by the use of a data factor.

2.1.2 Statistical Modelling

For the future, the use of state-of-the-art statistical modelling holds the most promise for the determination of creep-rupture strength values from small $t_u(T, s_o)$ datasets. With the latest techniques, there is a basis for increased confidence in extended strength extrapolations and the possibility to quantify associated levels of uncertainty. Moreover, state-of-the-art statistical modelling procedures allow the implementation of maximum likelihood (survival) statistics, and thereby enable the formal analysis of unfailed test data and the full utilisation of all available $t(T, s_o)$ information. Advances in the use of such techniques, in conjunction with the necessary metallurgical input, have already been exploited in the assessment of large datasets [9,10].

Preliminary work has shown that >50-70 data points are required for this approach. Feasibility depends on the distribution of the data. For an equi-balanced dataset, 50 data points can be sufficient. On the other hand, 100 data points may be insufficient when the dataset is not balanced. Guidance on balanced datasets is given in Appendix C.

Employment of the latest advances in statistical modelling has not been possible with the resources available to WG1. A successful outcome to this approach will only be possible through a focussed fundamental research activity with the appropriate funding.

2.1.3 Complementary Use of Creep Strain Data

The main (but not the only) problem in the assessment of sub-size datasets is the reliable extrapolation of $t_u^*(T, s_o)$ values to well beyond $t_{u,max}(T, s_o)$. An alternative strategy to the employment of survival statistics within an advanced statistical modelling approach is to exploit the information available from unfailed test data through the use of complementary strain data.

The technique is an integral part of the graphical multi-heat averaging and cross plotting method [2a]. This procedure recommends the generation of the following times to specific strains for *i)* heavy components and *ii)* thin walled components, with the longest $t_{e/T}$ values being of the same order of magnitude as the longest rupture times at each temperature.

i) $t_{0.2\%/T}$, $t_{0.5\%/T}$, $t_{1\%/T}$

ii) $t_{0.5\%/T}$, $t_{1\%/T}$, $t_{2\%/T}$

This approach can only be successfully employed if creep strain data has been collected during the course of creep-rupture testing, and from tests forming part of a balanced test programme in which $t(T, s_o)$ data is being collected homogeneously throughout the range of temperatures and stresses, for each material cast (Appendix B).

2.1.4 Complementary Use of Reference Master-Curves

In principle, the complementary use of reference $t_u^*(T, s_o)$ master-curves provides the most pragmatic solution for the assessment of sub-size datasets (Appendix D). The approach is particularly applicable to the assessment of weldment and post service exposed creep-rupture data (Part IIb and Part III). For such applications, it is likely that a full-size dataset exists for the parent steel of interest and that a master-curve has already (or may readily) be determined, e.g. [4,5]. The approach is less useful for new alloys since they are likely to have been developed to provide an improvement in properties relative to existing materials.

For the assessment of a new virgin material, the complementary use of a reference $t_u^*(T, s_o)$ master curve will only be possible if a datum line exists for a steel with a comparable material pedigree in terms of (i) chemical composition and heat treatment, (ii) strengthening element ratios, e.g. V/C, Mo/V, (iii) microstructural transformation product and grain size, and (iv) tensile strength.

2.1.5 Comparable Data

The limited number of $t_u(T, s_o)$ observations in certain types of 'small' dataset may be supplemented by *comparable* data. For example, in the case of testpieces removed from ferritic welds in which the fracture location is in the ICHAZ, it may be possible to show in data pre-assessment that filler metal pedigree and welding process requirements may be relaxed in assembling the dataset [2c]. Similarly, parent material pedigrees may be relatively unimportant for weld creep data for which fracture occurs in the main weld at a significant distance from the fusion boundary (e.g. certain austenitic weldments).

Post service exposed material data may be regarded as *comparable* if determined from virgin material, procured to the same alloy specification, which has experienced a service duty time within a range of factor 2 at a temperature within ±10°C and a stress within ±10% [2d].

The use of *comparable* data is unlikely to be appropriate for the assessment of small datasets of new alloys. Such materials are invariably developed to give a strength advantage over existing alloys and it is therefore unlikely that data for materials with equivalent pedigrees (see 2.1.4) will be available.

2.2 RECOMMENDATIONS

The ECCC-WG1 sub-size CRDA evaluation activity reported in the appendices has led to the following recommendations. The recommendations are specifically aimed at assessments leading to strength values to be externally published by ECCC but may be used for other purposes.

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

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 results of the main-assessment should satisfy the requirements of the post assessment acceptability criteria given in Sect. 2.4.

4) The results of the two CRDAs should predict $R_{u/t/T}$ to within 10%at $T_{min[10\%]}$, T_{main} and $T_{max[10\%]}$ at the maximum test time for each temperature.[1,3]

5) During subsequent use of the master equation derived from the CRDA, strength predictions based on extended time and extended stress extrapolations must be identified.

   Extended time extrapolations are those beyond $3.t_{u(S),max}$ at temperatures within ±25°C of that specified.[4] Results from tests in progress may be included when above the -20% scatterband limit at the appropriate duration.

   Extended stress extrapolations are those in the ranges '$0.9.s_{o,min}$ to $s_{o,min}$' and '$s_{o,max}$ to $1.1.s_{o,max}$'.

6) All predicted strength values determined by extrapolation from the assessment of a sub-size dataset should be regarded as provisional and qualified accordingly

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

8) There is no substitute for long-term test data. There is no substitute for long-term test data. Creep strength values determined from sub-size datasets should only be regarded as provisional until the appropriate long-term data is available to do a full assessment.

9) There is a clear need for a means of predicting long-term strength values from sub-size datasets ahead of the availability of long-term test data. However, an effective solution will not be achieved without a significant scientific effort with suitable funding support.

2.3 PRE-ASSESSMENT

Where possible, the pre-assessment of weld creep-rupture data should be performed according to the guidance given in Part I [2a].

Pre-assessment should include:

(i) confirmation that the data meet the material pedigree and testing information requirements recommended in ECCC Volume 3 Part I [11a].

(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 broken and unbroken testpiece data points with respect to temperature and time (e.g. Tables B?); identifying $t_{u(S),max}$, $s_{o,min}$, and the temperatures for which there are (a) ≥5% broken specimen test data ($T_{[5\%]}$) and (b) ≥10% broken specimen test data ($T_{[10\%]}$).

   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 for 566°C may be considered together with data for 565°C).

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

[4] Note the significant difference between this requirement and that for full-size datasets in Part I [2a]. This definition of extended time extrapolations is not recommended for the qualification of strength values for European product standards.

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

(v) a visual examination of isothermal log s_o versus log t_u plots (containing broken and unbroken data points) and a first assessment to characterise the trends and scatter in the data.

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

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 [11a], providing the material specification is realistic.

2.4 POST ASSESSMENT

For sub-size datasets, the three categories of post assessment acceptability criteria introduced for full-size datasets are retained, i.e. 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

An important addition to the original PAT-1.1 is a conformance check in circumstances where it is possible (and essential) to compare the predicted isothermal lines with existing $t_u(s_o)$ reference lines for the same, similar or parent materials. The application of PAT-1.1b is an integral part of assessment procedures involving the complementary use of reference master curves.

It is not the intention to dilute the PATs as defined in Part I for full-size datasets. Rather to use them to define the boundaries within which sub-size dataset predicted strength values can be applied with confidence. The one exception is the application of PAT-3.2 which will generally be impractical for sub-size datasets.

Guidance on the use of the PATs to define the boundaries within which sub-size assessment predicted strength values can be applied with confidence is given in the following sections.

Physical Realism of Predicted Isothermal Lines

PAT-1.1a Visually check the credibility of the fit of the isothermal logs_o versus log t_u* lines to the individual $t_u(T, s_o)$ data points over the range of the data

PAT-1.1b Visually check the credibility of the shape and the relationship of the isothermal logs_o versus logt_u* data lines with respect to available relevant reference lines, ideally established according to the requirements of Part I.

For the assessment of virgin material, this will only be possible if a reference line exists for a steel with a comparable material pedigree in terms of (i) chemical composition and heat treatment, (ii) strengthening element ratios, e.g. V/C, Mo/V, (iii) microstructural transformation product and grain size, and (iv) tensile strength.

For sub-size datasets of weld-creep or post service exposed data, predicted $R_{u(S)/t/T}$ values should never exceed $R_{u/t/T}$ values for the specific parent material or the alloy mean $R_{u/t/T}$+20%.

For sub-size weld-creep datasets, it is unlikely that $R_{u(W)/t/T}$ will fall below x0.4 the alloy mean.

PAT-1.2 Produce isothermal curves of log s_o versus log t_u* at 25°C intervals from 25°C below the minimum temperature to 25°C above the maximum application temperature, $T_{app,max}$.[5]

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

In the event that predicted lines (a) cross-over, (b) come-together or (c) turn-back, the magnitude of $T_{app,max}$ should be reduced until PAT-1.2 is passed.

PAT-1.3 Plot the derivative $-\partial(\log t_u^*)/\partial(\log s_o)$ 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 (i.e. $s_o \geq 0.8.s_{o,min}$)

The values of $-\partial(\log t_u^*)/\partial(\log s_o)$, i.e. n_r in $t_u^* \propto (s_o)^{nr}$, should not be ≤1.5.

It is permissible for n_r 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_r =1., e.g. diffusional flow.

Effectiveness of Model Prediction within Range of Input Data

PAT-2.1 To assess the effectiveness of the assessed model to represent the behaviour of the complete dataset, plot log t_u* versus log t_u for all input data for temperatures $\leq T_{app,max}$

The log t_u* versus log t_u diagram should show
- the log t_u* = log t_u line (i.e. the line representing an ideal fit),
- the log t_u* = log t_u ± 2.5.$s_{[A-RLT]}$ boundary lines,[6,7]
- the log t_u* = log t_u ± log 2 boundary lines,[8] and
- the linear mean line fit through the log t_u*(log t_u) data points for 100< t_u < 3.$t_{u,max}$ (extrapolated to $t_{u/100kh}$).

The model equation should be re-assessed:
(a) if more than 1.5% of the log t_u*(log t_u) data points fall outside one of the ±2.5.$s_{[A-RLT]}$ boundary lines,[9]
(b) if the slope of the mean line is <0.78 or >1.22, and
(c) if the mean line is not contained within the ±log 2 boundary lines for 100< log t_u <100kh.

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5 The maximum application temperature for which predicted strength values are required
6 $s_{[A-RLT]}$ is the standard deviation of the residual log times for all the data at all temperatures, i.e. $s_{[A-RLT]} = \sqrt{\{\sum_i(\log t_{u,i} - \log t_u^*)^2/(n_A - 1)\}}$, where i = 1,2, …. n_A, and n_A is the total number of data points
7 For a normal error distribution, almost 99% of the data points would be expected to be within log t_u* = log t_u ±2.5.$s_{[A-RLT]}$ boundary lines.
8 i.e. the t_u* = 2.t_u and t_u* = 0.5.t_u boundary lines
9 Experience has shown that the ±2.5.$s_{[A-RLT]}$ boundary lines typically intersect the t_u = 100h grid line at t_u*≤1kh and t_u*≥10h respectively [2a]. The explanation for those which do not is either an imbalance in the model fit (and hence the PAT-2.1a criterion) or excessive variability in the data set. In the latter case, consideration should be given to the scope of the material specification (in conjunction with the assessment instigator, e.g. WG3.x)

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

(i) log s_o versus log t_u* with individual $t_u(T, s_o)$ data points

(ii) log t_u* versus log t_u, with

- the log t_u* = log t_u line (i.e. the line representing an ideal fit),
- the log t_u* = log $t_u \pm 2.5.s_{[I\text{-}RLT]}$ boundary lines,
- the log t_u* = log t_u ± log 2 boundary lines, and
- the linear mean line fit through the log t_u*(log t_u) data points for $100 < t_u < 3.t_{u,max}$ (extrapolated to 100kh).

and identify the individual casts.

(a) Log t_u* versus log t_u plots for individual casts should have slopes close to unity and be contained within the $\pm 2.5.s_{[I\text{-}RLT]}$ boundary lines.[11] The pedigree of casts with ∂(log t_u*)/∂(log t_u) slopes of <0.5 or >1.5 and/or which have a significant number of log t_u*(log t_u) 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 [11b] and the specification set by the assessment instigator (e.g. WG3.x), the assessor should first consider with the instigator whether the scope of the cast specification is too wide. If there is no metallurgical justification for modifying the specification, the effectiveness of the model to predict individual cast behaviour should be questioned.

The distribution of the log t_u*(log t_u) data points about the log t_u* = log t_u line reflects the homogeneity of the dataset and the effectiveness of the predictive capability of the model. 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-assessed if at any temperature:

(b) the slope of the mean line through the isothermal log t_u*(log t_u) data points is <0.78 or >1.22, and

(c) the mean line is not contained within the ±log 2 boundary lines for $100 < \log t_u < 100$kh

Repeatability and Stability of Extrapolations

PAT-3 represents the most practical solution to the problem of evaluating the reliability of assessing 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 datasets. It is usually impractical to perform PAT-3.2 (as defined in Part I) for sub-size datasets. As a consequence, only the use of PAT-3.1 is recommended in these guidelines.

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[10] Providing these temperatures do not exceed $T_{app,max}$

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

PAT-3.1 Randomly cull 50% of data between $t_{u,max}/10$ and $t_{u,max}$ and repeat the assessment to check the repeatability of the extrapolation to variations in the dataset. If the CRDA $R_{u/3.tu,max}$ are not reproduced to within 10%, PAT-3.1 may be repeated. However, if the acceptability criterion is not met after the second cull:-

(i) the main assessment should be repeated using a different model equation or procedure, or
(ii) the extrapolation factor of 3x should be reduced until the within-10% criterion is satisfied

3. SUMMARY

ECCC Volume 5 Part IIa provides guidance for the assessment of sub-size creep-rupture datasets. The recommendations are specifically aimed at assessments leading to strength values to be externally published by ECCC but may be used for other purposes. The principle objective is to minimise the uncertainty associated with strength predictions by recommending pre-assessment, the implementation of post assessment acceptability criteria and the performance of duplicate assessments.

There is no substitute for long-term test data. Creep strength values determined from sub-size datasets should only be regarded as provisional until the appropriate long-term data is available to do a full assessment.

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APPENDIX A

WG1 REDUCED CREEP RUPTURE DATASETS FOR ASSESSMENT METHOD VALIDATION PURPOSES

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APPENDIX A

WG1 REDUCED CREEP RUPTURE DATASETS FOR ASSESSMENT METHOD VALIDATION PURPOSES

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A1 Background and Introduction

Reduced creep rupture datasets were prepared from the large collations employed by ECCC-WG1 during the preparation of ECCC Vol.5 Part I. Four large datasets were originally collated for i) 2¼CrMo (N+T), ii) 11CrMoVNb, iii) Type 304H and iv) Incoloy 800. The population statistics for the original datasets are given in App. A of Part I.

Two types of reduced dataset were prepared. The first, referred to as *x*RD1*z*, had a size of approximately 80-100 rupture data points with durations of up to 30-50kh (*x* designating the material, i.e. A, B, C or D). These were collated to represent a limited multicast dataset for a new material or a more extensive weldment or PEDS type dataset.

More than one version of each dataset was prepared and *z* refers to the version number (e.g. a, b etc.)

The second type of dataset, referred to as *x*RD2*z*, had a size of 10-20 rupture data points with durations of up to 20-30kh to be more representative of those more typically available for welded or post service exposed materials.

A2 Culling Philosophy

The culling philosophy adopted was as follows. Firstly, the datasets were right censored to take out the long duration data, ie. to <50kh for *x*RD1*z* and <30kh for *x*RD2*z*. In this process, the data was not eliminated. All rupture and on-test durations greater than 50kh or 30kh were respectively changed to 50kh and 30kh and the test classification changed to UB. The data collations were randomly culled on a cast by cast basis until the required number of rupture data points remained. The final random culling of the *x*RD1*z* and *x*RD2*z* versions for each material were performed independently.

A3 Dataset Statistics

The statistics for 17 datasets are given in Tables A1.1.2 to A8.

Two CRD2*z* files are given. CRD2DATB.XLS is the preferred 'small' dataset for material C. CRD2DATA.XLS was produced as a consequence of the first data reduction exercise for this material, but was not considered ideal for the purpose (Table)

Table A1.1 Quantity and duration of data in ARD1a dataset

Temps	No. of heats	Test Durations					
		h <3,000	h 3,000 to 9,999	h 10,000 to 19,999	h 20,000 to 29,999	h 30,000 to 50,000	Totals
°C		Number of test points available					
425	1	1		(1)			1 (1)
450	2	2 (2)	(1)		1	(2)	3 (5)
475	2	2	1	2	1	(2)	6 (2)
500	4	4 (1)	1 (2)	3	3 (1)	(6)	11 (10)
550	9	11 (1)	8	5	3	7 (8)	34 (9)
600	6	11	6 (2)	6 (1)	3	2 (5)	28 (8)
Totals	9	31 (4)	16 (5)	16 (2)	11 (1)	9 (23)	83 (35)
( ) Figures in parentheses denote unbroken tests							

Table A1.2 Quantity and duration of data in ARD1b dataset

Temps	No. of heats	Test Durations					
		h <3,000	h 3,000 to 9,999	h 10,000 to 19,999	h 20,000 to 29,999	h 30,000 to 50,000	Totals
°C		Number of test points available					
425	1	1		(1)			1 (1)
450	3	2 (2)	(1)	2	1 (1)	(2)	5 (6)
475	1			1		1 (2)	2 (2)
500	5	5 (1)	4 (2)	4 (1)	1 (1)	1 (8)	15 (13)
550	13	18	11	5	5	7 (6)	44 (8)
600	6	9	5 (2)	5	3	(2)	22 (4)
Totals	13	35 (3)	20 (5)	17 (2)	10 (2)	8 (21)	89 (34)
( ) Figures in parentheses denote unbroken tests							

Table A2.1 Quantity and duration of data in ARD2a dataset

Temps	No. of heats	Test Durations					
		h <3,000	h 3,000 to 9,999	h 10,000 to 19,999	h 20,000 to 29,999	h 30,000 to 50,000	Totals
°C		Number of test points available					
450	2	1		1	(4)		2 (4)
500	2	2	2	2	(4)		6 (4)
550	2	1	4	1	(2)		6 (2)
600	1	2	1	1 (1)			4 (1)
Totals	2	6	7	5 (1)	(10)		18 (11)
( ) Figures in parentheses denote unbroken tests							

Table A2.2 Quantity and duration of data in ARD2b dataset

Temps	No. of	Test Durations					
	heats	h <3,000	h 3,000 to 9,999	h 10,000 to 19,999	h 20,000 to 29,999	h 30,000 to 50,000	Totals
°C		Number of test points available					
450	1	2		1	(2)		3 (2)
500	1	4		1	1 (2)		6 (2)
550	2	2	1		(4)		3 (4)
600	2	3	2	2	1 (3)		8 (3)
Totals	2	11	3	4	2 (11)		20 (11)
( ) Figures in parentheses denote unbroken tests							

Table A3.1 Quantity and duration of data in BRD1a dataset

Temps	No. of	Test Durations					
	heats	h <3,000	h 3,000 to 9,999	h 10,000 to 19,999	h 20,000 to 29,999	h 30,000 to 50,000	Totals
°C		Number of test points available					
500	4	2	4	2	2		10
550	5	5	4	3	2	(3)	14 (3)
600	6	6	2	4	(1)	2 (1)	14 (2)
650	5	4	5	3	2	(3)	14 (3)
700	7	5	6	4	1	(3)	16 (3)
750	1	1					1
800	3	2	3			1	6
850	1	1					1
900	2	2	1	2			5
950	1	2		1			3
1000	1	2	1				3
Totals	7	32	26	19	7(1)	3 (10)	87 (11)
( ) Figures in parentheses denote unbroken tests							

Table A3.2 Quantity and duration of data in BRD1b dataset

Temps	No. of	Test Durations					
	heats	h <3,000	h 3,000 to 9,999	h 10,000 to 19,999	h 20,000 to 29,999	h 30,000 to 50,000	Totals
°C		Number of test points available					
500	3	5	2	(3)	(1)		7 (4)
550	3	3	1	2	(1)		6 (1)
600	5	6	3	3	1 (1)	(2)	13 (3)
650	4	2	3	3	1	1 (1)	10 (1)
700	8	9	6	4	(2)	2 (2)	21 (4)
750	2	1	3				4
800	5	11	2	3	1		17
850	1	1					1
900	4	8	1	4	(1)	2	15 (1)
1000	3	5	4			2	11
1050	2	2					2
Totals	9	53	25	19 (3)	3 (6)	7 (5)	107 (14)
( ) Figures in parentheses denote unbroken tests							

Table A4.1 Quantity and duration of data in BRD2a dataset

Temps °C	No. of heats	Test Durations h <3,000	h 3,000 to 9,999	h 10,000 to 19,999	h 20,000 to 29,999	h 30,000 to 50,000	Totals
		Number of test points available					
700	1	2	1	1	(1)		4 (1)
800	1	2	1	1	(1)		4 (1)
850	1	1	2				3
900	1	2	1 (1)	1	(1)		4 (2)
1000	1	3					3
Totals	2	10	5 (1)	3	(3)		18 (4)
( ) Figures in parentheses denote unbroken tests							

Table A4.2 Quantity and duration of data in BRD2b dataset

Temps °C	No. of heats	Test Durations h <3,000	h 3,000 to 9,999	h 10,000 to 19,999	h 20,000 to 29,999	h 30,000 to 50,000	Totals
		Number of test points available					
600	1	1	1				2
700	1	1	1				2
800	1	3	1				4
900	1	3	1				4
1000	1	2	1		1		4
1050	1	1					1
Totals	1	11	5		1		17
( ) Figures in parentheses denote unbroken tests							

Table A5.1 Quantity and duration of data in CRD1a dataset

Temps °C	No. of heats	Test Durations h <3,000	h 3,000 to 9,999	h 10,000 to 19,999	h 20,000 to 29,999	h 30,000 to 50,000	Totals
		Number of test points available					
600	7	14	8	2	1	1 (1)	26 (1)
625	2	1		2			3
650	7	13	7	8	2 (1)	1	31 (1)
700	7	14	5	2 (1)			21 (1)
800	6	2	(1)				2 (1)
Totals	7	44	20 (1)	14 (1)	3 (1)	2 (1)	83 (4)
( ) Figures in parentheses denote unbroken tests							

Table A5.2 Quantity and duration of data in CRD1b dataset

Temps	No. of heats	Test Durations					
		h <3,000	h 3,000 to 9,999	h 10,000 to 19,999	h 20,000 to 29,999	h 30,000 to 50,000	Totals
°C		Number of test points available					
550	1	2	2		1		5
565/70	2	5					5
600	7	16	3	2 (1)		1	22 (1)
620	1	2					2
649/50	7	18	7	4	1	(1)	30 (1)
670	1	3					3
700	4	12	4	1	1		18
720	1	3					3
800	1	2					2
Totals	9	63	16	7 (1)	3	1 (1)	90 (2)
( ) Figures in parentheses denote unbroken tests							

Table A6.1 Quantity and duration of data in CRD2a dataset

Temps	No. of heats	Test Durations					
		h <3,000	h 3,000 to 9,999	h 10,000 to 19,999	h 20,000 to 29,999	h 30,000 to 50,000	Totals
°C		Number of test points available					
565	1	4					4
570	1	3					3
600	2	5					5
620	1	2					2
670	1	3					3
720	1	3					3
Totals	2	20					21
( ) Figures in parentheses denote unbroken tests							

Table A6.2 Quantity and duration of data in CRD2b dataset

Temps	No. of heats	Test Durations					
		h <3,000	h 3,000 to 9,999	h 10,000 to 19,999	h 20,000 to 29,999	h 30,000 to 50,000	Totals
°C		Number of test points available					
550	1	4	2	1			7
593	1	2					2
600	1	1		1			2
649	1	1					1
650	2	4	1		1		6
700	1	2	1				3
Totals	4	14	4	2	1		21
( ) Figures in parentheses denote unbroken tests							

Table A6.3 Quantity and duration of data in CRD2c dataset

Temps	No. of heats	Test Durations					
		h <3,000	h 3,000 to 9,999	h 10,000 to 19,999	h 20,000 to 29,999	h 30,000 to 50,000	Totals
°C		Number of test points available					
600	1	2	2	1			5
650	1	3	2	3			8
700	1	5		1			6
Totals	1	10	4	5			19
( ) Figures in parentheses denote unbroken tests							

Table A7.1 Quantity and duration of data in DRD1a dataset

Temps	No. of heats	Test Durations					
		h <3,000	h 3,000 to 9,999	h 10,000 to 19,999	h 20,000 to 29,999	h 30,000 to 50,000	Totals
°C		Number of test points available					
450	1	3	1	1	(1)	1 (1)	6 (2)
475	1				1	(2)	1 (2)
500	2	7	2	1 (2)	1	1 (1)	12 (3)
525	2	5	4	3		3 (2)	15 (2)
550	3	8	2	2		1 (2)	13 (2)
565/6	2	5		1		1 (1)	7 (1)
575	2	5	2	2 (1)	2	(3)	11 (4)
593	1		1		1	(1)	2 (1)
600	2	7	1	2	(1)	1 (2)	4 (3)
620	1	1					1
650	1	1					1
Totals	5	42	13	12 3)	5 (2)	8 (15)	80 (20)
( ) Figures in parentheses denote unbroken tests							

Table A7.2 Quantity and duration of data in DRD1b dataset

Temps	No. of heats	Test Durations					
		h <3,000	h 3,000 to 9,999	h 10,000 to 19,999	h 20,000 to 29,999	h 30,000 to 50,000	Totals
°C		Number of test points available					
475	1	1	1	1		1 (1)	4 (1)
500	3	7	4	2	1	2 (4)	16 (4)
525	3	3	1	(2)		1	5 (2)
535/40	1	3					3
550	5	9	3	2	4	1 (6)	19 (6)
575	2	4	1	1	1		7
600	5	9	7	1	2	3	22
615/20	1	2					2
625/30	2	3	1				4
650	4	7	5				12
Totals	5	48	23	7 (2)	8	8 (11)	94 (13)
( ) Figures in parentheses denote unbroken tests							

Table A8.1 Quantity and duration of data in DRD2a dataset

Temps	No. of heats	Test Durations					
		h <3,000	h 3,000 to 9,999	h 10,000 to 19,999	h 20,000 to 29,999	h 30,000 to 50,000	Totals
°C		Number of test points available					
500	2	4	3			(2)	7 (2)
550	2	3		1		(3)	4 (3)
600	1	1	1	2	1	(1)	5 (1)
650	1	2	2				4
Totals	3	10	6	3	1	(6)	20 (6)
( ) Figures in parentheses denote unbroken tests							

Table A8.2 Quantity and duration of data in DRD2b dataset

Temps	No. of heats	Test Durations					
		h <3,000	h 3,000 to 9,999	h 10,000 to 19,999	h 20,000 to 29,999	h 30,000 to 50,000	Totals
°C		Number of test points available					
475	1			1	(4)		1 (4)
525	1	2	2		(2)		4 (2)
550	1	1					1
575	1	2		2	1 (1)		5 (1)
590	1	1					1
620	1	1					1
650	1	1					1
	1	8	2	3	1 (7)		14 (7)
( ) Figures in parentheses denote unbroken tests							

APPENDIX B

EVALUATION OF USE OF DATA FACTORS AND OTHER METHODS OF SUB-SIZE DATASET ASSESSMENT

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APPENDIX C

GUIDANCE ON BALANCED DATASETS

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APPENDIX C

Guidance on Balanced Data Sets

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1 Introduction

The results of creep-rupture data assessments, long term or low temperature strength predictions, and their credibility strongly depend on the amount, scope and distribution of the original experimental data.
For creep rupture data sets the following quality criteria may be adopted :

- Data generation criteria (s. Volume 3[1])
- Data distribution as a function of the independent variables temperature and stress :
  - Significant temperatures, dominant casts and data related to them
  - Distribution of casts and points as a function of stress and temperature
  - Data distribution in stress at the significant temperatures
- Random and/or systematic scatter within the data (here not further regarded).

Before starting an assessment, the data set properties should be evaluated. As a generality, the bigger the data set the less influential are shifts in distribution and the weight of single casts or temperatures. When assessing small or subsize data sets, the assessor must be aware of the balance of the data within the available data set in order to take account of any bias.

After identification and description of the actual situation pre-assessment methods can in some cases be used to either eliminate or correct the anomalies. Data reduction and/or conditioning procedures may be considered helpful.

The present appendix aims to give guidance on how to detect significant temperatures, dominant casts and distribution anomalies.

[1] ECCC Recommendations Volume 3, 2001, ‘Recommendations for data acceptability criteria and the generation of creep, creep rupture, stress rupture and stress relaxation data’, Eds. Granacher J., Holdsworth S.R., Klenk. A., Buchmayr B. & Gariboldi E., *Publ. ERA Technology Ltd., Leatherhead, UK*, (a) Part I: Generic recommendations for creep, creep rupture, stress rupture and stress relaxation data, (b) Part II: Creep data for welds, (c) Part III: Creep testing of PE- (ex service) materials.

For clarification examples from the WG1 round robin exercises are included in italics after each chapter (s. Appendix A). The 10 CrMo 9 10 data sets have been used for this purpose:

Name	Data Set type	Number of points N_{tot}	Number of casts
Whole set (s. Volume 5 part I)[2]	Full size	*1117*	*98*
Set 1a (Volume 5 part IIa)[2]	Small Size	*101*	*5*
Set 1b (Volume 5 part IIa)[2]	Small Size	*107*	*5*

The sub sets 1a and 1b were derived from the whole set.

2 Terminology and Symbols

The following terms and abbreviations will be used throughout the present appendix.

N_D	Number of data points available at a given temperature T
N_{Cj}	Number of data points belonging to the cast "j" over all temperatures
N_{tot}	Number of available points over all
$N_{D\text{-}cd}$	Number of points belonging to dominant casts at a given temperature T
N_{cast}	Number of available casts at a given temperature
N_{cast_dom}	Number of available dominant casts at a given temperature
N_S	Number of data points available at a given stress
$N_{S\text{-}cd}$	Number of points available for dominant casts at a given stress
$N_{cast\text{-}S}$	Number of casts available at a given stress
$N_{cast\text{-}S\text{-}dom}$	Number of dominant casts available at a given stress.
n	$= -1/[\partial (\log t_u)/\partial(\log \sigma_o)]$: Stress exponent estimate
T_{sign}	Significant temperature, i.e. temperature at which the big number of available data points will significantly influence the assessment
Dominant cast	A cast that at least at a certain temperature relevantly influences the isothermal data behaviour
T_{crit}	Critical are considered those temperatures at which either relevant changes in material behaviour are expected or due to data distribution important information is concentrated on a small number of data or casts.

[2] ECCC Recommendations Volume 5, 2000, 'Guidance for the assessment of creep rupture, creep strain and stress relaxation data', Eds. Holdsworth S.R. & Merckling G., *Publ. ERA Technology Ltd, Leatherhead, UK*, (a) Part I: Full-size datasets, (b) Part IIa: Sub-size datsets, (c) Part IIb: Weldment datasets, (d) Part III: Datasets for PE (ex-service) materials.

3 Data Distribution in Temperature and Identification of Significant Temperatures and Dominant Casts

3.1 Distribution in Temperature

3.1.1 Plot N_D and N_{cast} as a function of temperature. N_D and N_{cast} should behave similarly when plotted against temperature, i.e. to much data (high N_D) should correspond a big number of casts (high N_{cast}).

Significant temperatures are those with $V_D > V_{D\text{-mean}}$ [3,4]

Dominant casts are those that have
- $C_{Dj} > C_{D\text{-mean}} + 1{,}5\ s_{cd/mean}$ [5,6,7]
- or more than
  - 8 points at a single temperature
  - 7 points at two different temperatures
  - 6 points at three different temperatures.

$N_{D\text{-cd}}$ should be at least 1 per each T_{sign}.
It is recognised that for subsize data sets, which do not contain a lot of data points, often all available casts can be considered as dominant.

Figure 1 reports for the WG1-test data sets on 10 CrMo 9 10 these plots. The following results can be observed :

Data set	*Whole Set*	*Set 1a*	*Set 1b*
T_{sign}	*475°, 500°, 525°, 550°, 565-566°, 575°, 600° and 650 °C*	*500°, 525°, 550°, 575°, 600°*	*500°, 525°, 550°, 600°, 650°C*
Dominant Casts, N_{cast_dom}	*11 (see figure 5)*	*1 strongly dominant cast (D5)*	*1 (5) (D79)*
Distribution	*Ncast is very high at 500°, 550° and 600°C, and its distribution is quite similar to that of ND.*	*just 1 cast available at low and high temperatures*	*similar distribution in N_D and N_{cast}*

3.1.2 Plot the ratios N_{D_cd}/N_D and $N_{cast\text{-dom}}/N_{cast}$ as a function of temperature. At no temperature one of these ratios should pass 0.5.

Figure 2 shows this plot for the 10 CrMo 9 10 data sets:

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[3] $V_D = N_D/N_{tot}$
[4] $V_{D\_mean} = \Sigma_i(V_{D,i}/i)$ for all i available temperatures T
[5] $C_{Dj} = N_C/N_{tot}$
[6] $C_{D\_mean} = \Sigma_j(C_{D,i}/j)$ for all j available casts
[7] $s_{cd/tot} = \sqrt{[\Sigma_j(C_{D,j} - C_{D\_mean})^2]/(j+1)}$

Data set	*Whole Set*	*Set 1a*	*Set 1b*
N_{D-cd}/N_D	*well distributed between 10 and 40%*	*at all T_{sign} one cast is dominant*	*well distributed between 20 and 40%*
$N_{cast-dom}/N_{cast}$	*well distributed between 5 and 30%*	*at all T_{sign} one cast is dominant*	*well distributed between 20 and 30%*

3.2 Data Distribution in Stress

3.2.1 Plot N_S and N_{cast_S} as a function of stress (eventually grouped). The distributions of both should be similar. Normally a stress region in which data are concentrating may be noticed and stated.

Figure 3 shows these plots for the 10 CrMo 9 10 data sets:

Data set	*Whole Set*	*Set 1a*	*Set 1b*
Distribution	*similar between N_S and N_{cast_S}*	*Very confused situation. At many stresses only one cast present*	*similar between N_S and N_{cast_S}*
Concentrated region	*50 – 180 MPa*	*?*	*50 – 220 MPa*

3.2.2 Plot for the dominant casts identified above the ratios $N_{S-cd/NS}$ and $N_{cast-S-dom}$ /N_{cast-S} as a function of temperature. Both ratios should be smaller than 50% in the stress concentrated region but as close to 100% as possible outside it (to guarantee the credibility of the low and high stress limit values).

Figure 4 shows results for the 10 CrMo 9 10 sets:

Data set		*Whole Set*	*Set 1a*	*Set 1b*
N_{S-cd}/N_S		*well distributed*	*confused situation, lots of stress regions above 50% in the concentrated region*	*breakdown in the concentrated region (ca. 130 MPa)*
	s ® µ	*® 100%*	*® 100%*	*® 0%*
	s ® 0	*® 100%*	*® 100%*	*® 0%*
$N_{cast-S-dom}/N_{cas-St}$		*well distributed*	*confused situation, lots of stress regions above 50% in the concentrated region*	*well distributed*
	s ® µ	*® 100%*	*® 100%*	*® 0%*
	s ® 0	*® 100%*	*® 100%*	*® 0%*

4 Dominant Cast Analysis

4.1.1 Plot $N_{D\text{-}cd}$[8] and the available points for each dominant cast as a function of temperature. Verify whether there is a systematic within the distribution. Identify those casts that are present at the biggest number of T_{sign}.

Figure 5 shows results for the 10 CrMo 9 10 sets:

Data set	*Whole Set*	*Set 1a*	*Set 1b*
Data used	*Only dominant casts*	*all casts*	*all casts*
Distribution	*1) at the most T_{sign} a big number of casts, that are dominant at other temperatures as well, is present* *2) The temperatures 540, 565/566 and 593°C only include the dominant cast GB/13* *3) A systematic distribution problem was not found, even if at converted °F temperature only British and Japanese casts were found*	*Cast D5 is overwhelming for low to medium, but is missing at high temperatures* *Cast D8 is present everywhere*	*A systematic distribution problem was not found*
Best distributed (dominant) casts	*J/MAF, D/7R, GB/RG*	*D8, D5*	*D75, D79*

[8] For subsize data sets it may be suitable to plot N_D instead of $N_{D\text{-}cd}$, as only a small number of casts is generally available

4.1.2 *Plot for all dominant casts*[9] *all points in a stress vs. temperature diagram. Include for all temperatures the available maximum and minimum stresses.* The dominant casts should be possibly located close to the minimum stress line. Further identify those dominant casts that are present at the maximum number of stress levels, that may therefore considered to be even more representative.

Figure 6 shows results the for 10 CrMo 9 10 sets :

Data set	*Whole Set*	*Set 1a*	*Set 1b*
Data used	*Only dominant casts*	*all casts*	*all casts*
Distribution	*For low stresses the dominant casts include the majority of the points* *At high stresses the dominant casts do probably not represent fully the data behaviour* *Cast GB/13 is only present at temperatures where other casts are absent* *Cast D7/ZT includes most of the isothermal low stress points*	*Cast D5 is overwhelming on the low stress area*	*Well distributed with several casts at low isothermal stresses*
Best distributed dominant casts	*J/MAF, D/7R, D/7ZT*	*D5, D8*	*D75, D79*

[9] For subsize data sets it may be suitable to plot all points.

5 Identification of Critical Temperatures

Critical temperatures are

1) maximum and minimum T_{sign}, because they determine the extrapolability of the data
2) T_{sign} with $N_{D-cd} / N_D > 50\%$
3) T_{sign} with $N_{cast-dom} < 3$[10]
4) T_{sign} with $2\{n(1000h)-n(t_{u,max})\}/(n(1000h)+n(t_{u,max})) > 2$, because in this case a significant change in creep-mechanism could have occurred.
5) T_{sign} where no dominant cast contributes points at the 3 lowest and/or the three highest stress-groups.
6) T_{sign} where there are dominant casts with only isothermal points (i.e. cast is present only at this temperature).

Results for 10 CrMo 9 10 data sets

Data set	*Whole Set*	*Set 1a*	*Set 1b*
max. temperature	*650°C*	*650°C*	*650°C*
min. temperature	*450°C*	*450°C*	*475°C*
max. T_{sign}	*650°C*	*500°C*	*500°C*
min. T_{sign}	*475°C*	*600°C*	*650°C*
T_{sign} with $N_{D-cd}/N_D>$ 50%	*none*	*all T_{sign}*	*none*
T_{sign} with $N_{cast-dom} <$ 3	*565/6°, 575°C*	*not applicable (500°C with only 1 cast)*	*not applicable (no T_{sign} with only one cast)*
criterion 4	*none*	*none*	*none*
criterion 5	*none*	*none*	*none*
criterion 6	*none*	*none*	*none*

6 Conclusions

None of the points discussed precludes any assessment, but they give relevant information about the quality of the available data. The planning of additional tests to complete the actual data set, the following pre-conditioning (if any) and the assessment procedure should take into account the findings about data distribution in order to :

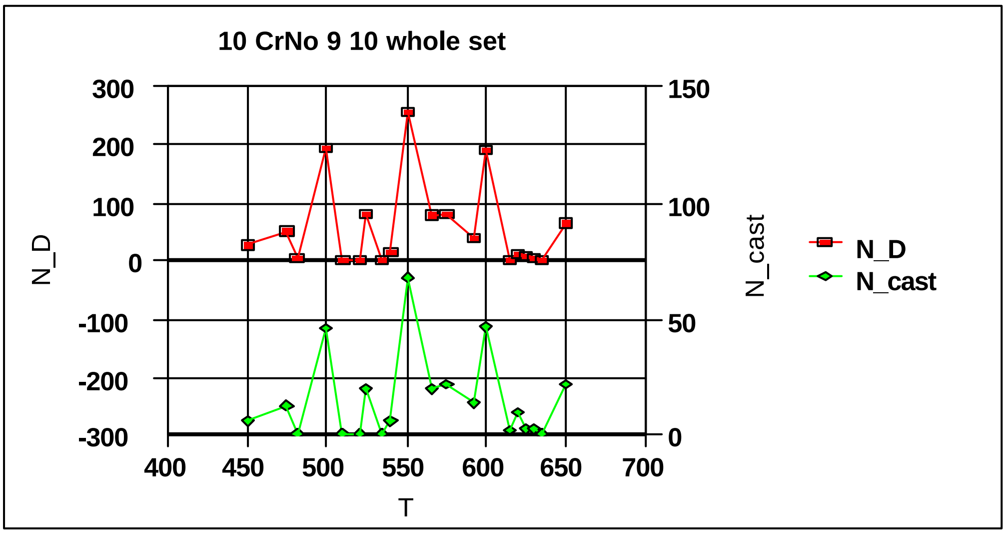
- eliminate T_{crit}
- increase the number of T_{sign}
- flatten the graphs in fig. 1 and 3.
- take into account if the data sets includes sub-populations (ex.: casts at low temperatures are different from those at high temperatures).
- reduce predominance of dominant casts and/or significant temperatures
- minimize not material caused tendencies (s. fig. 5)
- use the dominant casts at each T_{sign} and the overall dominant casts to validate the pre-conditioning (if applied) and the prediction trend of the assessment.
- check the assessment method compatibility with the data.

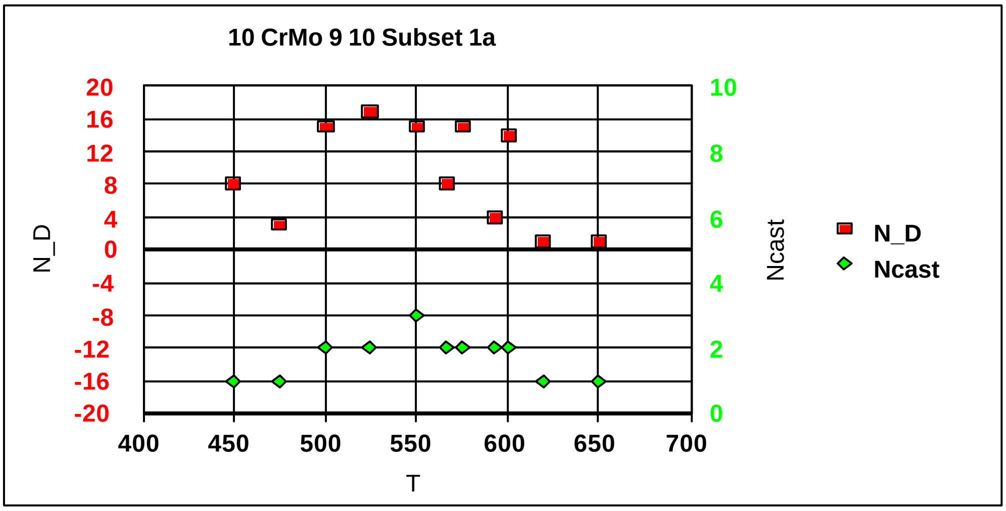
[10] Only for full size data sets. For subsize data sets, more than 1 dominant cast is desirable.

In the shown example for 10 CrMo 9 10, the whole data set is the most uniformly and homogeneously distributed set assessed by WG1. The subset 1 is strongly dominated by a single cast, which unfortunately is not available at the highest temperatures. Its assessment needs particular care. Subset 2 is a better distributed example, where the more uniform data distribution should encourage more reliable predictions.

7 Summary

This appendix analyses data distribution description methods and recommends to investigate data sets before assessment, in order to be aware of data set anomalies during evaluation. Some procedures for the check of data distribution as a function of independent variables temperature and stress are proposed and discussed by application to the data sets on 10 CrMo 9 10 applied by WG1 in the assessment round robin tests.





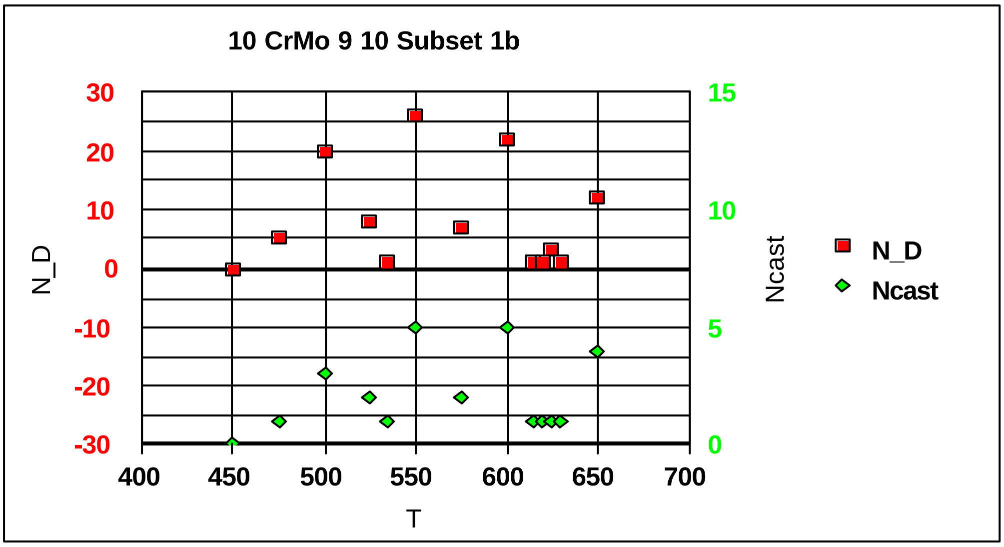
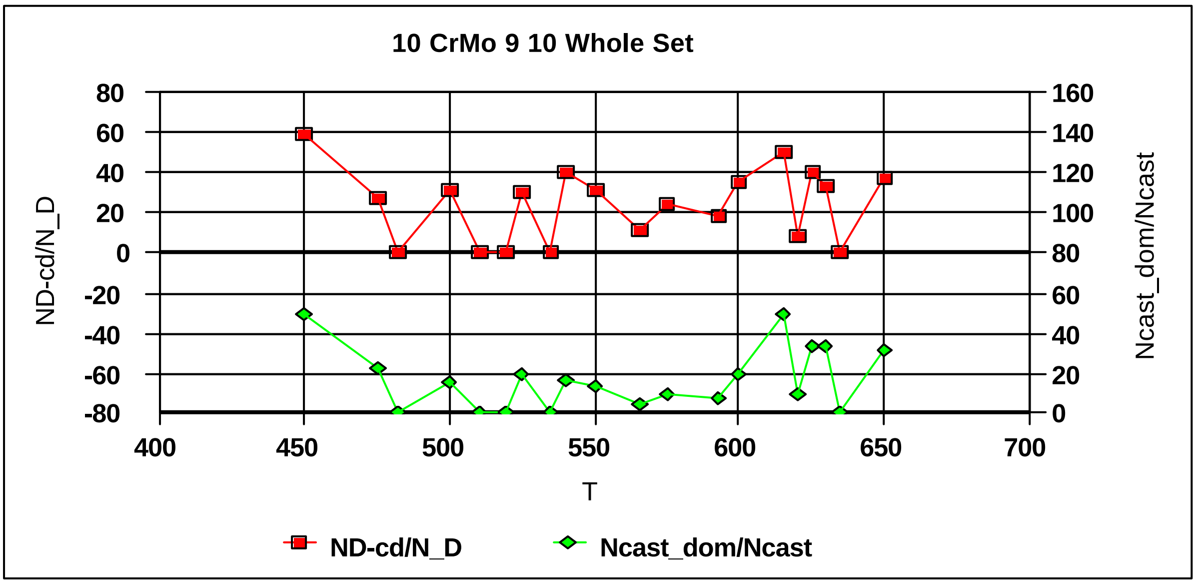
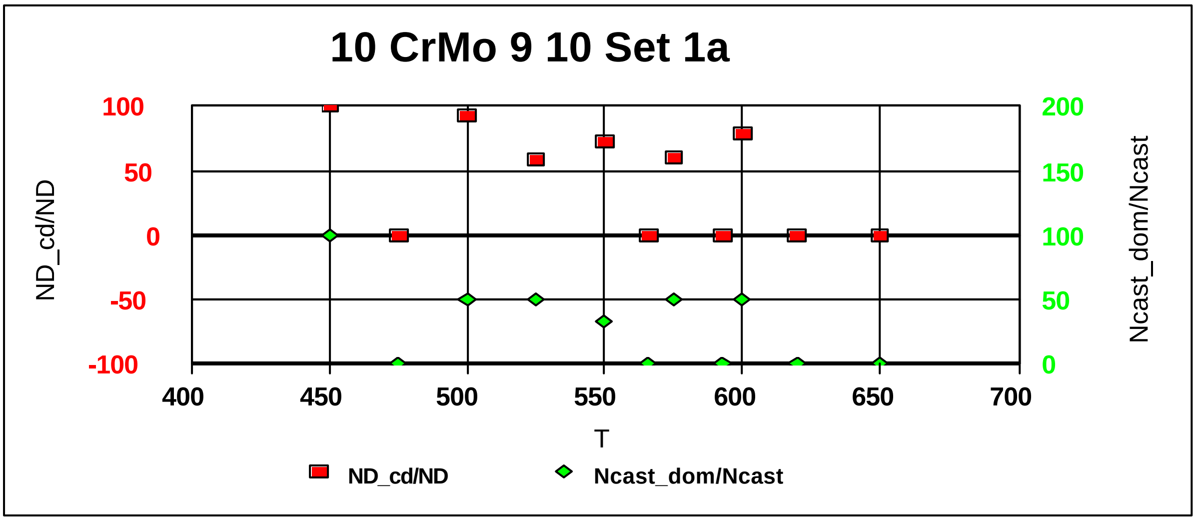


Figure 1: Data distribution in temperature (part 1)





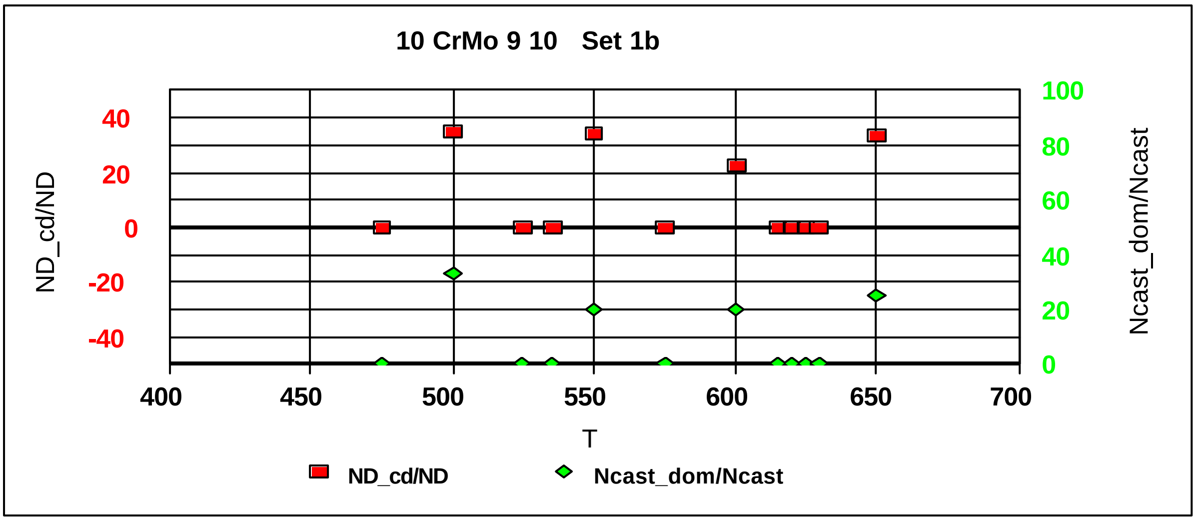
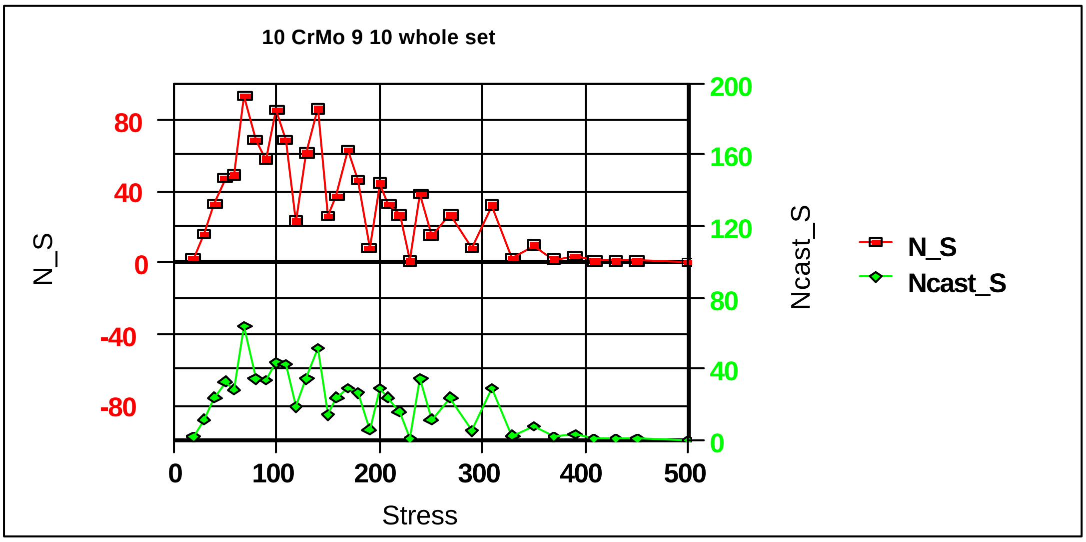
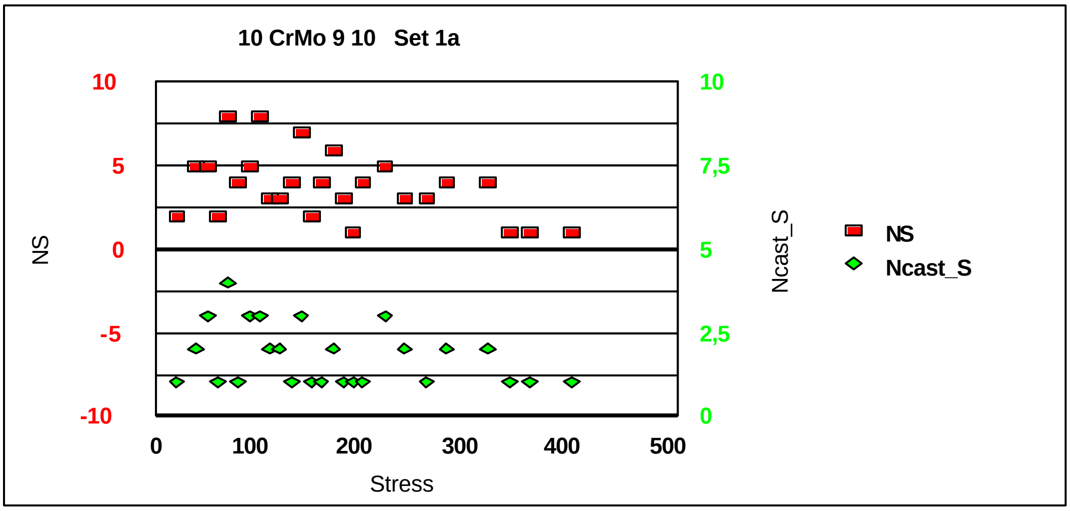


Figure 2: Data distribution in temperature (part 2)





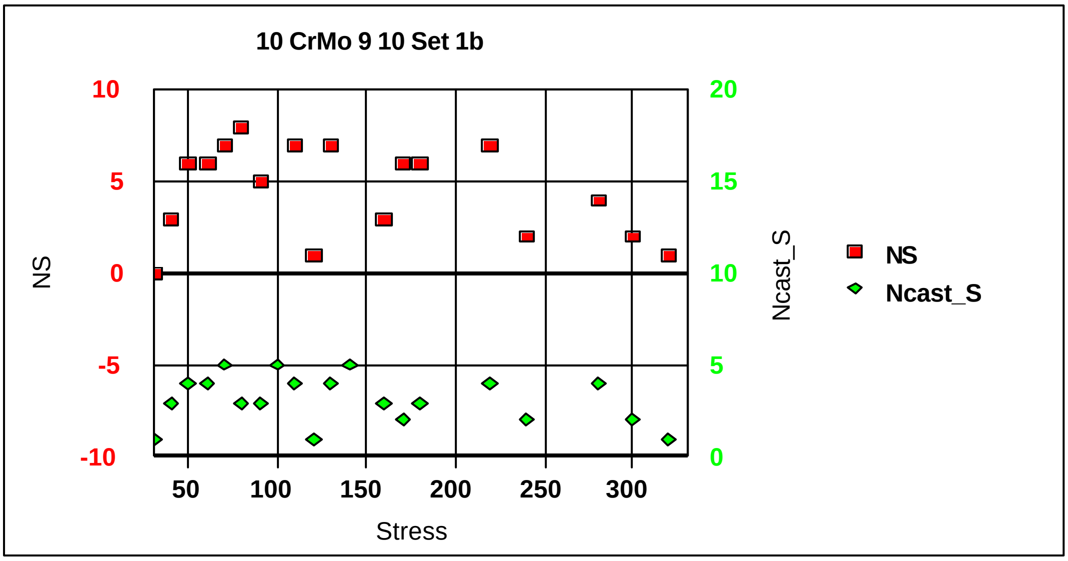
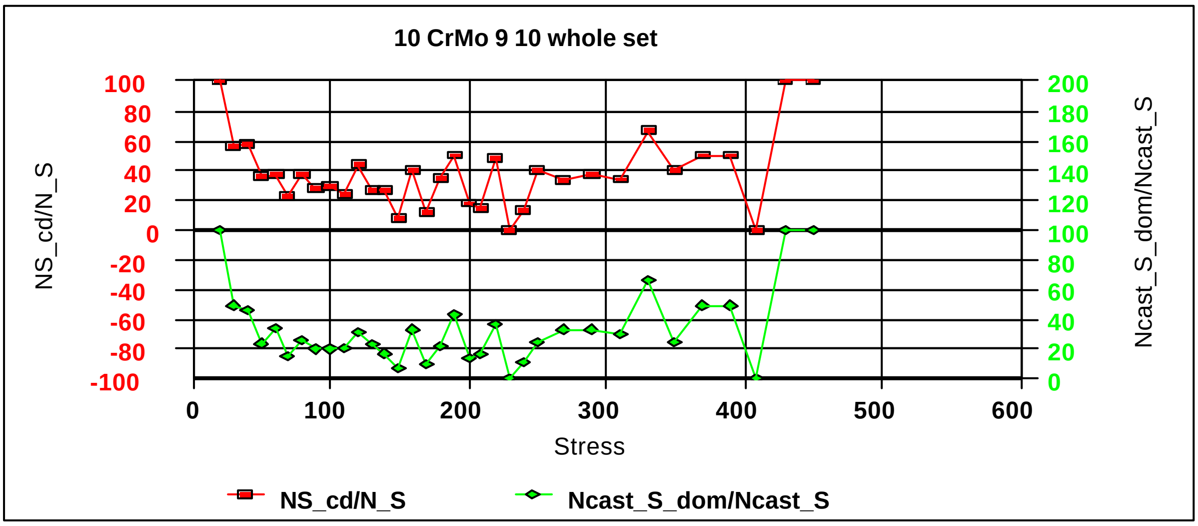
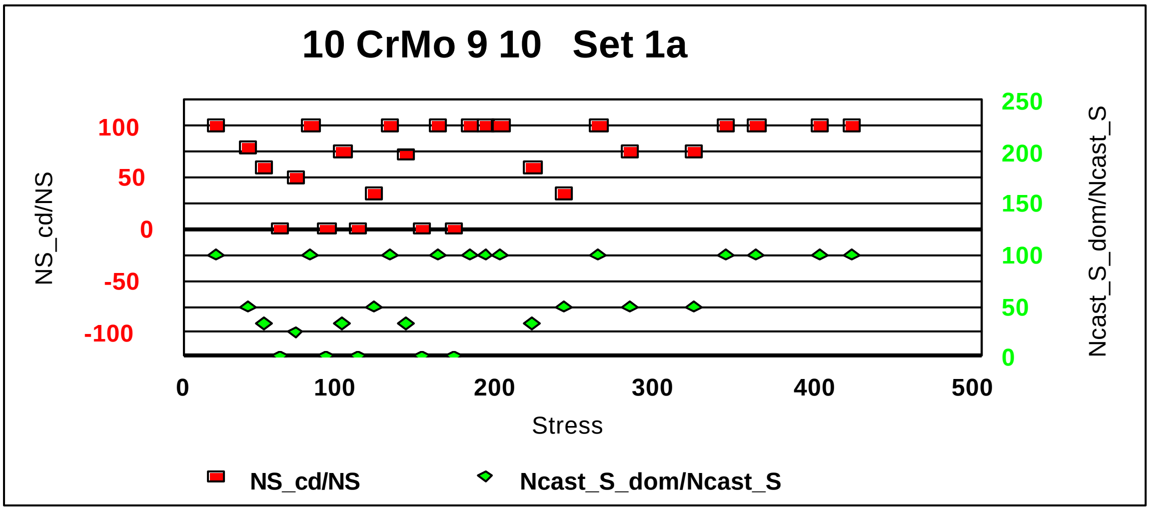


Figure 3: Data distribution in stress (part 1)





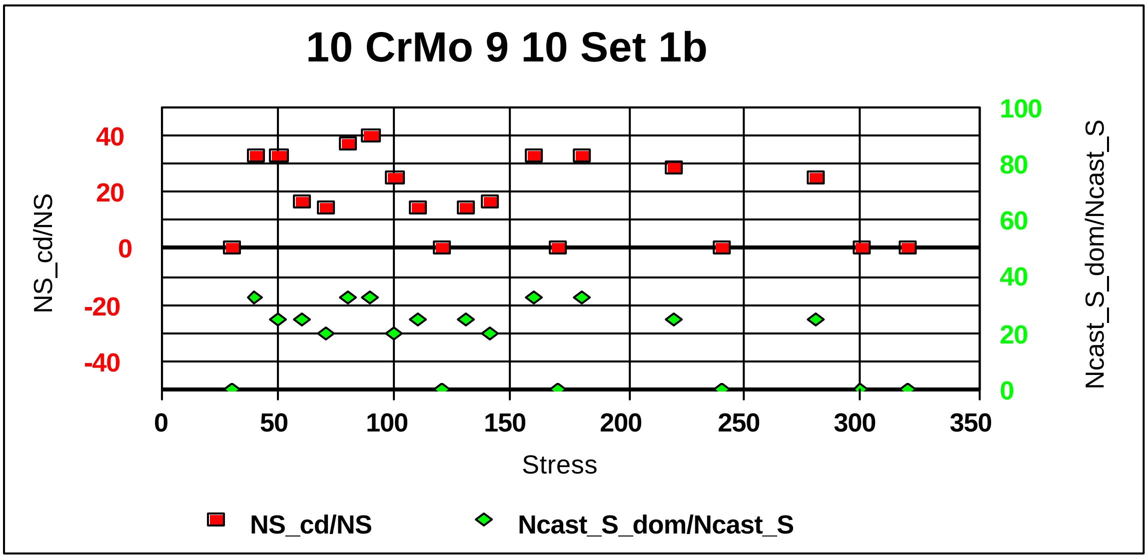
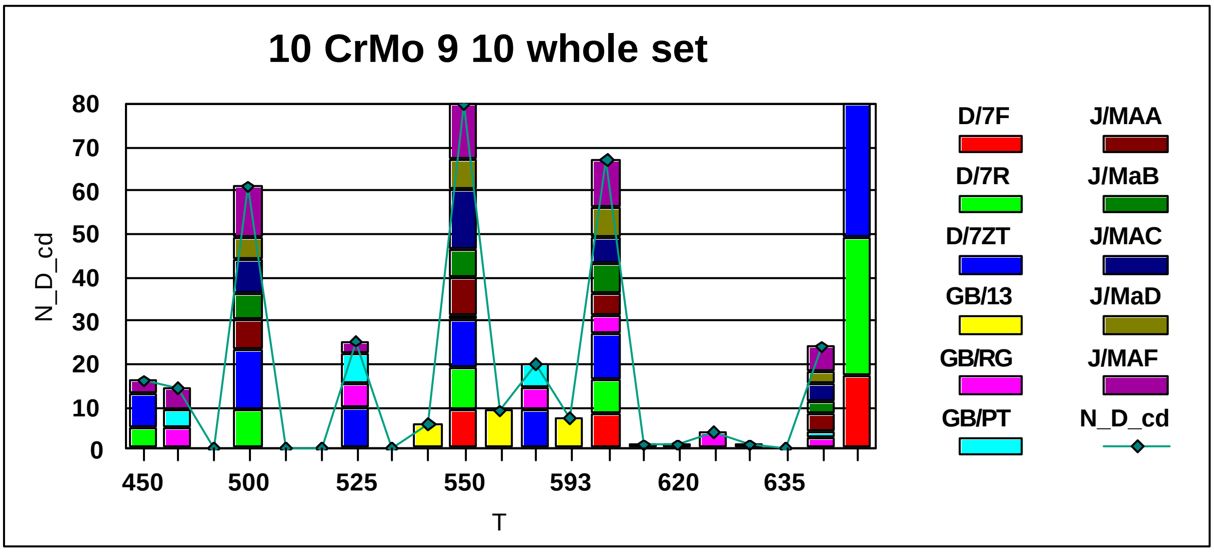
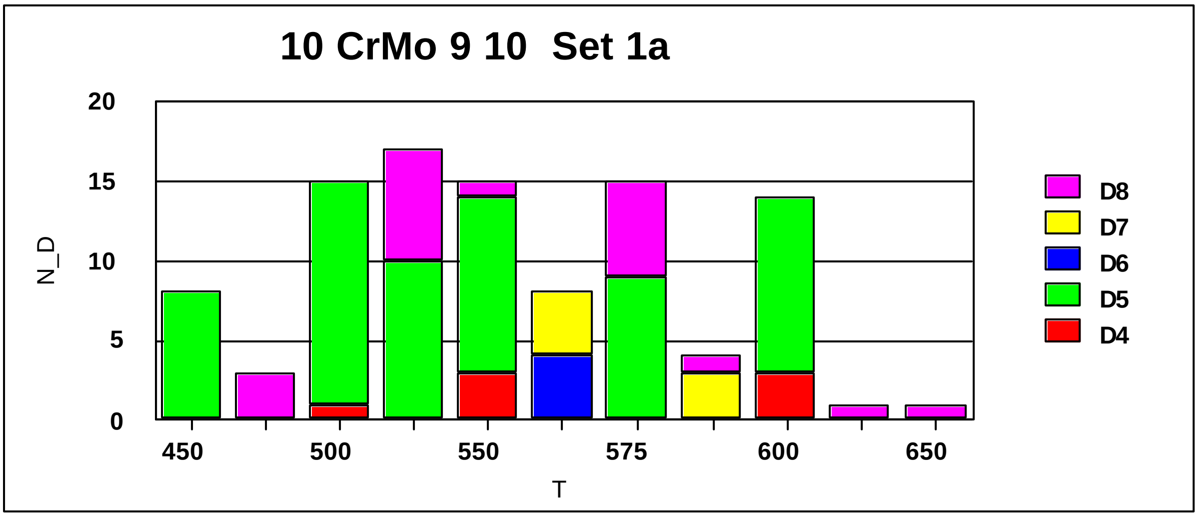


Figure 4: Data distribution in stress (part 2)





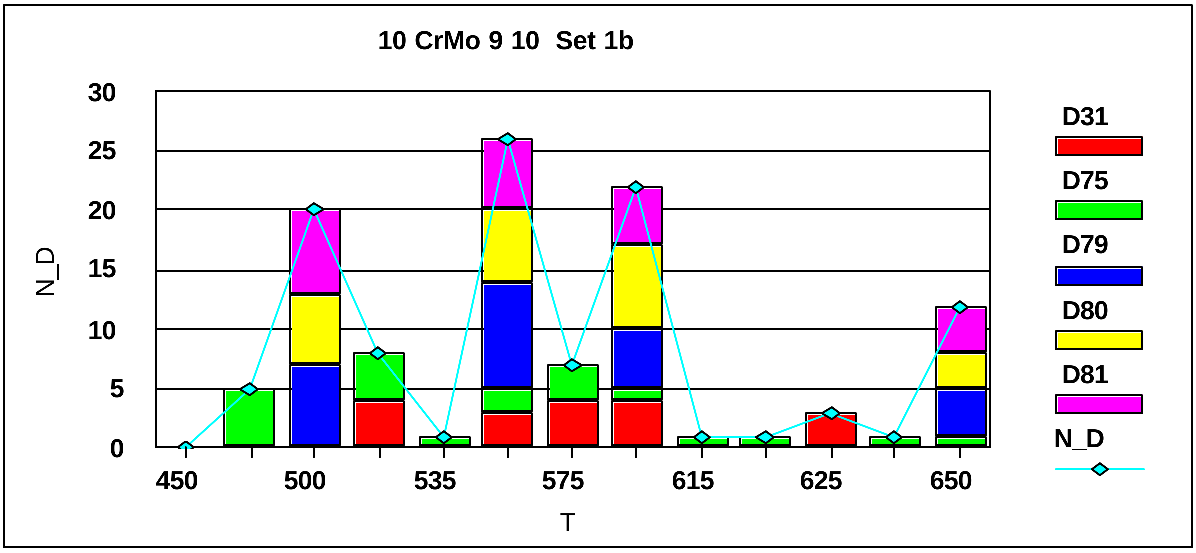
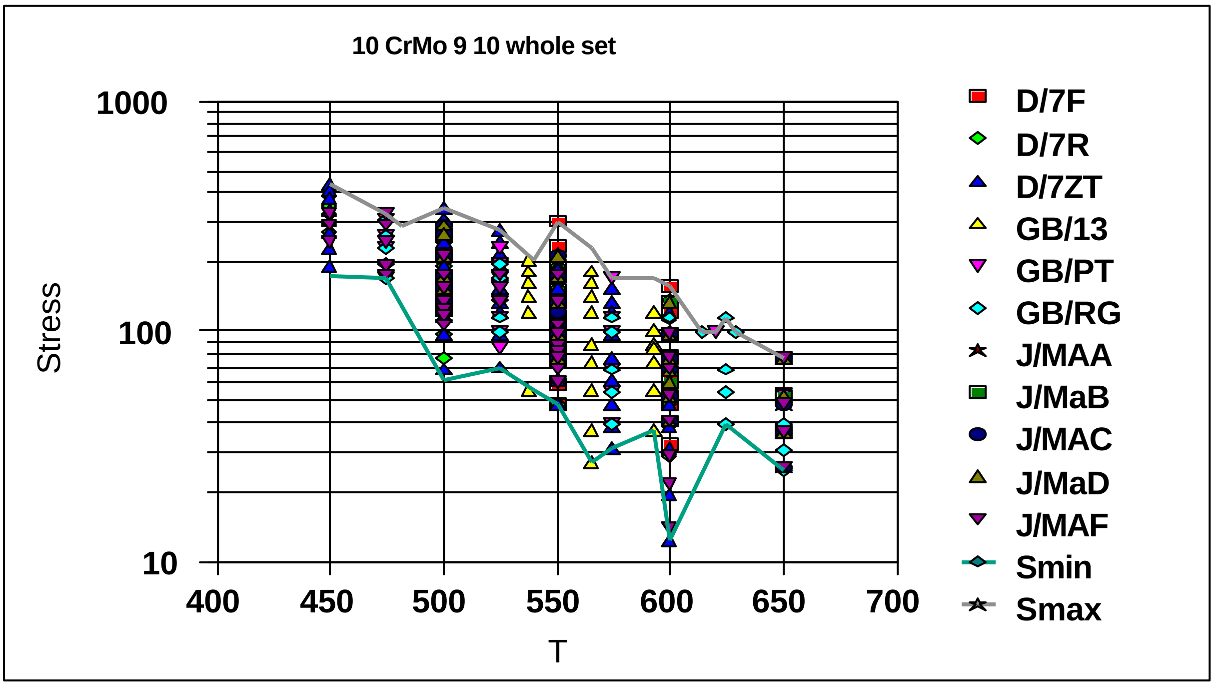
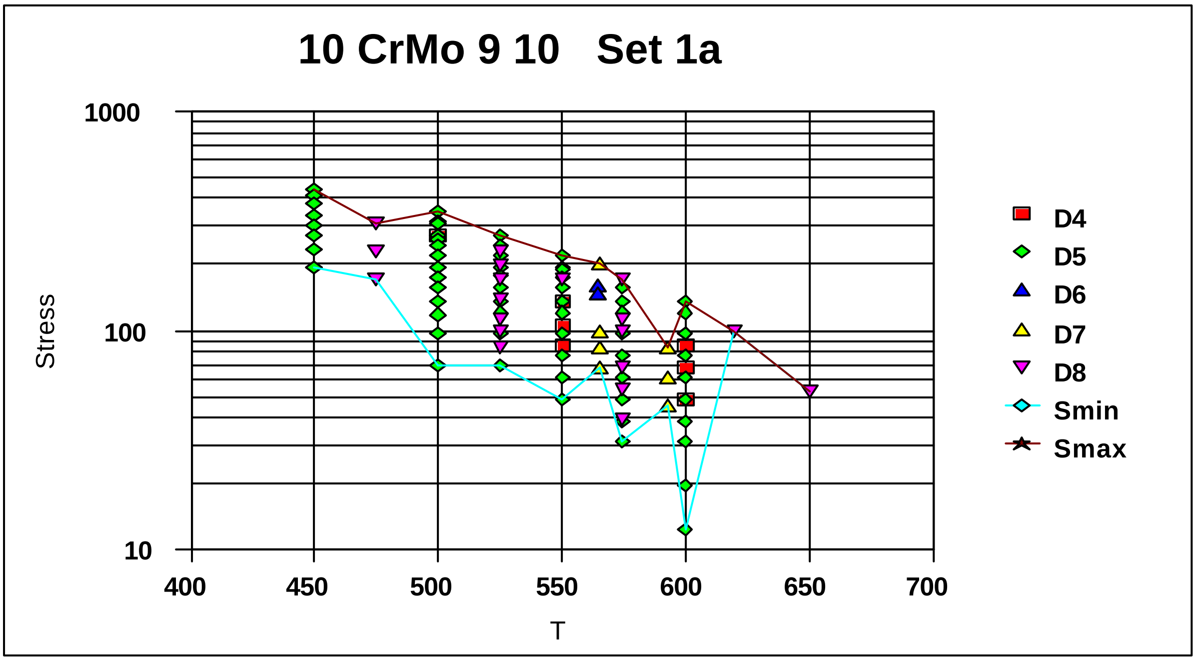


Figure 5: Dominant cast analysis (part 1)


10 CrMo 9 10 whole set
Stress
1000
100
10
400
450
500
550
600
650
700
T
D/7F
D/7R
D/7ZT
GB/13
GB/PT
GB/RG
J/MAA
J/MaB
J/MAC
J/MaD
J/MAF
Smin
Smax


10 CrMo 9 10 Set 1a
Stress
1000
100
10
400
450
500
550
600
650
700
T
D4
D5
D6
D7
D8
Smin
Smax

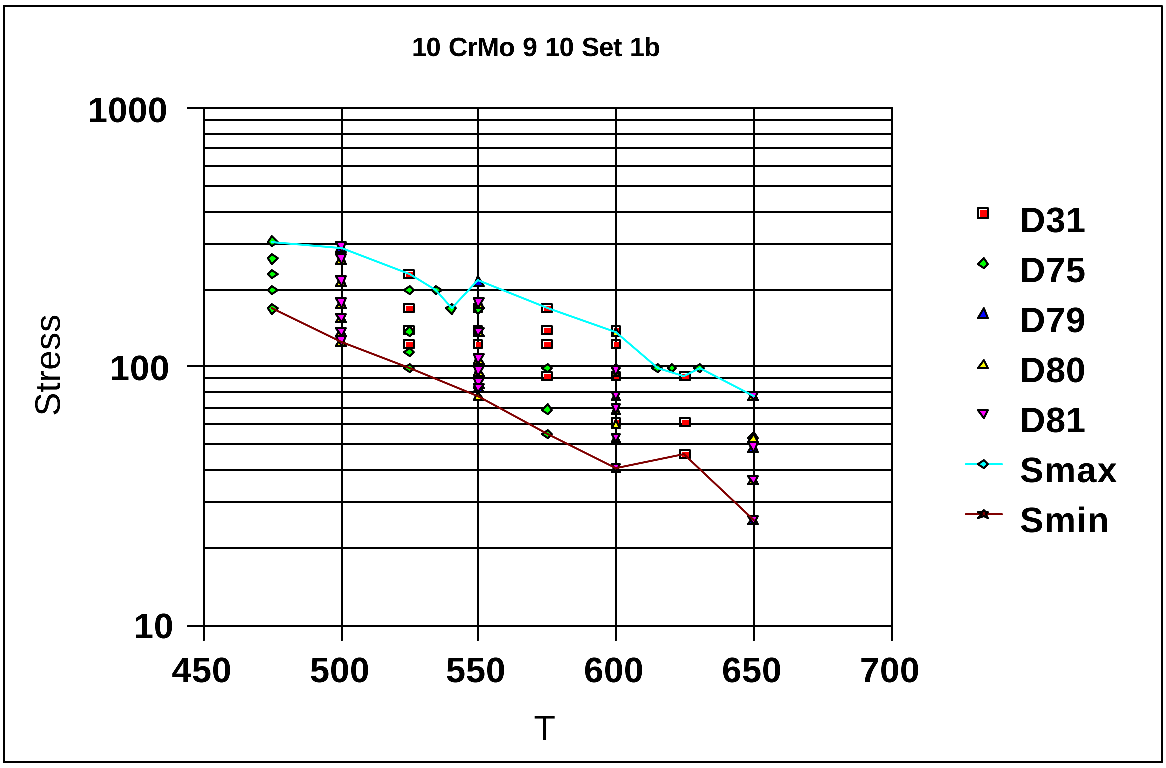


Figure 6: Dominant cast analysis (part 2)

APPENDIX D

REVIEW OF REFERENCE MASTER CURVES

S R Holdsworth

ALSTOM Power, Rugby, UK

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