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ECCC RECOMMENDATIONS - VOLUME 5 part III [Issue 2]

GUIDANCE FOR THE ASSESSMENT OF CREEP RUPTURE DATA

RECOMMENDATIONS FOR THE ASSESSMENT OF POST EXPOSURE (EX SERVICE) CREEP DATA

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RECOMMENDATIONS FOR THE ASSESSMENT OF POST EXPOSURE (EX SERVICE) CREEP DATA

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ABSTRACT

Volume 5 part III was prepared by ECCC-WG1 Post Exposure Creep Data Subgroup (PEDS) in order to provide guidance for the use of post exposure creep data, supported by virgin material data, in the computational assessment of the residual life of components service in the creep regime. The computation of the residual life is complementary to the non destructive and metallurgical control activities and the correlated application of all them is to be applied to establish if and how long a distinct component can be further serviced.
Several particular details distinguish the computation of residual life (CRL) from other creep strength assessments: CRL is always targeted to a distinct component and related to a well defined couple of service conditions in temperature and stress. On the other hand CRL is generally performed either with a very limited amount of post exposure creep data or with virgin material directly.
Volume 5 part III gives recommendations targeted to these particular details introducing procedures, which can help rounding up the available post exposure data set including "comparable" post exposure data, which guarantee a credible and stringent main assessment and which includes an evaluation of the CRL result, independent on the assessment method used, in terms of physical credibility, quality of data description and (only applicable to some particular cases) assessment stability.
The recommended procedure has been validated by an extended round robin, during which 16 different residual life assessments (briefly described in Appendix B) for the same component, a power plant steam pipe, were produced basing on post exposure creep data of the target component and others (appendix A) and related virgin material (see Appendix C).
A second validation and refinement activity took place in the period 2001-2004 during which 11 additional assessments were tested (see appendix D) and which confirmed the essential approach based on the PE-adapted Post Assessment Tests.

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RECOMMENDATION FOR THE ASSESSMENT OF POST EXPOSURE (ex service) CREEP RUPTURE DATA

Contents

1 Introduction

Consideration on post exposure creep data and their possible use and application was introduced in ECCC's field of interest following a strong request departed from utilities, research institutes dealing with residual life assessment and other users of materials in creep regime in 1997. The main aim was to find common approaches in testing, exchanging, documenting and assessing creep data obtained from material after or during service. Volume 5 part III, produced by the Post Exposure creep Data Subgroup PEDS of ECCC's WG1 is the result of the common effort to compare various data assessment approaches and to identify a procedure that could limit uncertainty on residual life assessment,

Residual life assessment (RLA) for component serviced in the creep regime is a very praxis oriented task that is generally split into two contemporaneous activities:

1. An on site inspection program including extensive non destructive controls and metallographic tests and
2. a computational approach

are applied to identify the further exploitability of a defined target component. For the computation of the remnant life under creep conditions (the "computational branch of RLA", short CRL) two main ways are identified: a) CRLs basing on virgin material should follow the recommendations of Volume 5 part I [1], b) CRLs using post exposure (PE-) creep data combine several assessment problems and may be improved by following the here proposed recommendations.

If CRL uses PE-data, generally small size data sets made of isothermal or iso-stress lines are given. Even recognising the limited aim of CRL, i.e. the extrapolation to one single condition for further exploitation of the component, the reliability of the prediction is often under discussion due to lack of credibility or demonstration of its reliability. The use of "comparable" PE-data, the strongly recommended use of a reference material for either the CRL itself or for the check of its result and the implementation of post assessment tests to verify the CRL prediction are meant as a step forward in ensuring computational credible results.

2 Motivation

Residual Life Assessment (RLA) is a task that generally decides about the future of a given component or plant and the computation of the remnant time 'till creep failure will occur is, combined with experimental non destructive and metallographic techniques, essential for the decision to be made.

Due to the particular conditions in which RLA is undertaken, the computation result often is not of the same quality and reliability like in virgin material strength evaluation. The main motivations for this is the big variety of assessment methods proposed in literature for computation of residual life, which cannot actually be discerned into recommended and not suitable ones, and, when undertaken with PE-creep data, the generally limited scope of data in duration and amount of experimental points.

The present volume therefore intends to set forth some recommendations, which will be upgraded on a regular basis following users' experiences and feedback, that state assessment method independent criteria to check the quality and reliability of the CRL performed.

3 Recommendations on the Computation of Residual Life

3.1 The General Aspect

Recommendations for computational residual life assessment (in short CRL) are based on a review of CRL-procedures (appendix B) and an evaluation of their effectiveness in Appendix C.

3.1.1 Characteristics of Methods for the Computation of Residual Life

All recommendations as stated below take into consideration, that each CRL is always

- related to a specific component, given by a geometry, a material and one or more critical points due to high temperature and/or stresses,
- related to a particular material condition, i.e. to material that has been exposed to service conditions, i.e. temperature T_{PE}[1], stress σ_{PE} and environment, for a particular service time t_{PE},
- related to particular service conditions, i.e. a combination of temperature, stress and environment under which the current component has been and will be further serviced – and the two conditions may not necessarily be identical,
- concentrated on a particular technical question, which generally is
  - either “how long can the component in the given or changed conditions still be serviced?” (new end-of-life prediction),
  - or “can the component in the given or changed service conditions still be serviced for a defined duration?” (limited life extension),
- performed in very time restricted conditions, because generally CRL related decisions need to be taken during a current maintenance session of the plant, i.e within a few weeks.

This leads to the fundamental need of stating simple but powerful recommendations focalised to the main question: Can the component, already serviced for $\Sigma_i t_{PE,i}$ in the i service conditions $(\sigma_{PE},T_{PE})_i$, be exploited at condition $(\sigma_{PE},T_{PE})_{i+1}$ ‘till reaching a target time t_{RL}?

3.1.2 Methods for the Computation of Residual Life

From literature several methods are known and their success and failure for single situations have been reported and have been experienced by several assessors

[1] The terminology used in Part III is as defined in [2]

operating in the field of CRL. For the purpose of the present recommendations, CRL methods have been grouped according to their basic approach:

A) Data Use
    a. Methods which use creep data of virgin material and or strength values from standards as the only basis of CRL.
    b. Methods which use creep data obtained from material sampled from serviced components, i.e. use post exposure (PE-) creep data
        i. Methods which rely on PE-data obtained exclusively from the target component[2]
        ii. Methods which accept a data set improvement by including creep data from "similar" materials.

B) Data Description, when PE-data are available
    a. Methods that describe the PE-data behaviour and extrapolate this to t_{RL}
        i. Methods basing on isothermal approaches
        ii. Methods with "parametric" approaches, i.e which basically construct a Larson-Miller curve around the target residual life,
        iii. Methods basing on isostress approaches
        iv. Methods enhanced by including creep strain
    b. Methods that define a minimum acceptable behaviour for a material just being allowable to continue service up to t_{RL} and compare then the actual PE-data with this minimum acceptance limit.

As a straight recommendation for single methods cannot be presented, objective criteria for the evaluation of the CRL result and for the suitability of the method for the single case are discussed below, which are applicable to all listed assessment method categories and their combinations.

3.2 The Approach

The recommendations detailed below were derived by applying and amending the recommended creep rupture data assessment procedure, as stated in Volume 5 part I [1] for big data sets, to the CRL task. To practically experience the additional difficulties of the CRL and the effect of the recommended procedure, among the participants in the PED-Subgroup a round robin took place, based on a commonly gathered dataset (see Appendix A). This data set contained for a common steel grade of the 2,25% Cr type 12 series of test results obtained from serviced pipes of power plant and refinery units, exposed to creep conditions at different temperatures and stresses, for different durations. The round robin participants got the goal to determine whether "Pipe D", serviced in a power plant, was allowable to continue service for another 50000 h and for which total duration it could be foreseen, before fracture occurs. Participants were free to come to their result by using

- only the to pipe D belonging PE-creep rupture data (12 points)
- all supplied PE-data or reduced sub-groups, as suitable
- creep rupture data of virgin material and/or their assessment.

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[2] The target component is the distinct component, for which CRL is intended

Appendix B gives an overview over the selected methods.
The results of the round robin exercise allowed agreement among all, that Pipe D could be serviced easily for another 50000 h, but the range of durations to end of life was considerable (see Appendix C).
The hereafter explained recommendations allowed, when applied to the results of the round robin exercise, to narrow the dispersion range of the results by a factor of ca. 10. It must be agreed, that due to the particular problems related to this sort of data sets, very small sizes and short durations, dedicated experimental techniques etc., the in appendix C reported round robin exercise may be still too less for a complete procedure validation, but the results already highlight some relevant aspects, which allow a qualification of the predicted remnant lives. In this sense it is believed that the application of the recommended procedure for CRL could be a helpful tool in determining realistic features for the future serviceability of components in the creep regime, features which supported by non destructive and metallographic inspection, will positively help the remnant life computation, instead of hindering it due to unrealistic results.

3.3 The Confirmation

A second round robin could take place in the period 2001 to 2004, the results of which are reported in Appendix D.
In this case the same pipe D could be assessed with the same goals, but the data set was enhanced by additional creep strain PE-data.
15 assessments were prepared, although they all used the MPC-Omega method [3] and modifications of it. A common application of the recommendations as stated below was then jointly performed on all assessments in order to identify their ability to highlight non realistic results.

3.4 Similarity and Comparability of PE-Creep Data

3.4.1 Definition

In the present technical sense “similar” should be intended as:

I. When related to materials: Similar means that the chemical composition, the original (i.e. prior to service exposure) mechanical characteristics and the manufacturing process of the component, from which the material was sampled, could be related both to the same specification.
II. When related to components: Similar means the same component type (technical function, position in plant, etc.) operated in a different plant under conditions that, at least for two of the following conditions, differ less than ±10% in nominal pressure and/or less than ±10 K in nominal temperature and/or factor 2 in service exposure.

III. Related to creep test results: Similar means that the test were performed on the basis of procedures that guarantee reliable, reproducible results which are not related to too localised material situations.

“Similar” is a weaker concept than comparable, which is assumed to be the only real technical interest. Comparability is given

1) if both together apply.
2) and if criterion III is respected. This criterion has a different status and is a “conditio sine qua non” for comparability. The acceptance criteria for testing are stated in Volume 3 part III [4]

3.4.2 Evaluation of Comparability

3.4.2.1 Simple Methods

It is generally not recommended to mix data obtained from different material grades. The relevance of the original heat treatment may depend on the total exposure time to service, but is generally preferred to be the same for comparable data.

3.4.2.1.1 Comparison Among Post Exposure Data Only

The easiest comparison is a simple plot of the supposed comparable data and the target component data in a $\log(\sigma_0)$ vs. $\log(t_{u\text{-}PE})$ diagram. All points which fall within a scatter band of ±20% around the common mean line are acceptable, provided the material grade and original heat treatment were the same.
The same principle can be used in a $\log(\sigma_0)$ versus damage parameter (i.e. Larson-Miller). In this case the allowable scatter band is fixed to ±15%.

3.4.2.1.2 Comparison Including Creep Data from Virgin Material

If a creep strength mean line or the virgin material of the same grade is available, the above criterion can be improved by including a mean distance of the post exposure data form the virgin material. So all additional PE-data, coming from the same material grade with the same original heat treatment, included in the range between the virgin material mean line and the target component PE-data mean line could be acceptable, as long as the overall scatter band around the target component PE-data is smaller than ±30% in stress and the distance form the virgin material is smaller than 45% in stress.

3.4.2.2 Complex Methods

3.4.2.2.1 By Expert Judgement

If enough service relevant information is available, the decision about similarity of service conditions may be as simple as entering service information for each data set available (same material grade and original heat treatment) in a comparison table adding up the duration of service in similar conditions. All data sets that have an equivalent distribution of service duty are obviously similar. As a very rough “rule of the thumb”, comparability is assumed if the service temperatures of two components are within ±10 K, the creep relevant service stresses within ±10 % and the exposure time to these conditions is within a range of factor 2. As a function of stress state and metallurgical details, these rough figures may need refinement or can be released.

3.4.2.2.2 By Inclusion of a Damage Accumulation Rule

If a suitable reference material and enough service information are available, damage accumulation rules, e.g. [5], can be used to relate to each other PE-data made available from different sources, but of the same material grade with same original heat treatment. Most simple attempts including the Linear Damage Accumulation Rule LDAR via a parametric approach are explained in appendix B.

3.5 Use of Reference Data with the Computation of Residual Life

From the round robin assessments of the PEDS (Appendix C), it appears that reference materials were used in several occasions with the following purposes:

1. The behaviour of the PE-data of the CRL target component has been cross-checked with the aid of PE-creep data derived from "comparable" components. "Comparable" was here intended as "made of the same steel grade with similar heat treatment, same product form". In addition in some cases "same service surroundings" have been included too, but this seemed - at least for the 10 CrMo 9 10 material, not to be mandatory.
2. The PE-data assessment line was generally validated by visual comparison with the assessed result on a "similar", generally virgin, material. "Similar" was here intended as "belonging to the same steel grade, having got the same heat treatment and exhibiting with high probability the same long term behaviour in creep due to the assessor's experience". This step during assessment and assessment validation has proven to be fundamental to obtain acceptable results (s. Post Assessment).
3. As a particular application of the former, in some cases a minimum acceptable creep strength is derived by shifting the creep strength line of the reference material in order

to contain the target service conditions for the target component. In this case the virgin material of the same steel grade with the same heat treatment was applied.
4. When during pre-assessment, further PE-data were made “comparable” using damage accumulation rules (LDAR), a basis for the establishment of the damage caused by the service exposure period and condition is needed. Generally virgin material of the same grade and heat treatment was used.
5. An assessment derived the final time, temperature stress function for CRL from the behaviour of PE-data from material of very similar chemical composition but different heat treatment, obtaining an applicable guess for the target component remnant life by shifting and twisting of the reference material curve according to the Concept of Similar Curves (CSC).
6. Not yet tested, but often used in praxis, a forecast on the remnant life in nominal service conditions is made by using only the corresponding virgin material, subtracting from the result the already spent exposure time. This method could probably be enhanced by including LDAR in the evaluation of the time to be subtracted from the extrapolated remnant life.

From the tests related to reference material use, these recommendations can be summarised:
- the selection of the reference material has to be done with great care.
- generally the reference material should be the virgin material of the target component itself. If not available, data for the same steel grade and heat treatment can be used (possibly in each detail, i.e. 10 CrMo 9 10 according European specification (ECCC assessments) not to be used for ASTM A335 P22 and vice versa).
- it is preferred, but, as long as LDARs are considered valid and no metallurgical objections are relevant, not mandatory, to use reference data measured on material of the same product form and size.

3.6 Recommendations for the Computation of Residual Life

The round robin exercise as described in appendix C, suggested a sequence of recommendations, which enhance the credibility and the reliability of the result. The recommended procedure bases on that applied by WG1 to big data sets of virgin materials, includes some additional statements related to the particular properties of PE-data and of the RLA goals and is in principle applicable to all CRL method categories as listed in chapter 3.1.2.
The following recommendations should be followed for an effective CRL:

1) component and the relevance of the available service data are ensured.
2) For CRL the availability of the components service data at sampling and at verification location (if different) is essential. For both positions the information required is
   a) preference 1: the complete stress, temperature, exposure interval history
   b) preference 2: real stress and temperature values, averaged in time per service periods
   c) preference 3: nominal and/or design data for stress and temperature.

3) A (minimum) target residual life t_{RL} for which life extension is wished, is generally to be defined[3].
4) The aim of CRL for target component is generally one of the two following
   a) Definition of a "new" end of life. CRL will deliver an estimate of the residual life t_{RL}*, for which fracture is predicted in service conditions. If $t_{RL}* > S\ t_{RL}$, the component can be further exploited (S: Safety factor depending on the design code).
   b) Check of further exploitability for a specified duration (life extension) in fixed further service conditions (which may be the same as the prior ones). In this case CRL will deliver the stress σ_{RL}*[4] for which rupture is predicted at T_{PE} in t_{RL}. If $\sigma_{RL}*/\sigma_{PE} > S$[5], the component can be exploited till t_{RL} (S: Safety factor depending on design code).
5) For each CRL 2 different analyses using two different methods should be performed. Both should be able to predict the material behaviour and therefore the component remnant life 'till the requested t_{RL}.
6) Generally all procedures used for CRL should be detailed in a procedure document to such an extent, that other assessors could easily repeat the assessment coming to the same results.
7) All data used for CRL should undergo an accurate pre-assessment (s. below), in order to fix clearly the starting conditions of the assessment, i.e. the suitability of the data for the target.
8) The results of a CRL should be subjected to Post Assessment Criteria (PATs) and shall not fail any of them.
9) Both CRLs, if passed through all PATs, should produce a mathematical equation the use of which allows the computation of t_{RL}* and/or σ_{RL}* in service conditions.
   a) In the case of new end of life prediction, predicted residual lives t_{RL}* at T_{PE} and σ_{PE} which are within a range of factor 2.
   b) In the case of limited life extension, the predicted stresses σ_{RL}* which produce rupture at t_{RL} should be within 20%[6].
10) If both CRLs fulfil the requirements 5-9, the results of the proceduralised method are to be adopted. If both methods got satisfying procedures the more conservative residual life prediction is to be adopted.
11) If assessments do not comply with the requirements 5-9, repeat the data assessment and residual life determination up to a maximum of 2 times. But before any additional CRL is undertaken, check whether enough data (virgin or PE- depending on method used) are available and whether the data distribution is sufficiently representative. Finally it should be ensured that both applied CRL methods are suitable for the amount, type and distribution of the available data.
12) Results are to be reported according Vol. 5 part III app. E (to be added in the next issue).

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3 In some cases t_{RL} is decided after knowing t_{RL}*, because a general check of the further exploitability of the target component is aimed at.

4 σ_{RL}* is the stress computed at t_{RL}, if t_{RL} is not end-of life

5 Some methods (see 3.1.2 Bb) compute the minimum acceptance limit by setting $\sigma_{RL}*=S\ \sigma_{PE}$. In this case the experimental PE- data must lie reasonably above the computed CRL line.

6 In the case of footnote 2, both CRL lines should lie reasonably beyond the experimental PE-data.

13) To obtain the CRL target information, generally extended extrapolation is required. It is essential that the assessor as well as the eventually involved safety authority are aware about the extrapolation factor used, i.e. about the ratio between longest reference duration (virgin or PE-data) t_u and the target residual life t_{RL}. Volume 5 part IIa reports essential information about the reliability of results obtained by extrapolation from small sized data sets as generally used in CRL. The uncertainty of the CRL results must be taken into account for the final judgment on further service continuation of the component.
14) The definition of a minimum recommended data set size for CRL is generally difficult, and depends on the CRL method applied or applicable. All CRL methods are sensitive to data distribution, so that the use of homogeneous data sets is recommended, for instance:
    a) If PE-data based assessments are used, the amount of points available depends on the amount of material that can be sampled from the target component. Ideally creep tests at least at three temperatures in the range T_{PE}-50°C < T_{PE} < T_{PE}+50°C with four stress levels each and durations of at least $t_{RL}/10$ should be envisaged. Alternatively at least three iso-stress lines at stress levels in the range 0.8 – 1.2 σ_{PE} with duration of at least $t_{RL}/10$ should be available. Minor amounts of data must be faced, if localised or semi non destructive sampling methods are used.
    b) If virgin material is used, the same criteria as per Volume 5 part I apply. An exception may be allowable, if strength values from standards are used, but the assessor must be aware, that standards contain extrapolated values, which already exploited entirely the quality and reliability of the experimental data. I.e no further extrapolation beyond the maximum duration of the standard strength is recommended.
15) In CRL some benefit in reliability can be obtained by including comparable data in the assessment. Comparable data should only be used, if the comparability is proven. The following recommendation shall be considered necessary but may be not sufficient:
    a) comparable PE- data can be used to enlarge the scope of the available experimental PE-data of the target component, if
        (1) they are positioned within the ±20% scatter band in stress around the target component PE-data.
        (2) they come from the same component type, fabricated from the same material grade, serviced in conditions, which should not be outside the ranges (T_{PE}±10 K, 0.9-1.1σ_{PE}, 0,5-2t_{PE}).
    b) comparable PE-creep data can in some cases be obtained by suitable data pre-conditioning (see below). After pre-conditioning recommendation a(1) above should be valid.
    c) similar virgin material creep data can be reasonably used as a reference material, if they were produced from the same steel grade like the target component, which was given a similar heat treatment and if the available data points include durations t_u>100 kh.
16) PE-data based CRLs need to be evaluated against a (virgin) reference material. For selection of suitable reference materials
    a) Preference 1: Experimental creep data from the virgin material of the target component itself, or an assessed strength function based on these data validated according ECCC Volume 5 part I or II.

b) Preference 2: Standard strength values of the same virgin material, i.e. supplied to the same technical specification or standard
c) Preference 3: Similar material or an assessed strength function based on such data validated according ECCC Volume 5 part I or II.

17) Use of PE-data for design strength derivation is not recommended.
18) If t_{RL} is determined from virgin data only, all criteria as per Volume 5 part I or part IIa (as applicable) apply.

3.7 Recommendations on Pre-Assessment

Prior to compute any residual life related quantity, the available information should undergo a pre-assessment, that should contain the following considerations, based on ECCC Volume 5 part I and IIa.

1) Confirm that the material is conform to the intended pedigree and that the experimental results were obtained in circumstances which are in accordance to ECCC Volume 3 part III [3].
2) Confirm that all experimental data meet the minimum pedigree and testing information requirements as per ECCC Volume 3 part III.
3) If comparable material data are used, the confirmation of their applicability is an integral part of the pre-assessment.
4) If procedures are used which allow other PE-data to become "comparable", their applicability has to be proven[7].
5) CRL needs the comparison with a reference material. During Pre-assessment the kind of reference material should be identified and the available creep data (if used) screened as per the pre-assessment of ECCC Volume 5 part I. If an assessed line for reference virgin material is used, this function needs to be validated according to the recommended procedure for virgin material data as per ECCC Volume 5 part I (preferred) or II (if only a small data set is available).
6) An evaluation of the distribution of unbroken and broken test pieces per T and t, including the eventually used similar data is needed to identify $t_{u\text{-}PE,max}$ and $\sigma_{o,min}$. If sufficient data are available, the for isothermal (isostress) PE-data temperatures (stresses) at which (a) ≥5% broken specimen test data ($T_{[5\%]}$ or $\sigma_{[5\%]}$) and (b) ≥10% broken specimen test data ($T_{[10\%]}$ or $\sigma_{[10\%]}$) are to be identified and the distribution of the data belonging to which component at each temperature, clearly outlining where the target component PE-data are located.
7) A visual comparison of all PE-data with the chosen reference material at T_{PE} (isothermally based PE-data) or at σ_{PE} (isostress based PE-data) should ensure, that the reference material is applicable.
8) The CRL target duration t_{RL}, the applicable safety factors S and the future service conditions for the target component need to be defined.
9) The former service conditions need to be established, including the type of available information type and its reliability and/or credibility.

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[7] A possible way to demonstrate the applicability, is to show that after pre-conditioning the "comparable" data fit into the scatter band of the target component data.

10) Any CRL must be accompanied by metallurgical information on the status of the material and by non destructive inspection results on the structural integrity of the target component.
11) If only virgin material data are used for CRL, ECCC Volume 5 part I applies entirely.

The failure of one of the above criteria should lead to a re-organisation of the available data (e.g. including or deleting "comparable" or reference data), of the planned target (t_{RL}) or to further investigations about service conditions (T_{PE}, σ_{PE}, t_{PE}) before CRL is undertaken.

3.8 Recommendations on Post Assessment

When CRL is based on PE-data, generally only very small data sets are available. In this case it is very unlikely that a CRL could produce a line satisfying all post assessment tests (PATs) as defined for full size datasets[8]. It must further be recognised, that CRL aims for strength resistance extrapolation and prediction for only one condition (T_{PE}, σ_{PE}, t_{RL}) and is not likely to be repeated. Therefore the following PATs are proposed:

Physical Realism and Credibility of Predicted Isothermal Lines

PAT-1.1a Visually check the credibility of the fit of

- the isothermal $\log\sigma_o$ vs. $\log t_u$*[9]
- the isostress $\log T$ vs. $\log t_u$* lines (as applicable)

to the individual $t_{u\text{-PE}}(T,\sigma_o)$ points over the range of data.

PAT-1.1b Plot for isothermal (isostress) PE-data isothermal (isostress) curves for the CRL and the reference virgin material at T_{PE}-50 K, T_{PE} and T_{PE}+50 K (0.8 σ_{PE}, σ_{PE} and 1.2 σ_{PE}) in the range 100 h $\leq$ t $\leq$ 3 t_{RL} (or for even longer times). Add to the reference virgin material the confidence limits on the mean or, if not available, a scatter band of $\pm$20% in stress ($\pm$25 K). For sufficient long times, the CRL curve should merge into the confidence interval of the reference virgin material and approximate the reference virgin material behaviour.

PAT-1.2 Produce for isothermal (isostress) PE-data isothermal (isostress) curves of $\log\sigma_o$ vs. $\log t_{u\text{-PE}}$* at 25 K (0,1 σ_{PE}) intervals from T_{PE}-50 K (0.8 σ_{PE}) to T_{PE}+50 K (1.2 σ_{PE}).
For times between 100 h and 3 t_{RL} and stresses (temperatures) $\geq$ 0,8 σ_{PE} ($\leq$ T_{PE} +50 K), predicted lines must not (a) cross-over, (b) come-together, (c) turn-back.

PAT-1.3 Plot the derivative $n_r = -\partial(\log t_{u\text{-PE}}^*)/\partial(\log\sigma_o)$ as a function of σ_o with respect to temperature to show whether the predicted isothermal lines fall away to quickly at low stresses (i.e. $\sigma_o \geq 0.8\ \sigma_{PE}$).

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8 The underlying background to the development of the original post assessment tests for virgin material CRDA, ECCC Volume 5 part I.

9 Through out all PATs, in some cases $t_{u\text{-PE}}$* may be substituted by t_u* or t_u of virgin material or by suitably corrected times $t_{u\text{-PE}}$**, if LDAR or other damage accumulation rules are used.

The values of n_r should not be ≤ 1.5 and the tendency of n_r for $\sigma_o \rightarrow 0$ should asymptotically towards 1.
It is permitted 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 the Range of Input Data

PAT-2.1 To assess the effectiveness f the assessed model to represent the behaviour of the complete dataset, plot $\log t_{u\text{-PE}}^*$ versus $\log t_{u\text{-PE}}$ for all input data:

The $\log t_{u\text{-PE}}^*$ versus $\log t_{u\text{-PE}}$ diagram should show
- the $\log t_{u\text{-PE}}^* = \log t_{u\text{-PE}}$ line (i.e. the line representing an ideal fit),
- the $\log t_{u\text{-PE}}^* = \log t_{u\text{-PE}} \pm 2.5\ s_{[A\text{-}RLT]}$ boundary lines[10,11]
- the $\log t_{u\text{-PE}}^* = \log t_{u\text{-PE}} \pm \log 2$ boundary lines[12]
- the linear mean line fit through the $\log t_{u\text{-PE}}^*$ ($\log t_{u\text{-PE}}$) data points for 100 h < $t_{u\text{-PE}}$ < 3 $t_{u\text{-PE,max}}$.

The model equation should be re-assessed :
(a) if more than A_o points of the $\log t_{u\text{-PE}}^*$ ($\log t_{u\text{-PE}}$) data points, with A_o= max(1,5% n_A, 2), fall outside one of the $\pm 2.5\ s_{[A\text{-}RLT]}$-boundary lines,[13,14]
(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 $\pm$ log 2 boundary lines for 100 h < $t_{u\text{-PE}}$ < 3 $t_{u\text{-PE,max}}$

PAT-2.2 To assess the effectiveness of the model prediction the behaviour of individual component PE-data (if present), plot for isothermal (isostress) PE-data at temperatures (stresses) for which there are ≥5 points within the range T_{PE} -50K ≤ T ≤ T_{PE} +50K (0,8 $\sigma_{PE} \leq \sigma \leq 1.2\ \sigma_{PE}$) :
(i) log σ_o (log T) versus $\log t_{u\text{-PE}}^*$ with individual $t_{u\text{-PE}}$ (T,σ_o) data points
(ii) $\log t_{u\text{-PE}}^*$ versus $\log t_{u\text{-PE}}$ with
  - o the $\log t_{u\text{-PE}}^* = \log t_{u\text{-PE}}$ line (i.e. the line representing an ideal fit),
  - o the $\log t_{u\text{-PE}}^* = \log t_{u\text{-PE}} \pm 2.5\ s_{[I\text{-}RLT]}$ boundary lines[15,16]

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10 $s_{[A\text{-}RLT]}$ is the standard deviation of the residual log times for all data at all temperatures, i.e. $s_{[A\text{-}RLT]} = \sqrt{\{\Sigma_i(\log t_{u\text{-PE},i} - \log t_{u\text{-PE},i}^*)^2/(n_A-1)\}}$, 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 be within $\log t_{u\text{-PE}}^* = \log t_{u\text{-PE}}^* \pm 2.5\ s_{[A\text{-}RLT]}$ boundary lines

12 i.e. the $t_{u\text{-PE}}^* = 2\ t_{u\text{-PE}}$ and $t_{u\text{-PE}}^* = 0{,}5\ t_{u\text{-PE}}$ boundary lines

13 n_A is the number of all data at all temperatures

14 Experience has shown, that the $\pm 2.5\ s_{[A\text{-}RLT]}$ boundary lines typically intersect the $t_{u\text{-PE}}$ =100 h grid line at $t_{u\text{-PE}}^* \leq 1000$ h and $t_{u\text{-PE}}^* \geq 10$ h respectively (?). The explanation for those which do not is either an unbalance in the model fit (and hence the PAT-2.1 criterion) or excessive variability in the data set. In the latter case, consideration should be given to the scope of the material specification.

- o the $\log t_{u\text{-PE}}^* = \log t_{u\text{-PE}} \pm \log 2$ boundary lines
- o the linear mean line fit through the $\log t_{u\text{-PE}}^*$ ($\log t_{u\text{-PE}}$) data points for $100 < t_{u\text{-PE}} < 3\ t_{u\text{-PE,max}}$.

and identify the individual component PE-data.

(a) $\log t_{u\text{-PE}}^*$ versus $\log t_{u\text{PE}}$ plots for individual component PE-data should have slopes close to unity and be contained within the $2.5 \pm s_{[I\text{-RLT}]}$ boundary lines. The pedigree or the comparability of component PE-data with linear regression mean lines with $\partial(\log t_{u\text{-PE}}^*)/\partial(\log t_{u\text{-PE}})$ slopes of <0.5 or >1.5 and/or which have a significant number of $\log t_{u\text{-PE}}^*$($\log t_{u\text{-PE}}$) data points outside the $\pm 2.5\ s_{[I\text{-RLT}]}$ boundary lines should be re-investigated.

(b) The distribution of the $\log t_{u\text{-PE}}^*$ ($\log t_{u\text{-PE}}$) data points about the $\log t_{u\text{-PE}}^* = \log t_{u\text{-PE}}$ 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 data, in particular at longer times.
The model equation should therefore be re-assessed if at any temperature (stress) in the above range
(i) the slope of the mean line through the isothermal (isostress) $\log t_{u\text{-PE}}^*$ ($\log t_{u\text{-PE}}$) data points is <0,78 or >1.22, and
(ii) the mean line is not contained within the $\pm \log 2$ boundary lines for $100\text{ h} < t_{u\text{-PE}} < 3\ t_{u\text{-PE,max}}$.

Repeatability and Stability of Extrapolation

As CRLs generally are not repeated in time the PAT-3 test series are not required. However, if a CRL based prediction is used to continuously monitor the situation of the target component, these tests become significant:

PAT-3.1 Repeat the CRL after culling randomly 50% of all data between $t_{u\text{-PE,max}}/10$ and $t_{u\text{-PE,max}}$ to check the repeatability of the extrapolation to variations in the data set. The assessment is considered to be sufficiently stable [17], if
(a) in the case of new end of life prediction: $\log t_{RL}^*$ at (T_{PE}, σ_{PE}), (T_{PE} +50K, 0.8 σ_{PE}) and at (T_{PE} -50 K, 1.2 σ_{PE}) are repeatable within ±50%
(b) in the case of limited life extension: σ_{RL}^* at (T_{PE}, t_{RL}), (T_{PE} +50 K, t_{RL}) and (T_{PE} -50 K, t_{RL}) are repeatable within ±20%

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[15] for isothermal PE-data, $s_{[i\text{-RLT}]}$ is the standard deviation of the n_i residual log times at the temperature of interest, i.e. $s_{[i\text{-RLT}]} = \sqrt{\{\Sigma_j(\log t_{u\text{-PE},j} - \log t_{u\text{-PE},j}^*)^2/(n_i-1)\}}$, where j = 1,2,… n_i, and n_i is the total number of data points

[16] for isostress PE-data, $s_{[I\text{-RLT}]}$ is the standard deviation of the n_i residual log times at the stress of interest.

[17] It is recognised, that when using small size data sets, particularly unlucky data configurations can arise after culling, which prevent any attempt to produce a stable prediction (e.g. lost of both the longest experimental times in a 2 isotherms data set). If such an “unlucky culled set” is produced, a second culled data series may be used sequentially, if the first fails.

PAT-3.2 Repeat the CRL after removing for isothermal PE-data the lowest stress data from main test temperatures or for isostress PE-data the lowest stress iso-stress curve to check the sensitivity and stability of the extrapolation procedure. The assessment is considered sufficiently stable[17], if

(a) in the case of new end of life prediction: $\log t_{RL}$* at (T_{PE},σ_{PE}), (T_{PE} +50K, 0.8 σ_{PE}) and at (T_{PE} -50 K, 1.2 σ_{PE}) are repeatable within ±50%

(b) in the case of limited life extension: σ_{RL}* at (T_{PE} , t_{RL}), (T_{PE}+50 K, t_{RL}) and (T_{PE} -50 K, t_{RL}) are repeatable within ±20%

Meeting the requirements of PAT-3.2 is not mandatory in circumstance where it can be shown that the material is metallurgically unstable (see Volume 5 part I).

4 Summary

Within residual life assessment of a given component, computation of the further exploitability is a relevant task, that combined with the experimental on site results of non destructive tests and metallurgical exams, will decide on the future serviceability of the component investigated.
ECCC Volume 5 part III provides guidance for the computation of the remnant life of a serviced component, basing both on post exposure (PE-) and virgin material creep data. It is the principle aim to ensure a credible extrapolation of the generally small and short time PE-data sets by applying rigorously pre-assessment, main assessment and post assessment recommendations.

5 References

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2 ECCC Recommendations Volume 2, 2001, ‘Terms and terminology for use with stress rupture, creep, creep rupture and stress relaxation: Testing, data collation and assessment’, Eds. Orr J., Morris P., Servetto C. & Seliger P., *Publ. ERA Technology Ltd., Leatherhead, UK*, (a) Part I: Generic terms and item specific to parent and virgin materials, (b) Part IIa: Welding processes and weld configurations, (c) Part IIb: Weld creep testing, (d) Part III: Post exposure creep data.

3 Prager, 'Development of the MPC Omega Method for Life Assessment in the Creep range', J. Press. Vess. Techn, 117, 1995 p. 95

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4 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.

5 Robinson D.N, Nouaillhas D., “A Unified Constitutive Model for Cyclic Viscoplasticity and Its Applications to Various Stainless Steels”, NASA CR174836, 1985

APPENDIX A

PE Data set for Recommendation Validation

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1 The Data Set

The Post Exposure creep Data Subgroup PEDS of ECCC's WG1 collated from different sources post exposure creep data on pipe and tube material of steel grade ASTM A335 grade P22 (2,25% Cr 1 Mo, similar to 10 CrMo 9 10), normalised and tempered. Post exposure data were available on 12 pipes, 7 of which were serviced in power plants at temperatures around $T_{serv} \approx$ 540°C for exposure durations 80.000 h < t_{serv} < 150.000 h. The other 5 pipes were serviced in refinery context at $T_{serv} \approx$ 530°C for similar exposure. The following table gives an overview on the available data.

Table I: Available Post Exposure Data and Materials

T °C	Points	Pipes	$10<t_u<100$ h	$100<t_u<1000$ h	$1000<t_u<10000$ h	$10000<t_u$ h	$t_{u,max}$ h
460	1	1	1	-	-	-	215
520	35	7	2	9	20	4	11500
550	3	1	-	3	-	-	980
560	10	2	1	5	4	-	6800
570	25	5	-	5	17	3	11150
595	1	1	-	1	-	-	400
600	9	2	1	5	3	-	3200
610	1	1	-	-	1 (1)	-	3300
620	2	2	-	-	2	-	1800
630	3	2	-	-	3 (1)	-	2800
635	1	1	-	-	1	-	2900
640	3	2	-	2	1	-	1700
650	3	2	-	-	3 (1)	-	4100
655	1	1	-	1	-	-	750
660	2	2	-	-	2	-	2100
670	3	2	2	-	1	-	1100
680	2	2	-	2	-	-	600
690	2	2	1	1	-	-	280
695	1	1	-	1	-	-	1000
715	1	1	1	-	-	-	80
Total	109	12	9	35	58 (3)	7	11500

For power plant pipes the longest durations were around 11000 h, for refinery pipes 4000 h, with unbroken specimens. It further appeared that elder data were sometimes obtained at extremely high temperature.
The pipes were tested according to different approaches, depending on the local assessor's preference, the available time for testing and the CRL technique "en vogue" at time. The following table gives an overview;

Table II: Overview on Testing Techniques Used

Pipe	Pipe Origin	PE-Testing approach	Available points	Distribution	$t_{u,max}$ h
A	Power Plant	2 isotherms around T_{serv}	10	5 per isotherm	10000
B	Power Plant	2 isotherms around T_{serv}	10	5 per isotherm	11000
C	Power Plant	2 isotherms around T_{serv}	10	5 per isotherm	11000
D	Power Plant	2 isotherms around T_{serv}	10	5 per isotherm	8000
E	Power Plant	2 isotherms around T_{serv}	10	5 per isotherm	7000
F	Power Plant	2 isotherms around T_{serv}	10	5 per isotherm	11000
G	Power Plant	2 isotherms around T_{serv}	10	5 per isotherm	10000
H	Refinery	3 isostress curves around σ_{serv}	8	4, 2, 2, per isostress	4000
I	Refinery	2 isothermes above T_{serv}, material from 2 different sampling locations on the same pipe	6	3 per isotherm, 1 isotherm per sampling location	1000
J	Refinery	parametric curve around target life extension	4	-	1500
K	Refinery	1 isotherm above T_{serv}, material from two different sampling locations on the same pipe	6	3 per sampling location	3000
L	Refinery	3 isostress curves at and above σ_{serv}	15	5 per isostress line	3500 (UB)

An overview on available data is given as well in Figure 1.

2 <u>The Target Component</u>

Power Plant type pipe D was selected as the target component for the Round Robin Computation of the residual life. At the date of the PE-data production pipe D was given allowance for further service. Pipe D is today, ca. 12 years after the PE-data were produced, out of service and may be available for further investigations.

3 Reference Material

For reference purposes were available (see Figure 1):

- o the by ECCC-WG1 during its Round Robin 1994-6 produced, all recommendations satisfying equation for the European steel grade 2,25% Cr 1% Mo, normalised and tempered, see Volume 5 part I.
- o the standard strength values as available in DIN 17175 for grade 10 CrMo 9 10,
- o experimental data collated by ASTM on ASTM A335 grade P22 and roughly assessed 1992.

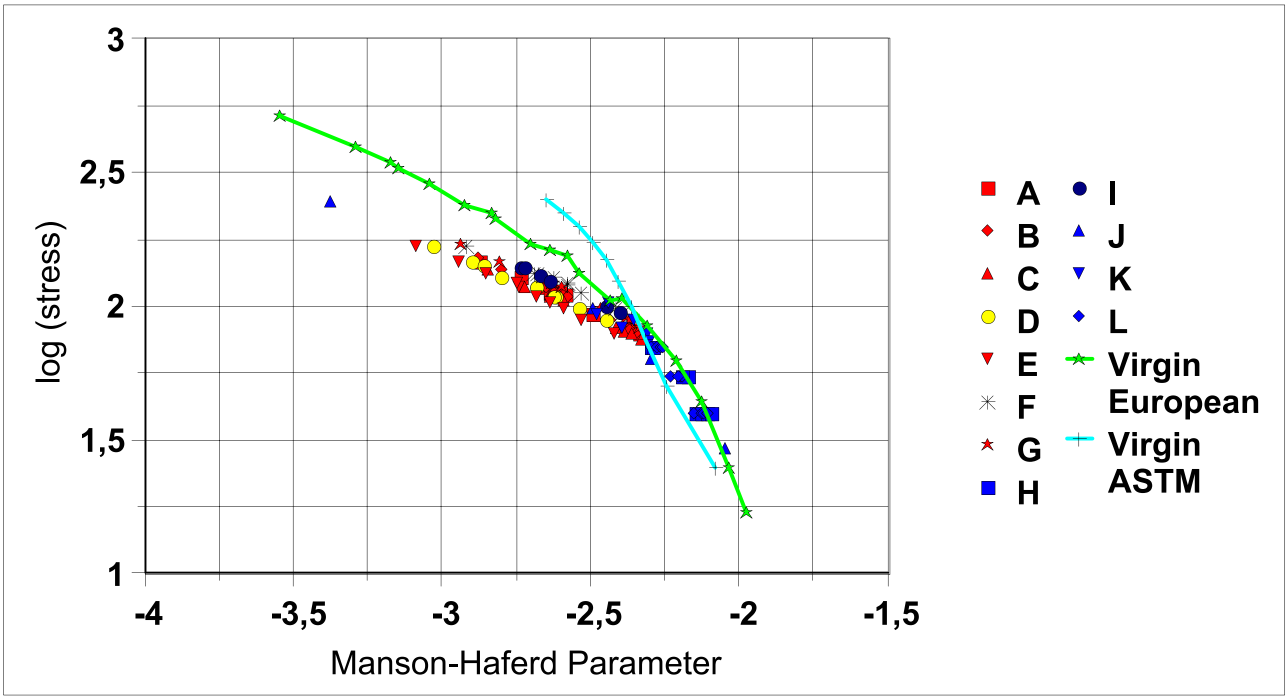

Figure 1: All available data: Red symbols: Power plant pipes, Blue Symbols: refinery plant pipes; curves: virgin material strength according to respectively ECCC WG1 Volume 5 part I and ASTM. The target component Pipe D is highlighted in yellow.

APPENDIX B

Review of Methods for the Computation of Residual Life Used in Recommendation Validation

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Appendix C shows the results of the assessments performed by various assessors on the same data set, detailed in Appendix A, for evaluation of the residual life of the same target component. The present document wants to give an overview on the particular assessment methods as used in the round robin, organised in 1999-2000 by ECCC WG1 PEDS.

1 Parametric Assessments

Parametric assessments base all on the assumption of equivalent effects between temperature and time and assess creep data (T, σ_0, $t_{u\text{-}PE}$) by applying a damage parameter which combines temperature and rupture time (generally). Parametric assessments can be applied to all sort of data distributions, isothermal or isostress test series. In some cases (see Appendix A) test series are programmed just to provide 4-6 points suitable to define the line parameter vs. $\log\sigma_o$.

Assessments belonging to this type, following the nomenclature of appendix C, table I, are listed in the table below:

Assessment name (see Appendix C, table I)	Assessor	Parameter used	Notes
Only D	ISB	Manson-Haferd	material constant optimised
Only D, ENEL	ENEL	Larson Miller	fixed material constant to C_2=20
Only D, SIEM	Siempelkamp	Larson Miller	material constant optimised
Only D, SIEM2	Siempelkamp	Larson Miller	material constant optimised
All SIEM	Siempelkamp	Larson Miller	material constant optimised
All SIEM2	Siempelkamp	Larson Miller	material constant optimised
All ENEL	ENEL	Larson Miller	fixed material constant to C_2=20
All1	ISB	Larson Miller	material constant optimsed
All2	ISB	Manson-Haferd	material constant optimsed
All_ECCC	ISB	Manson Haferd	PE-data made comparable
All_ASTM	ISB	Larson Miller	PE-data made comparable

The assessment procedure is in principle as per ISO 6303 appendix [1], see Volume 5 appendix D1 [2], with two exceptions:

1. In several methods the parameter to be used is fixed to the Larson-Miler approach (material constant can be fixed for steel grade classes)
2. The isothermal data conditioning as per ISO 6303 is not performed, but all data are transformed directly into the appropriated parameter P and are then fitted in the (P, $\log\sigma_o$)-plot by multiple linear regression to obtain an equation of the type

$$P(T, \log t_{u-PE}) = \sum_{i=0}^{n} a_i (\log \sigma_0)^i$$
$$P = \frac{(T - C_1)\sigma^q}{(C_2 + \log t_{u-PE})^r}$$

where, generally q=0, C_1 and C_2 are material constants, for r=1 P is the Manson Haferd parameter [3], for r=-1 and C_1=0 the Larson Miller parameter [4]; the a_i are constants to be fitted.
While ISO 6303 and the ECCC WG1 procedure in Volume 5, part I, appendix D1, recommend the use of 4^{th} order polynomials, when dealing with PE-data, which generally are subsize data sets, the degree n of the polynomial depends on the number of data acceptable to the fit.
So, following the table above, the “SIEM” approaches are based on a second order, the “only-D-ENEL” on a third order and all others on a fourth order polynomial.

2 Parametric Assessments with Linear Damage Accumulation Rules

When PE-data coming from different sources are used, they could be fitted all together with a simple parametric method (see chapter 1 of this appendix), but to reduce uncertainty they could be made comparable, if the service damage is accounted for in the assessment.
Several attempts on this subject are known, but a very simple one only has been tested during the PEDS round robin (appendix C). In this case the parametric method (see assessment all_ECCC and all_ASTM) was applied after having, again using parametric approaches, pre-conditioned the data with a Linear Damage Accumulation Rule (LDAR) according to Robinson [5]. The damage accumulation representing parameter PR was computed according:

$$PR = \sum_{x=1}^{Sx} t_{PE\_x}/t_{uS\_x}$$ for each service interval Sx at constant T_{PE} and σ_{PE}

t_{uS} is the rupture time of virgin material subjected to creep tests in service conditions, i.e. at $T=T_{PE}$ and $\sigma_0=\sigma_{PE}$.
When the damage parameter PR reaches 1 - in theory - the cumulated damage should induce failure.

PR is the same for each specimen machined from the same location on the component and is therefore the same for all following post exposure creep tests. PR is assumed to be independent of T_{PE} and σ_{PE}, because all combinations of exposure stress and temperature that result in the same PR-value are expected to have been damaged to the same amount (not necessarily in the same way).
An even more stringent approach substitutes time with parametric expressions, for instance the Larson-Miller-Parameter PLM:

$$PR' = \sum_{x=1}^{Sx} PLM_{PE}/PLM_{VS}$$ for each service interval Sx at constant σ_{PE} or σ_o

where $PLM_{PE} = T_{PE}\,(\mathrm{const} + \log(t_{PE}))$ and
$PLM_{VS} = T_{PE}\,(\mathrm{const} + \log(t_{uS}))$

The damage accumulation parameters can now be transferred easily into a $\log(\sigma)$ versus $\log(t)$ or versus PLM diagram due their independence in time and stress:
At constant test temperature T for each testing stress σ the effect of the cumulated damage is - related to a single loading condition -

$$PR = t_{PE}'/t_u$$ at constant testing T and σ_o

where t_{PE}' is that equivalent time that the service induced damage, characterised by PR has already consumed at the actual loading level (T, σ_o), at which virgin material has a life time of t_u. Vice versa this equation means that the "starting position" of the post exposure tests is a $\log(\sigma)$, $\log(t_u)$ curve parallel to the virgin material creep strength curve shifted by a factor PR towards shorter values (as PR obviously is smaller than 1).

In a similar way the parametric approach can be used. For each specimen

$$PR' = PLM_{PE}'/PLM_V$$ at constant testing stress σ_0

It follows that the starting condition for the post exposure creep tests are located on a curve parallel to the parametric virgin material creep strength curve but shifted by a factor PR' towards lower parameter values:
For each experimental point at each constant stress σ_0

$$PLM(t=0h)=PLM_V * PR'$$

If the same procedure is applied for each component service conditions and related PE-creep data a direct comparison among the PE-data of the various components becomes available simply by plotting either a $\log(\sigma_o)$ versus $\log(t_{u-PE}+t_{PE}')$ or $\log(\sigma_0)$ versus $PLM+PLM_{PE}'$ diagram.

3 PD6605

PD6605 [6] is a modern statistics based assessment method, which was developed for the assessment of bigger data sets and already applies the concept, on which the PATs as recommended in ECCC Volume 5 part I are based, during the assessment itself. The method, applied by Alstom during the PEDS-round robin for the first time to a smaller data set, is described in detail in ECCC Volume 5 part I, appendix D3.

4 ISPESL Procedure

The CRL procedure prescribed by the ISPESL (Italian Pressure Vessel Authority) guidelines [7] foresee, that t_{RL}* is computed by a linear isothermal extrapolation in the $\log(\sigma_o)$ versus $\log(t_u)$-diagram, obtained from the linear interpolation line through the two points available from an applicable standard closest to σ_{PE}. In the same way a limited life extension for the component can be computed, when the two closest points to t_{RL} are linearly interpolated.
If the applicable standard does not include values at the service temperature T_{PE}, they an be derived by linearly interpolating the standard values transformed into a Larson-Miller plot with fixed constant C_2 depending on the material grade.

5 Original ENEL CRL Procedure

The original procedure adopted in ENEL is outlined in [8]. It is based on the availability of a few PE-creep data and a suitable creep reference line, generally the virgin material creep strength line for the same steel grade as derivable from the applicable standard. The general principle is the construction of a lower bound curve, that shows the limit for material still just acceptable. For this construction the standard reference curve is moved downwards by 20% to take account for the material scatter, and is then horizontally moved through the point $\{PLM(T_{PE}, \log(t_{PE}+t_{RL}), \log(S^*\sigma_{PE})\}$, where PLM is the Larson Miller parameter at service temperature T_{PE} and total target service time (i.e. already consumed t_{PE} + aspired t_{RL}), and $S^*\sigma_{PE}$ is the service stress increased by a suitable safety factor, generally 1.6. If the PE-data all fall on the right side of the so constructed lower limit acceptance curve in the $\log(\sigma_o)$ versus Larson Miller Parameter, the pipe can be further serviced for t_{RL}.
The big advantage of this method is given by the immediate use of a well assessed line derived from a big data set on virgin material for the RL prediction. Two problems arise nevertheless: A suitable virgin material reference curve must be defined (that should meet the Volume 5 part I requirements) and no “end-of-life” prediction for the component is available.

6 Creep Strain Based Methods

Although several methods are known which relate time to rupture predictions with creep strain models, in the round robin exercise taken place in 2001-2004, all methods were based on the same theory, the MPC Omega Method [9].

The omega method describes the creep curve tertiary and partial secondary range.
The Omega-Method uses the following formula for the creep curve description:

$$\varepsilon(t)=\frac{-\ln\left(\frac{1}{\Omega\varepsilon_0^\bullet}-t\right)+\ln\left(\frac{1}{\Omega\varepsilon_0^\bullet}\right)}{\Omega}$$
eq. 1

where the time to rupture is given by:

$$t_u=\frac{1}{\Omega\,\varepsilon_0^\bullet}$$
eq. 2

while specific times tpx at strain εx can be computed via:

$$t_{px}=t_u-\exp\left[\varepsilon_x\Omega-\ln(t_u)\right]$$
eq. 3

The main parameters are Ω and $\varepsilon^\bullet_0$ which depend on stress σ and temperature T.

The adaptation procedure to compute Ω and $\varepsilon^\bullet_0$ foresees originally, that a linear regression is performed on the logarithmic (t,ε) – data belonging to the increasing strain rate branch of each available creep strain curve. Due the relatively small amount of Ω and $\varepsilon^\bullet_0$ values, two distinct methods for the descriptions of their stress and temperature dependence have been adopted in different details:

Alternative 1 (classical "polynomial approach", following Prager):

$$\Omega=d+d_1T+d_2\sigma+d_3(T\sigma)^m$$
$$\varepsilon_0^\bullet=g_1+g_2T+g_3\sigma+g_4(T\sigma)^{m_1}$$
eq.s 4 , 5

Alternative 2 (parametric approach: A parameter like Larson-Miller including Ω and $\varepsilon^\bullet_0$ is related to an expression including stress and temperature. The following equations show examples for such an approach)

$$T\ \left(C + \log[\Omega]\right) = \sum_{i=0}^{4} a_i \log^i(\sigma)$$

$$T\left(C_1 + \log\left(\varepsilon_0^{\bullet}\right)\right) = \sum_{i=0}^{4} b_i \log^i(\sigma)$$

eq.s 6, 7

Other approaches relate the experimentally found Ω and $\varepsilon^{\bullet}_0$ with data bases founded on previous assessments, on recommended values by the Materials Properties Council and the API 579 standard or derived from the related virgin materials. An additional possibility is to relate Ω and $\varepsilon^{\bullet}_0$ via a Linear Damage Accumulation Rule to values computer from reference or virgin materials.
In any case, the quality of the Omega procedure prediction, resides evidently in the correct interpretation and extrapolation of the Ω and $\varepsilon^{\bullet}_0$, which still depends significantly from the assessor's skill, experience and material properties understanding.

All details about the used equations are included in the model results description in the Annex to Appendix D

7 References

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8 Billi B., D'Angelo D., Livraghi M., Maciga G. "Structural Integrity Assessment and Lifetime Predictions of Operating Thermal Power Pipelines"; International Symposium on "Prediction of Residual Lifetime of Constructions Operating at High Temperatures", The Hague, 3-4/11/1977
9 Prager M., "Development of the MPC Omega Method for Life Assessment in the Creep range", J. Press. Vess. Techn, 117, 1995 p. 95

APPENDIX C

Recommendations' Validation Based on Creep Rupture PE-Data

G. Merckling

Istituto Scientifico Breda, Italy

1 Introduction

The Post Exposure creep Data Activity PEDS was developed as a sub-group to ECCC's WG1 "Creep Data Generation and Assessment Procedures" following the request of utilities and other users of materials in the creep regime. PEDS has the purpose to actively compare the assessment as performed by skilled assessors and to derive a methodus operandi to identify the most suitable assessment method and the therefore most reliable assessment result.

2 The Approach

From collation within the PEDS group a post exposure data set and a target component, the so called pipe D, could be identified (s. Volume 5 part III Appendix A). The task to test the performance of several approaches in computing the residual life (CRL), presented to the 4 participating assessors, was to decide

1. on the allowance for pipe D to continue service for additional 50000 h and
2. to estimate the probable end-of-life of the component.

As the available data set contains additional PE-creep results, derived from other pipes than pipe D, as well as data from virgin material, it was up to the assessors' preference to use

- PE-data from pipe D only
- all PE-data as one common data set
- all PE-data after been made fully "comparable", i.e. using a virgin material, either European (ECCC) or ASTM grade, and a damage accumulation hypothesis to include the service damage into the assessment.
- virgin material data (experimental or assessed) for European (ECCC) or ASTM grade (as only data or in combination with PE-data)
- standard strength values (here according DIN 17175 for 10 CrMo 9 10 grade).

The following Table I gives an overview on the produced assessments and the results obtained for pipe D.

Each CRL produced was independently evaluated first with the post assessment tests as proposed in Volume 5 part I and thereafter with those of part III. As a basis for comparison two options were tested, firstly all PE-data available from all pipes, secondly only the PE-data belonging to the target component, pipe D. Where damage accumulation rules were included into the assessment, the experimental $t_{u\text{-}PE}$-values were allowed to be corrected by the same principle, in order to permit comparison on the same time scale basis.

The attached figures, Table IV and Table V show for all PATs the performance of the various assessments.

In Table II and Table III the overviews on the generic results are given. CRLs passing the Volume 5 part I PATs were not found, those complying with Volume 5 part III PATs are highlighted.

It appears that:

- PAT-1.1b is fundamental to filter out the assessments predicting mostly straight lines, which would have been successful in the case of only pipe D PE-data for comparison.
- PAT-2.2 becomes extremely severe when all PE-data are considered for comparison.
- Generally those assessments relying on more data, possibly made comparable, as well as those relying on virgin material only (possibly already assessed with a model satisfying ECCC Recommendation Volume 5 part I), have more chances in succeeding the PATs.

Table I: Overview on Methods for the Computation of the Residual Life (CRL)

CRL Name used in following figures and tables	Assessor	Assessment Method	Used Data Type	Is Pipe D allowed to continue for additional 50kh ?	Estimated new end-of-life h
Only D, Only D, ENEL Only D SIEM Only D SIEM2	ISB ENEL Siempelkamp Siempelkamp	Parametric Parametric Parametric Parametric	Only Pipe D PE-data	Yes Yes Yes Yes	2.8M 32M 17M 17M
All SIEM	Siempelkamp	Parametric	Only Power plant PE-data	Yes	6.5M
All2, Alstom All1, All SIEM2, All ENEL	ISB Alstom Power ISB Siempelkamp Enel	Parametric PD6605 Parametric Parametric Parametric	all PE- data	Yes Yes Yes Yes Yes	330k 800k 1.4M 1.7M 6.9M
All ECCC All ASTM	ISB ISB	LDAR based on ECCC + Parametric LDAR based on ASTM + Parametric	all PE-data after been made comparable	Yes Yes	200k 790k
New ASTM	ISB	ISO 6303	Virgin data ASTM P22	Yes	204k
New ECCC	IfW for ECCC WG1	DESA	Virgin data Eur. grade	Yes	240k
ISPESL	ISB	ISPESL guideline 15/92	DIN 17175 strength values	Yes	1,2M
Original ENEL	ENEL	ENEL procedure	Virgin ASTM data + Pipe D PE-data	Yes	>50k
Reality			after +100k disassembled: No evident damage		

LDAR: Linear Damage Accumulation Rule

Table II: PAT results, basing on all available PE-data

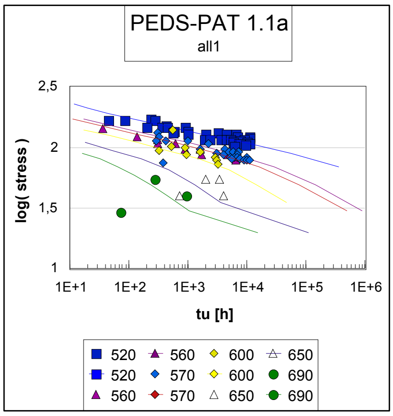
CRL	PAT-1.1a	PAT-1.1b	PAT-1.2	PAT-1.3	PAT-2.1	PAT-2.2	PAT-3.1	PAT-3.2	Residual life t_{RL} [h]
Only D	ok	no	no	?	no	no	ok	n.p.	2.8M
Only D ENEL	ok	no	?	ok	ok	no	ok	ok	32M
Only D SIEM	ok	no	ok	ok	ok	no	ok	n.p.	17M
Only D SIEM2	ok	no	ok	?	no	no	n.p.	n.p.	17M
All SIEM	ok	no	ok	ok	ok	no	ok	n.p.	6.5M
All1	ok	no	?	?	ok	no	ok	n.p.	1.4M
Alstom	ok	no	no	ok	ok	no	ok	ok	800K
All2	ok	ok	?	ok?	ok	no	ok	n.p.	330k
All SIEM2	ok	no	no	ok	ok	no	ok	n.p.	1.7M
All ENEL	ok	no	no	ok	ok	no	ok	n.p.	6.9M
All ECCC	ok	ok	ok	ok	ok	ok	ok	ok	200k
All ASTM	ok	no	no	ok	no	no	no	no	790k
New ASTM*	ok	n.a.	no	ok	n.a.	n.a.	no	no	204k
New ECCC*	ok	n.a.	ok	ok	n.a.	n.a.	ok	ok	240k
ISPESL	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	ok	n.a.	1.2M
Orig. ENEL*	ok	ok	ok	ok	ok	ok	ok	ok	>50k

Explanations:
ok : PAT has been fulfilled
no : PAT requirement is not fulfilled
? : border line PAT requirement fulfilled
n.a. : not applicable
n.p. ; not performed
* : comparison with virgin material.

Table III: PAT results, basing on target component, pipe D, PE-data only

CRL	PAT-1.1a	PAT-1.1b	PAT-1.2	PAT-1.3	PAT-2.1	PAT-2.2	PAT-3.1	PAT-3.2	Residual life t_{RL} [h]
Only D	ok	no	no	?	ok	ok	ok	n.p.	2.8M
Only D ENEL	ok	no	?	ok	ok	ok	ok	ok	32M
Only D SIEM	ok	no	ok	ok	ok	ok	ok	n.p.	17M
Only D SIEM2	ok	no	ok	?	ok	ok	n.p.	n.p.	17M
All SIEM	ok	no	ok	ok	?	ok	ok	n.p.	6.5M
All1	no	no	?	?	ok	?	ok	n.p.	1.4M
Alstom	ok	no	no	ok	no	no	ok	ok	800k
All2	?	ok	?	ok?	ok	ok	ok	n.p.	330k
All SIEM2	ok	no	no	ok	ok	no	ok	n.p.	1.7M
All ENEL	ok	no	no	ok	no	no	ok	n.p.	6.9M
All ECCC	ok	ok	ok	ok	ok	ok	ok	ok	200k
All ASTM	ok	no	no	ok	ok	no	no	no	790k
New ASTM*	ok	n.a.	no	ok	n.a.	n.a.	no	no	204k
New ECCC*	ok	n.a.	ok	ok	n.a.	n.a.	ok	ok	240k
ISPESL	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	ok	n.a.	1.2M
Orig. ENEL*	ok	ok	ok	ok	ok	ok	ok	ok	>50k

Explanations:
ok : PAT has been fulfilled
no : PAT requirement is not fulfilled
? : border line PAT requirement fulfilled
n.a. : not applicable
n.p. ; not performed
* : comparison with virgin material.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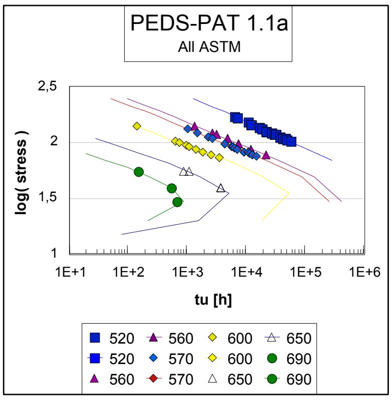
all1
log(stress)
2,5
2
1,5
1
1E+1 1E+2 1E+3 1E+4 1E+5 1E+6
tu [h]
520 560 600 650
520 570 600 690
560 570 650 690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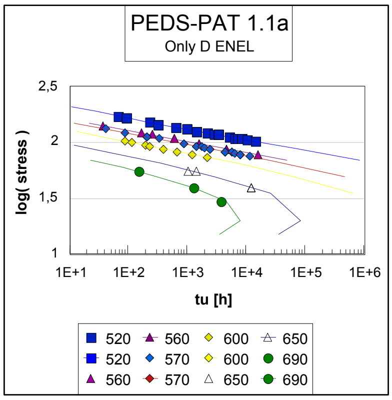
All ASTM
log(stress)
2,5
2
1,5
1
1E+1 1E+2 1E+3 1E+4 1E+5 1E+6
tu [h]
520 560 600 650
520 570 600 690
560 570 650 690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Only D ENEL
log(stress)
2,5
2
1,5
1
1E+1 1E+2 1E+3 1E+4 1E+5 1E+6
tu [h]
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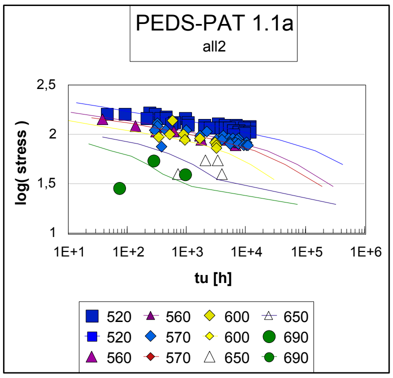
520 570 600 690
560 570 650 690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all2
log(stress)
2,5
2
1,5
1
1E+1 1E+2 1E+3 1E+4 1E+5 1E+6
tu [h]
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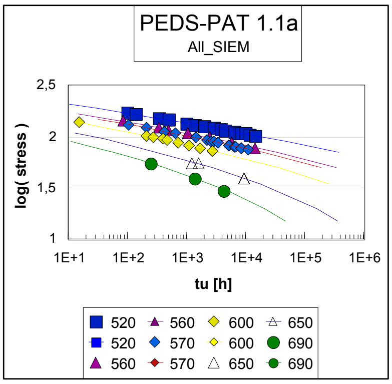
520 570 600 690
560 570 650 690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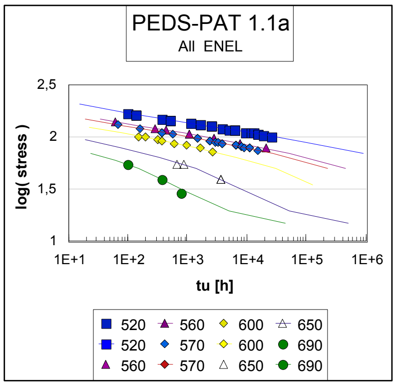
All_SIEM
log(stress)
2,5
2
1,5
1
1E+1 1E+2 1E+3 1E+4 1E+5 1E+6
tu [h]
520 560 600 650
520 570 600 690
560 570 650 690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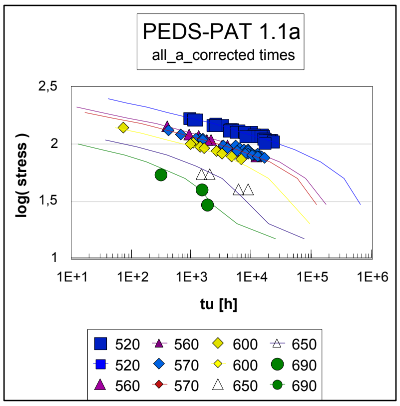
All ENEL
log(stress)
2,5
2
1,5
1
1E+1 1E+2 1E+3 1E+4 1E+5 1E+6
tu [h]
520 560 600 650
520 570 600 690
560 570 650 690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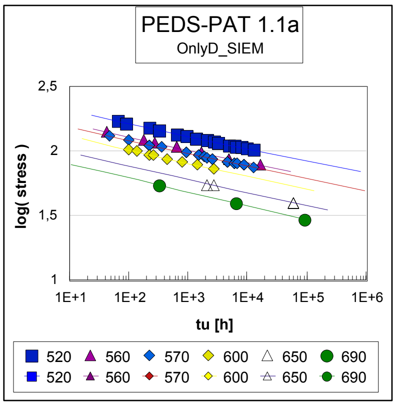
all_a_corrected times
log(stress)
2,5
2
1,5
1
1E+1 1E+2 1E+3 1E+4 1E+5 1E+6
tu [h]
520 560 600 650
520 570 600 690
560 570 650 690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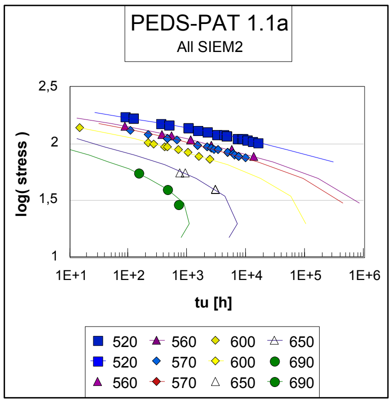
OnlyD_SIEM
log(stress)
2,5
2
1,5
1
1E+1 1E+2 1E+3 1E+4 1E+5 1E+6
tu [h]
520 560 570 600 650 690
520 560 570 600 650 690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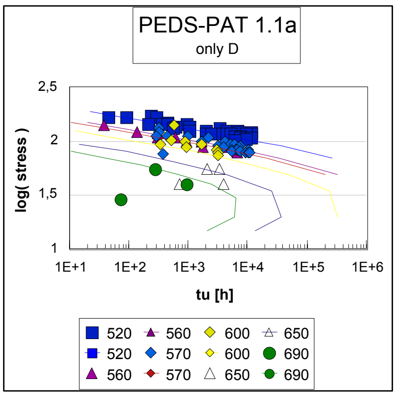
All SIEM2
log(stress)
2,5
2
1,5
1
1E+1 1E+2 1E+3 1E+4 1E+5 1E+6
tu [h]
520 560 600 650
520 570 600 690
560 570 650 690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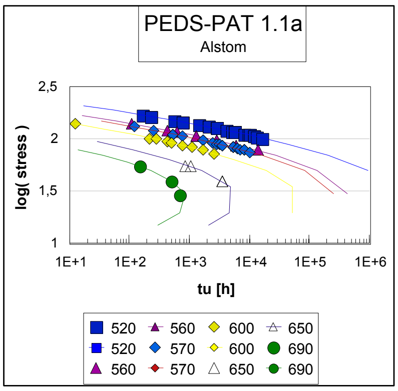
only D
log(stress)
2,5
2
1,5
1
1E+1 1E+2 1E+3 1E+4 1E+5 1E+6
tu [h]
520 560 600 650
520 570 600 690
560 570 650 690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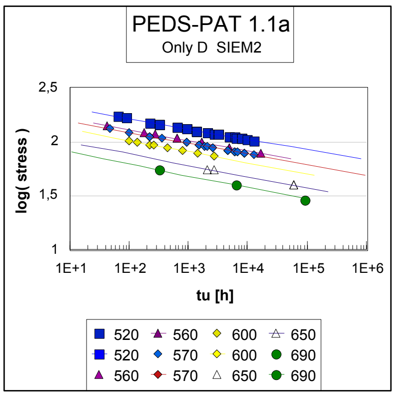
Alstom
log(stress)
2,5
2
1,5
1
1E+1 1E+2 1E+3 1E+4 1E+5 1E+6
tu [h]
520 560 600 650
520 570 600 690
560 570 650 690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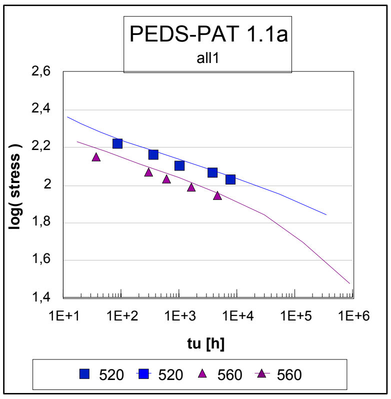
Only D SIEM2
log(stress)
2,5
2
1,5
1
1E+1 1E+2 1E+3 1E+4 1E+5 1E+6
tu [h]
520 560 600 650
520 570 600 690
560 570 650 690

Figure 1: Check of PAT 1.1a: Visual check of the fit between all available PE-data and assessed lines. The LDAR including assessment methods use by service exposure fraction damage corrected $t_{u\text{-}PE}$ data in order to use the same time scale.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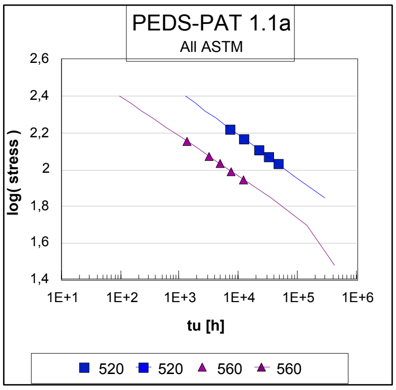
all1
2,6
2,4
2,2
2
1,8
1,6
1,4
log(stress)
1E+1
1E+2
1E+3
1E+4
1E+5
1E+6
tu [h]
520
520
560
560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All ASTM
2,6
2,4
2,2
2
1,8
1,6
1,4
log(stress)
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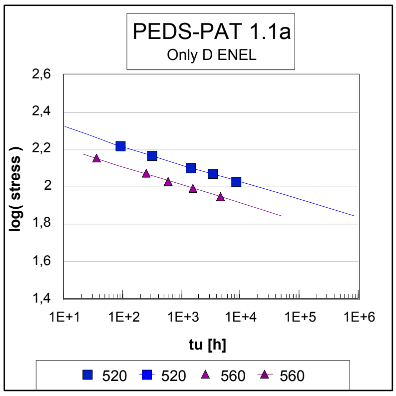
1E+2
1E+3
1E+4
1E+5
1E+6
tu [h]
520
520
560
560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Only D ENEL
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2,4
2,2
2
1,8
1,6
1,4
log(stress)
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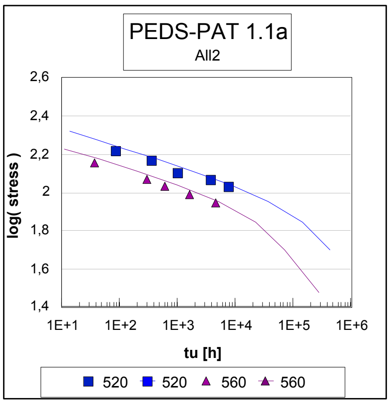
1E+2
1E+3
1E+4
1E+5
1E+6
tu [h]
520
520
560
560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2,4
2,2
2
1,8
1,6
1,4
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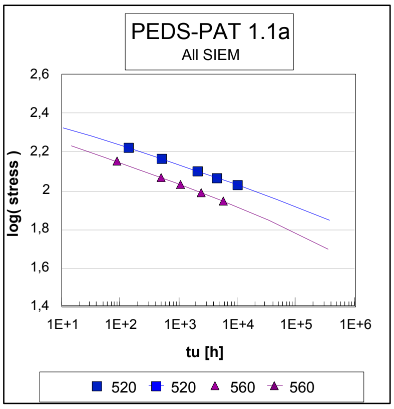
1E+2
1E+3
1E+4
1E+5
1E+6
tu [h]
520
520
560
560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All SIEM
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2,4
2,2
2
1,8
1,6
1,4
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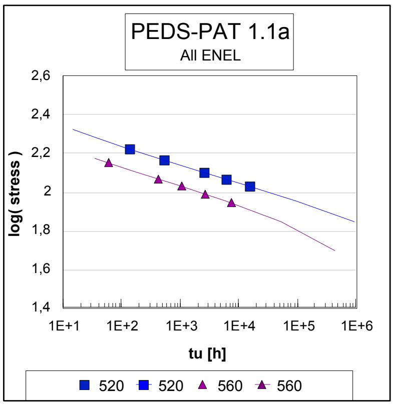
1E+2
1E+3
1E+4
1E+5
1E+6
tu [h]
520
520
560
560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2,4
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2
1,8
1,6
1,4
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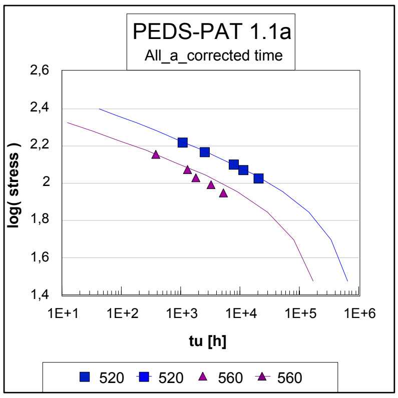
1E+2
1E+3
1E+4
1E+5
1E+6
tu [h]
520
520
560
560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All_a_corrected time
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2,4
2,2
2
1,8
1,6
1,4
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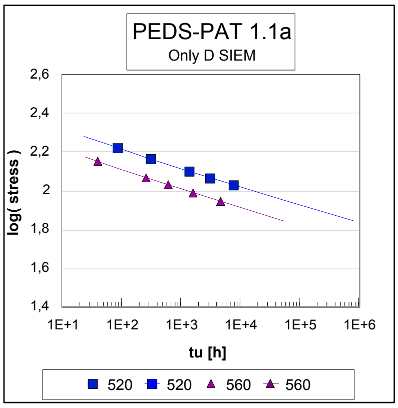
1E+2
1E+3
1E+4
1E+5
1E+6
tu [h]
520
520
560
560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Only D SIEM
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2,4
2,2
2
1,8
1,6
1,4
log(stress)
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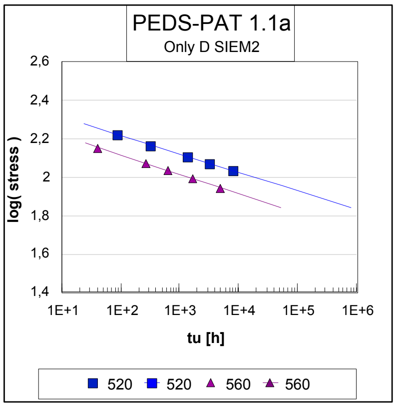
1E+2
1E+3
1E+4
1E+5
1E+6
tu [h]
520
520
560
560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2,2
2
1,8
1,6
1,4
log(stress)
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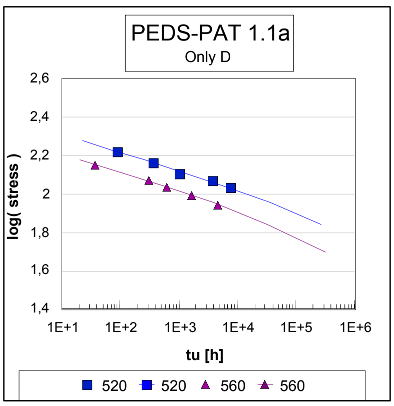
1E+2
1E+3
1E+4
1E+5
1E+6
tu [h]
520
520
560
560


PEDS-PAT 1.1a
Only D
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2,4
2,2
2
1,8
1,6
1,4
log(stress)
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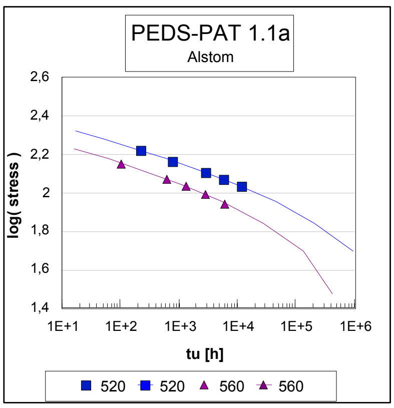
1E+2
1E+3
1E+4
1E+5
1E+6
tu [h]
520
520
560
560


PEDS-PAT 1.1a
Alstom
2,6
2,4
2,2
2
1,8
1,6
1,4
log(stress)
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1E+2
1E+3
1E+4
1E+5
1E+6
tu [h]
520
520
560
560

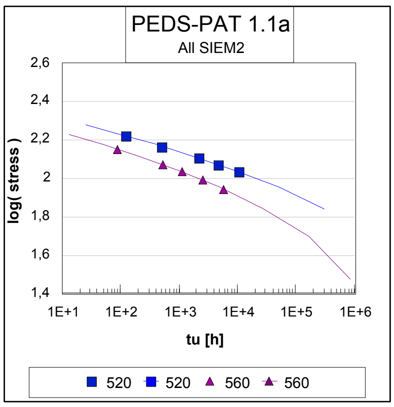
PEDS-PAT 1.1a
All SIEM2
2,6
2,4
2,2
2
1,8
1,6
1,4
log(stress)
1E+1
1E+2
1E+3
1E+4
1E+5
1E+6
tu [h]
520
520
560
560

Figure 2: Check of PAT-1.1a: Visual check of the fit between PE-data of target component pipe D only and assessed lines (corrected times: s. Figure 1).

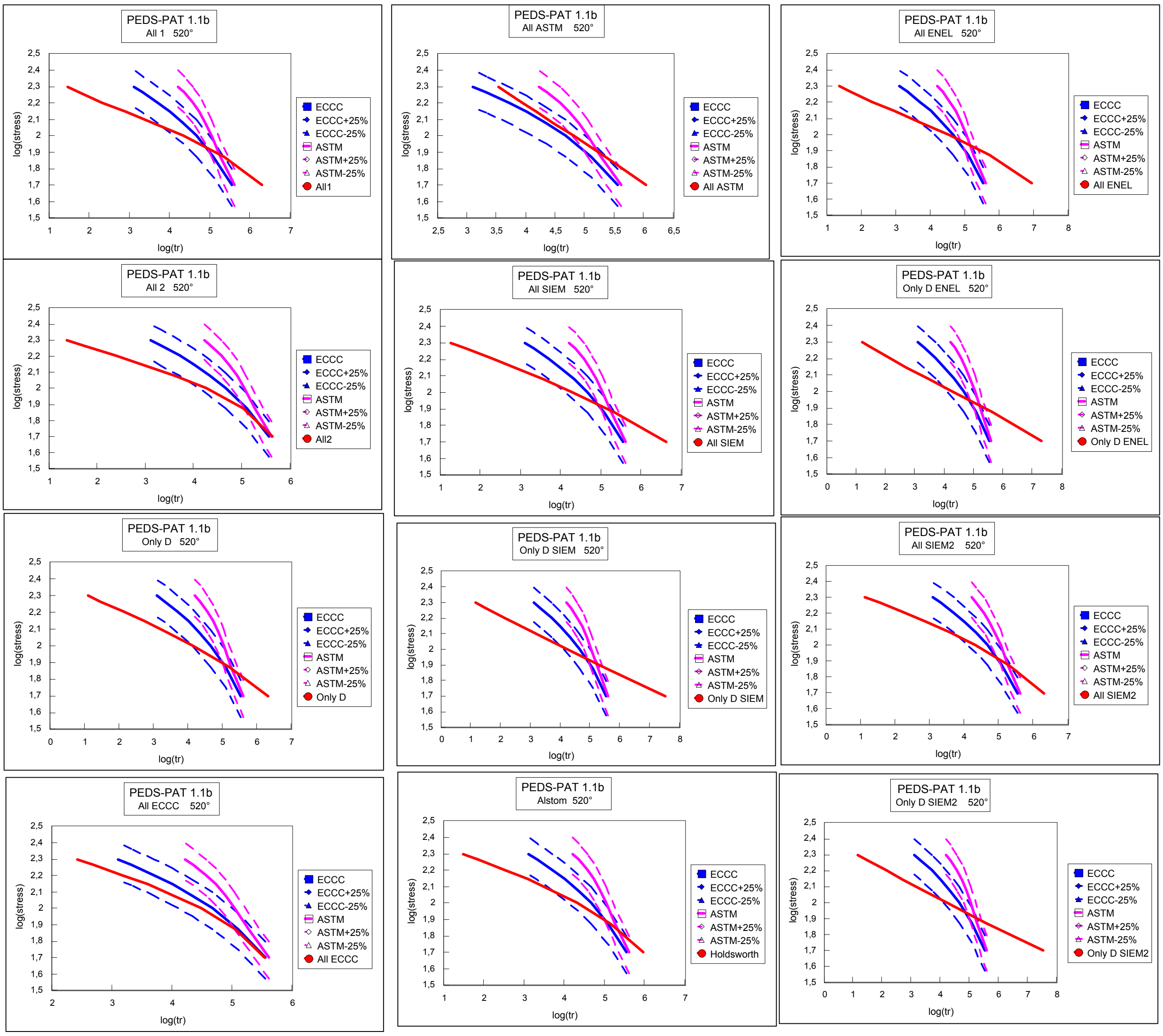

Figure 3: **Check of PAT-1.1b at 520°C. Each diagram reports the assessed line, the predicted line for virgin European grade 2,25Cr1Mo according to ECCC-WG1 (Volume 5 part I) with its ±20% scatter band in stress (ECCC±20%-lines, dashed) and the correspondent lines predicted for ASTM A335 grade P22.**

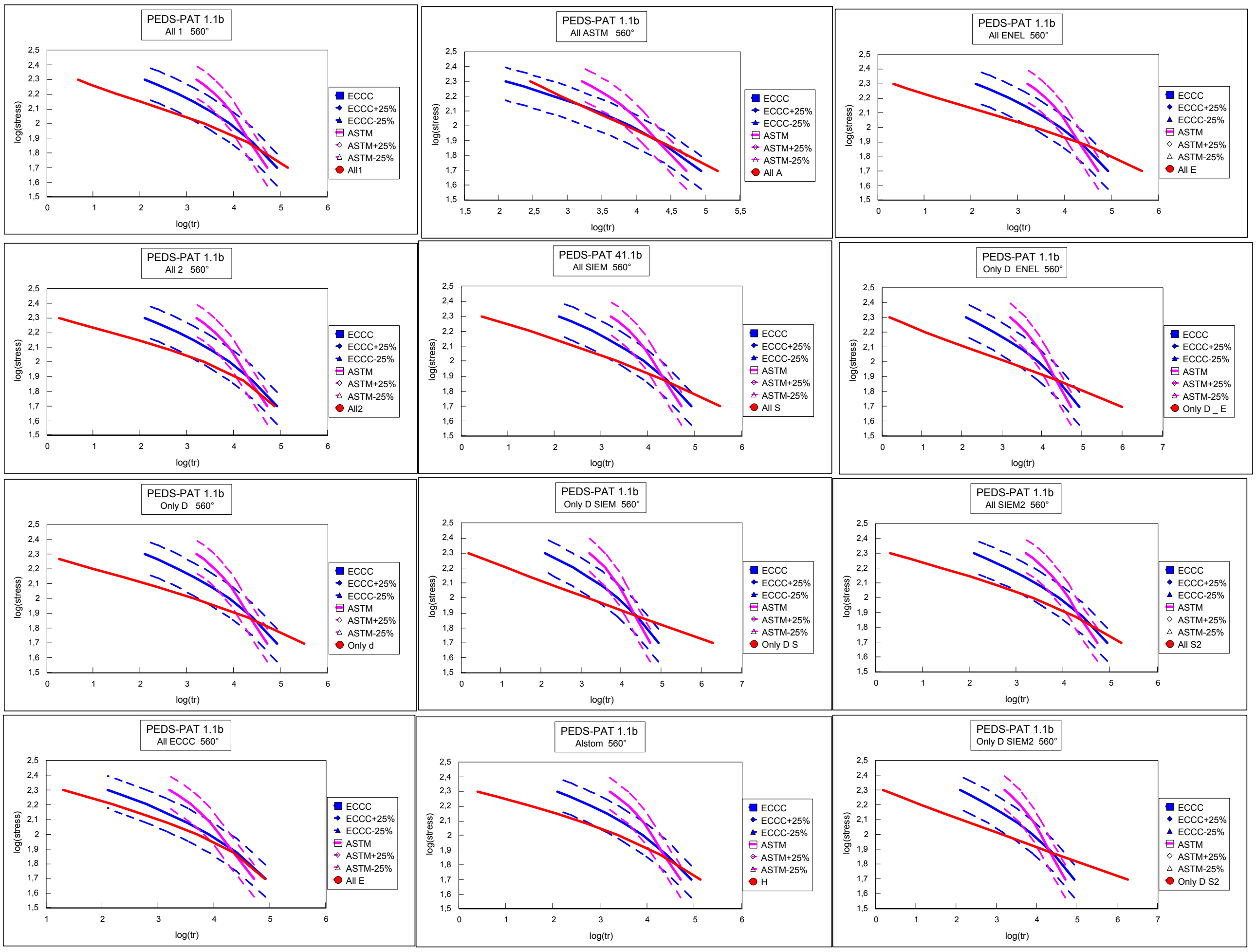

Figure 4: **Check of PAT-1.1b at 560°C. Each diagram reports the assessed line, the predicted line for virgin European grade 2,25Cr1Mo according to ECCC-WG1 (Volume 5 part I) with its ±20% scatter band in stress (ECCC±20%-lines, dashed) and the correspondent lines predicted for ASTM A335 grade P22.**

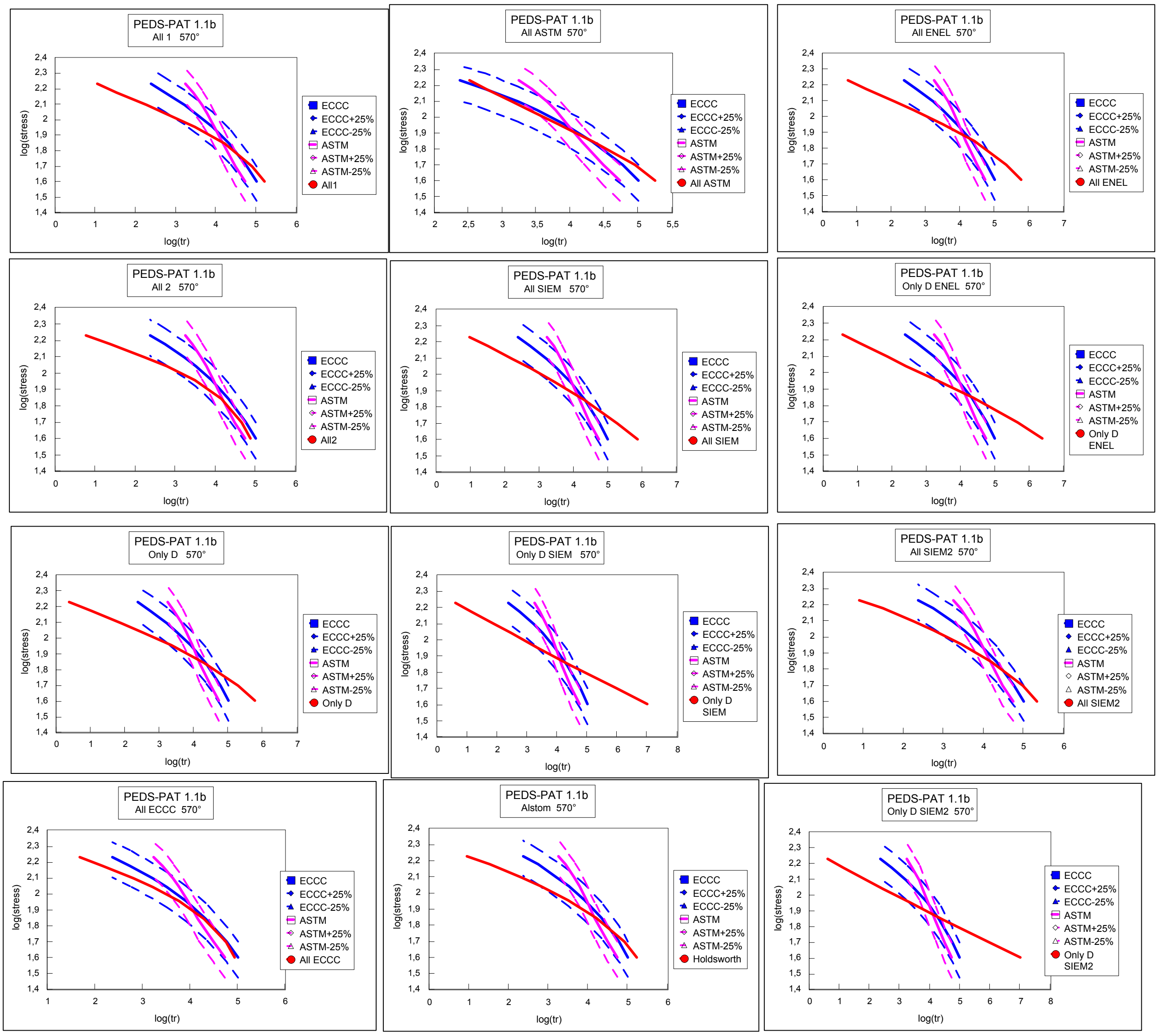

Figure 5: Check of PAT-1.1b at 570°C. Each diagram reports the assessed line, the predicted line for virgin European grade 2,25Cr1Mo according to ECCC-WG1 (Volume 5 part I) with its ±20% scatter band in stress (ECCC±20%-lines, dashed) and the correspondent lines predicted for ASTM A335 grade P22.

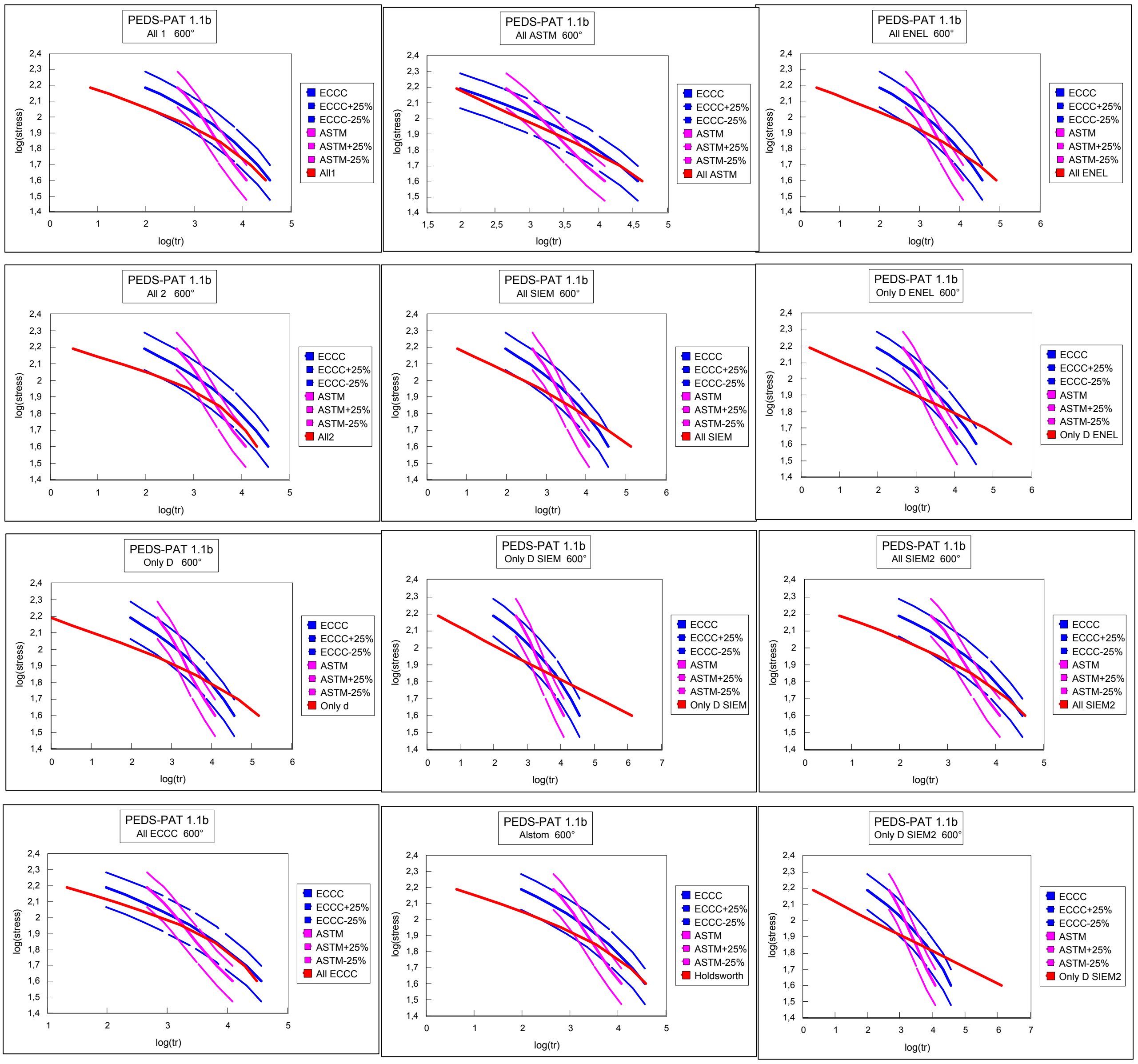

Figure 6: Check of PAT-1.1b at 600°C. Each diagram reports the assessed line, the predicted line for virgin European grade 2,25Cr1Mo according to ECCC-WG1 (Volume 5 part I) with its ±20% scatter band in stress (ECCC±20%-lines, dashed) and the correspondent lines predicted for ASTM A335 grade P22.

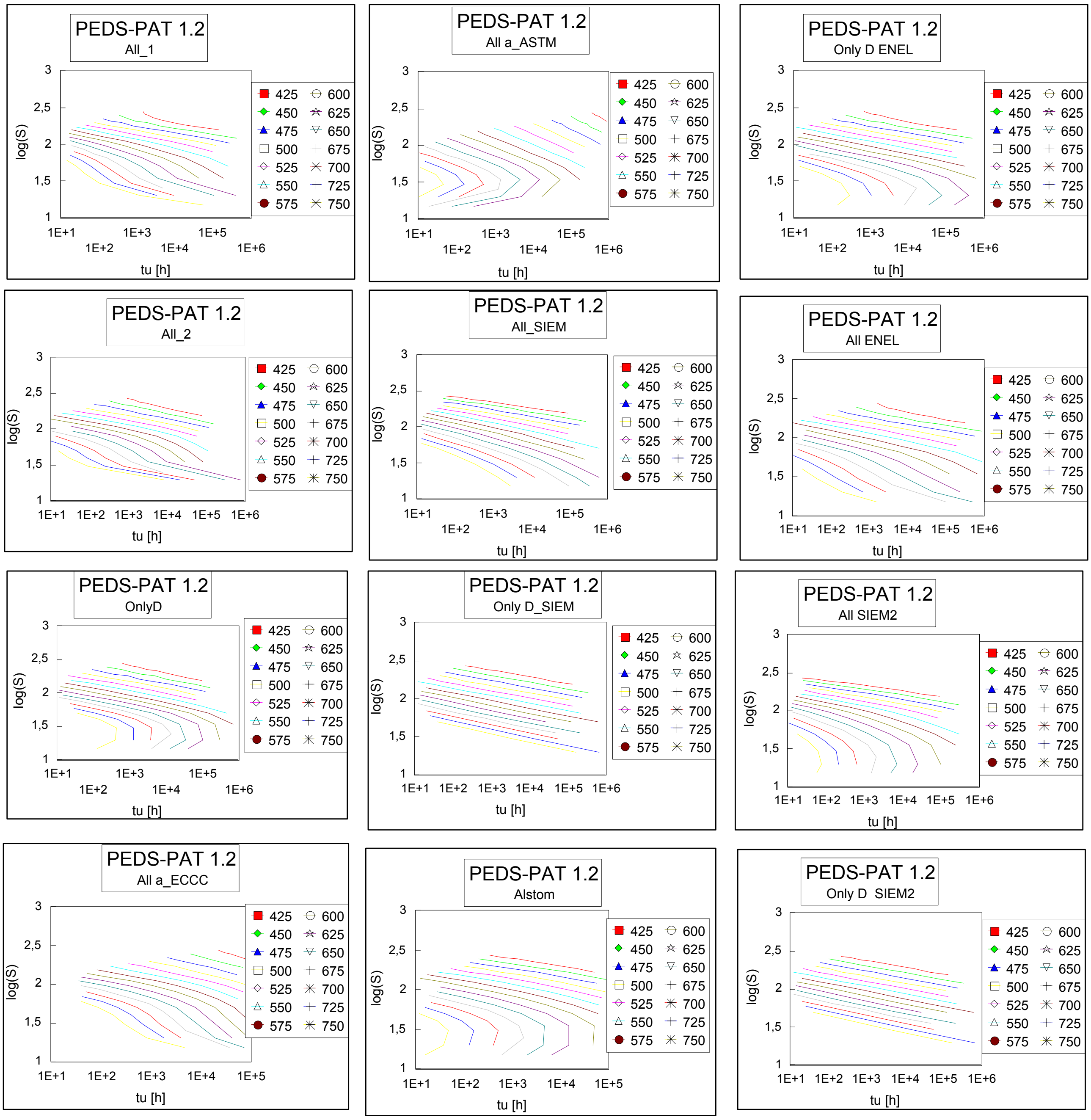

Figure 7: Check of PAT-1.2: Physical realism of assessed lines over the whole available temperature range (corrected times: see Figure 1).

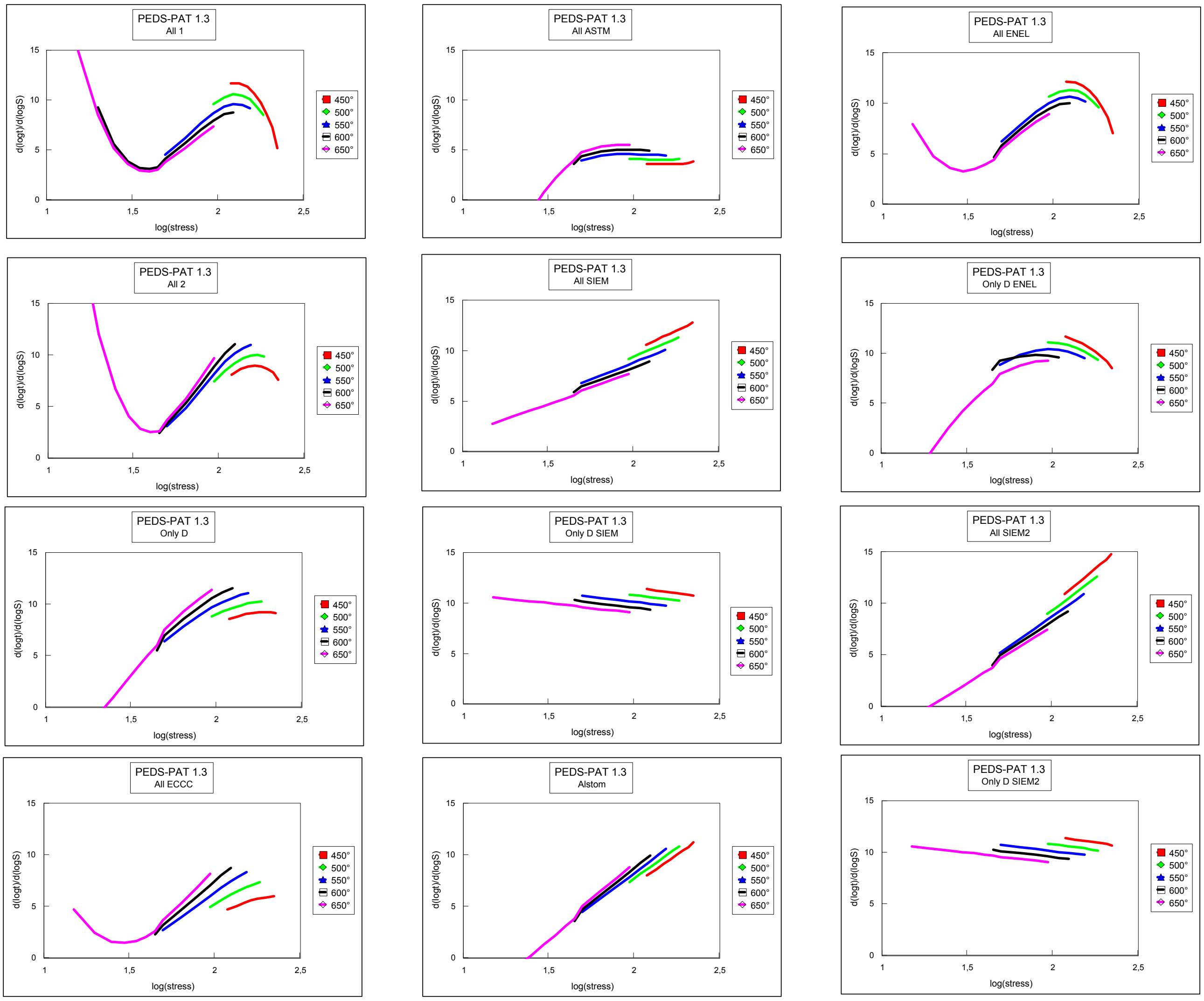

Figure 8: Check of PAT-1.3: Stress dependence of the slope of assessed lines over the whole available temperature range (corrected times: see Figure 1).

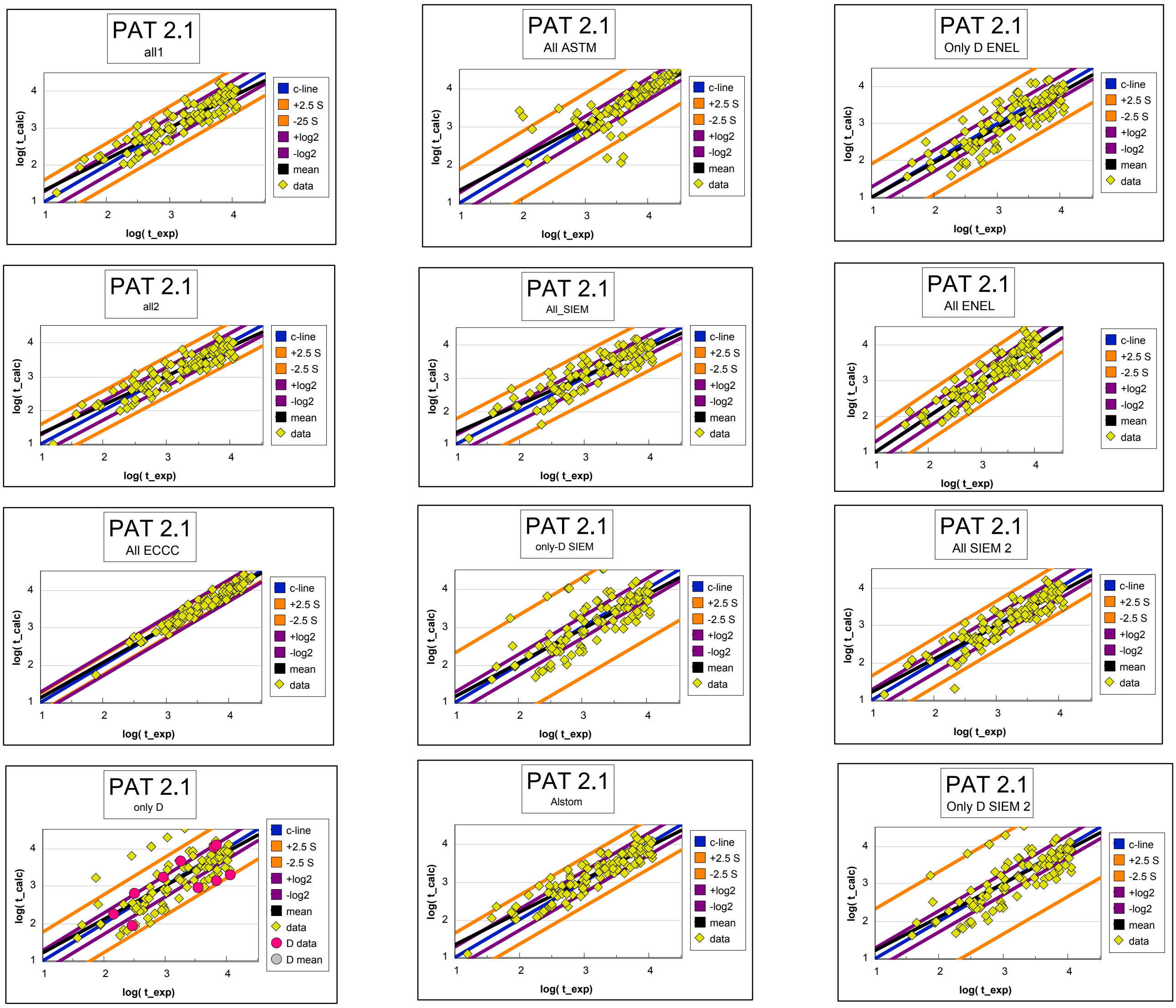

Figure 9 : Check of PAT-2.1, basing on all available PE-data.

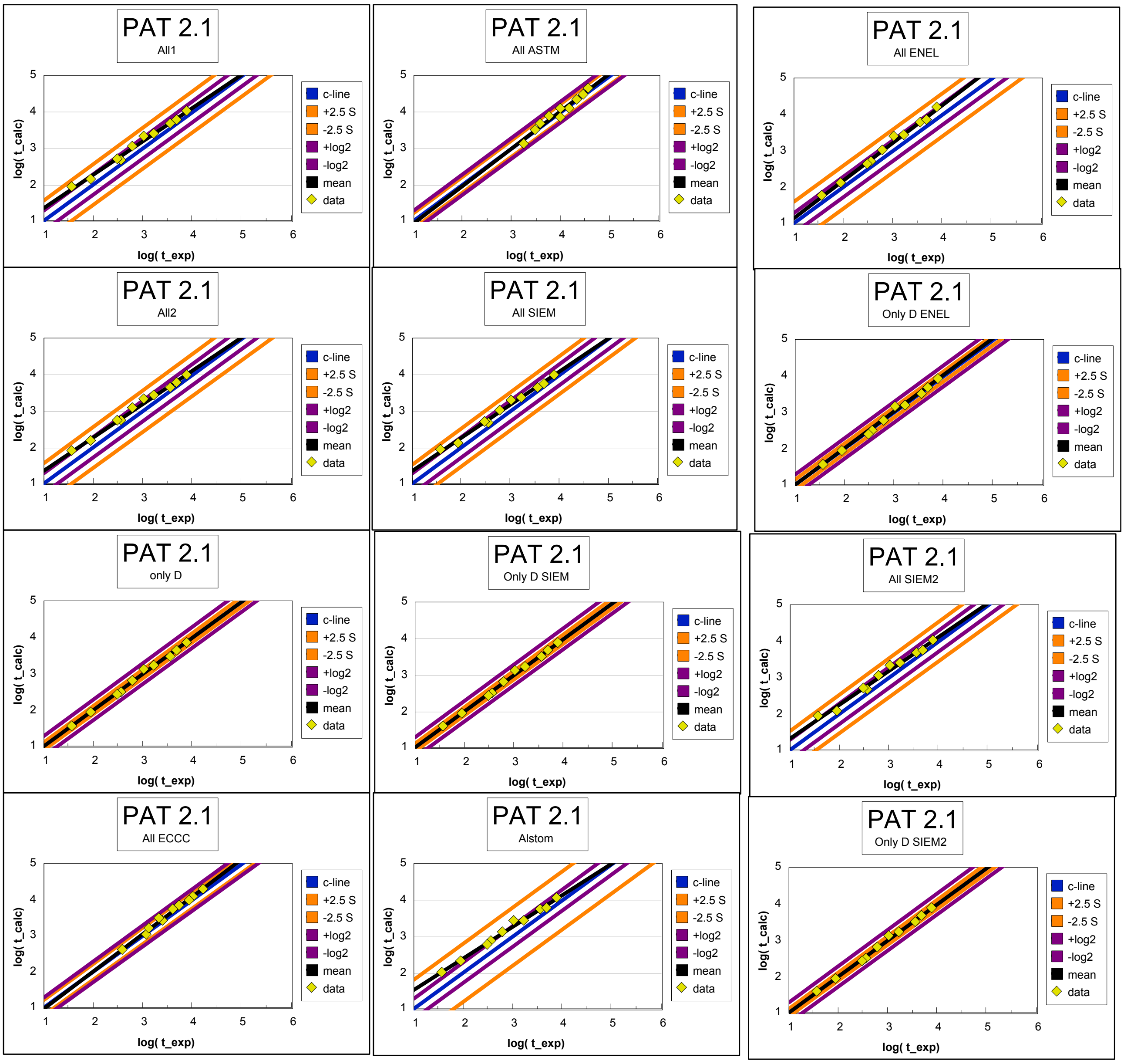

Figure 10: Check of PAT-2.1, basing on target component, pipe D, PE-data only.

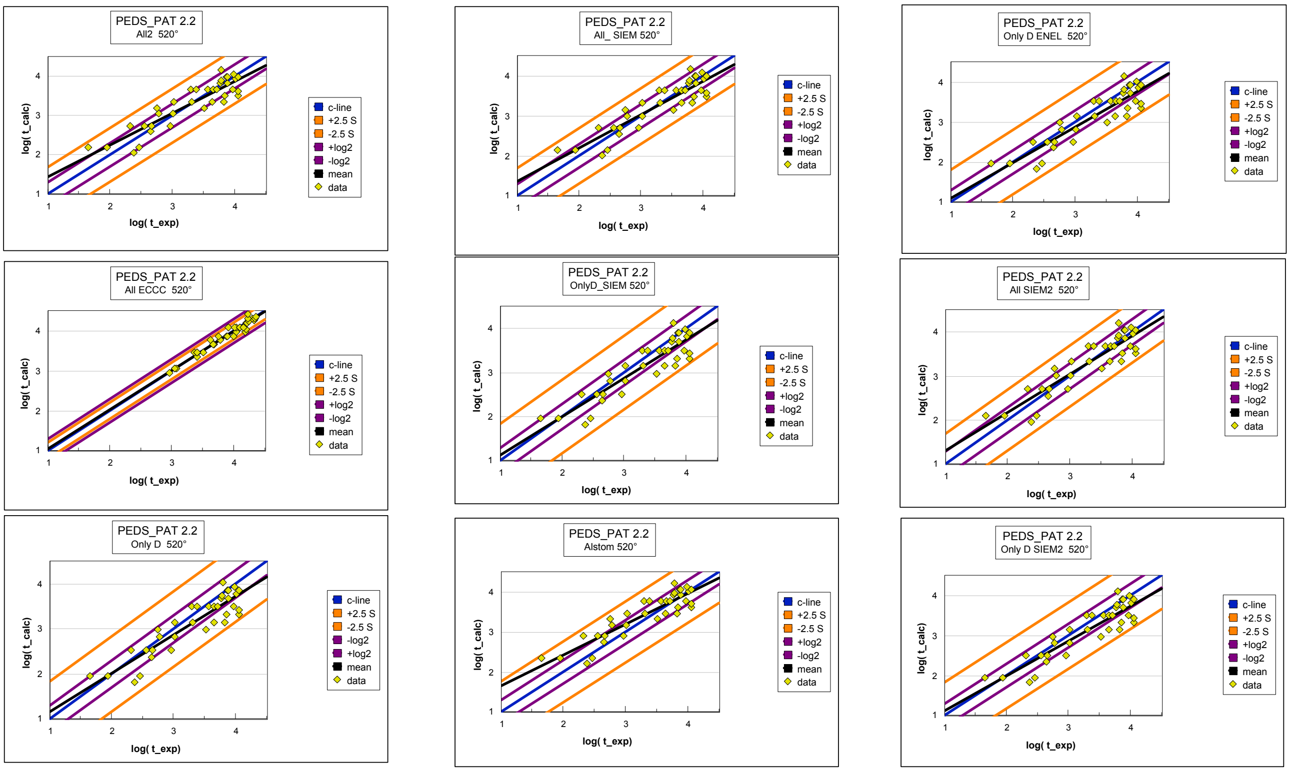

Figure 11: Check of PAT-2.2 at 520°C, basing on all available PE-data.

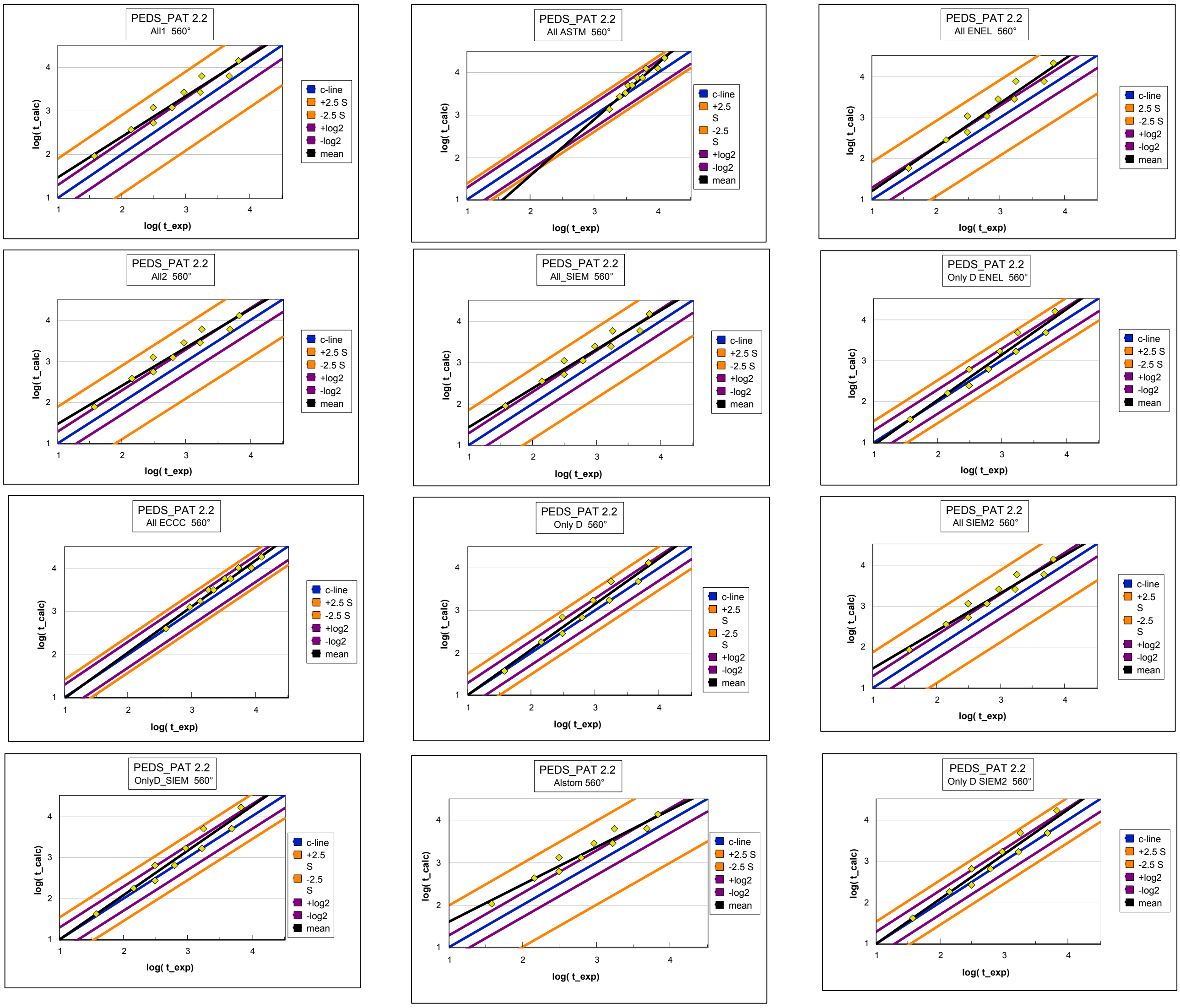

Figure 12: Check of PAT-2.2 at 560°C, basing on all available PE-data.

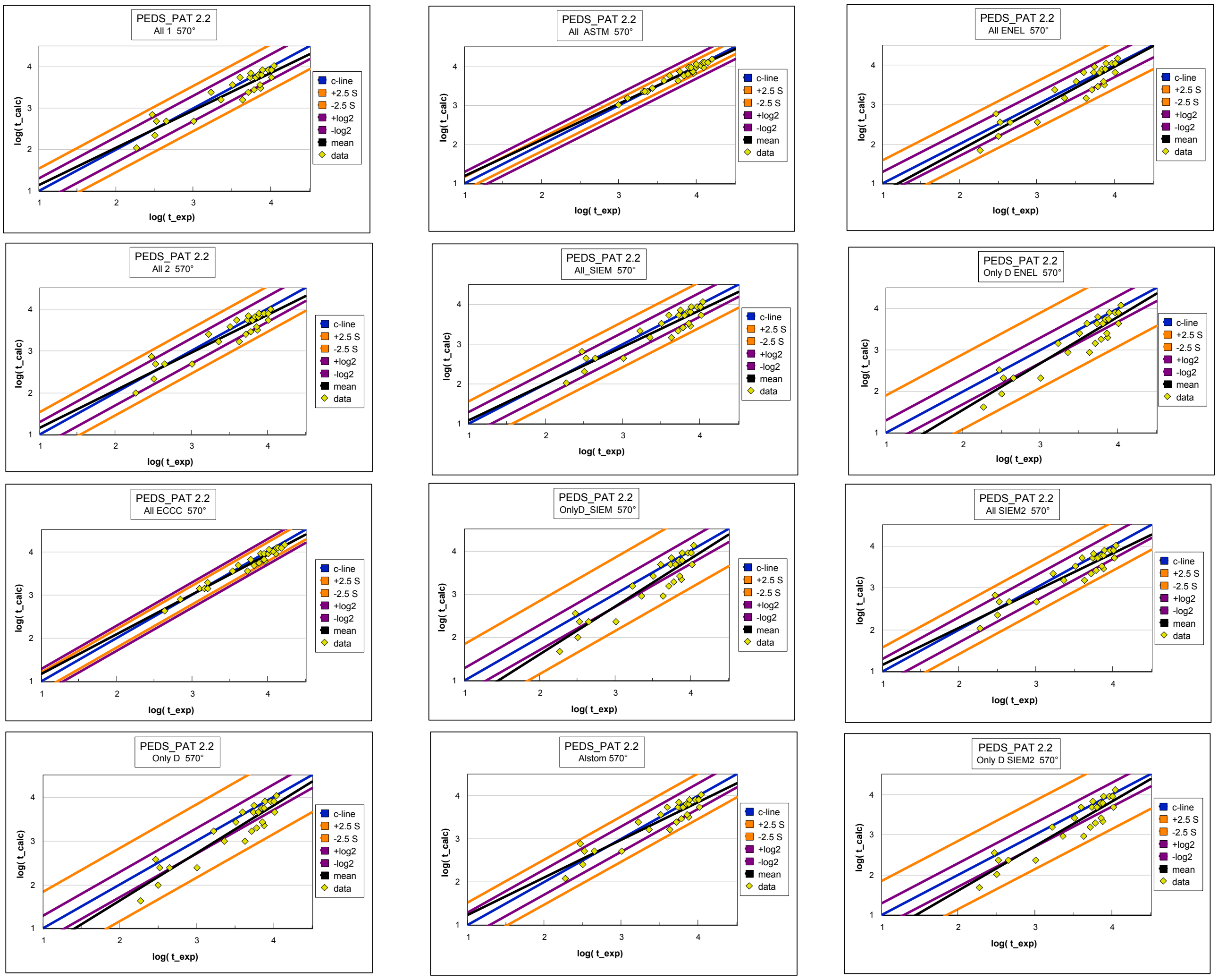

Figure 13: Check of PAT-2.2 at 570°C, basing on all available PE-data.

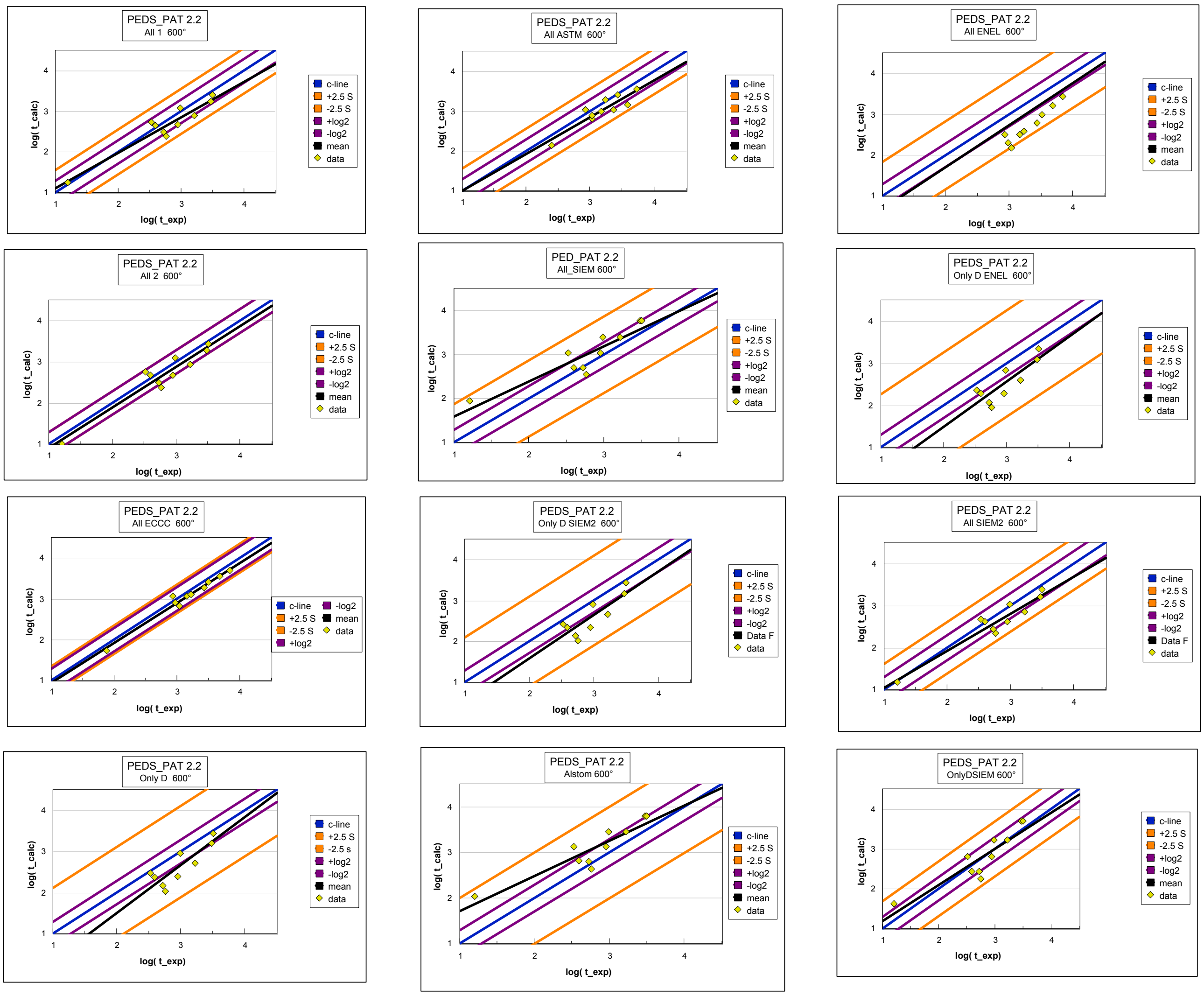

Figure 14: Check of PAT-2.2 at 600°C, basing on all available PE-data.

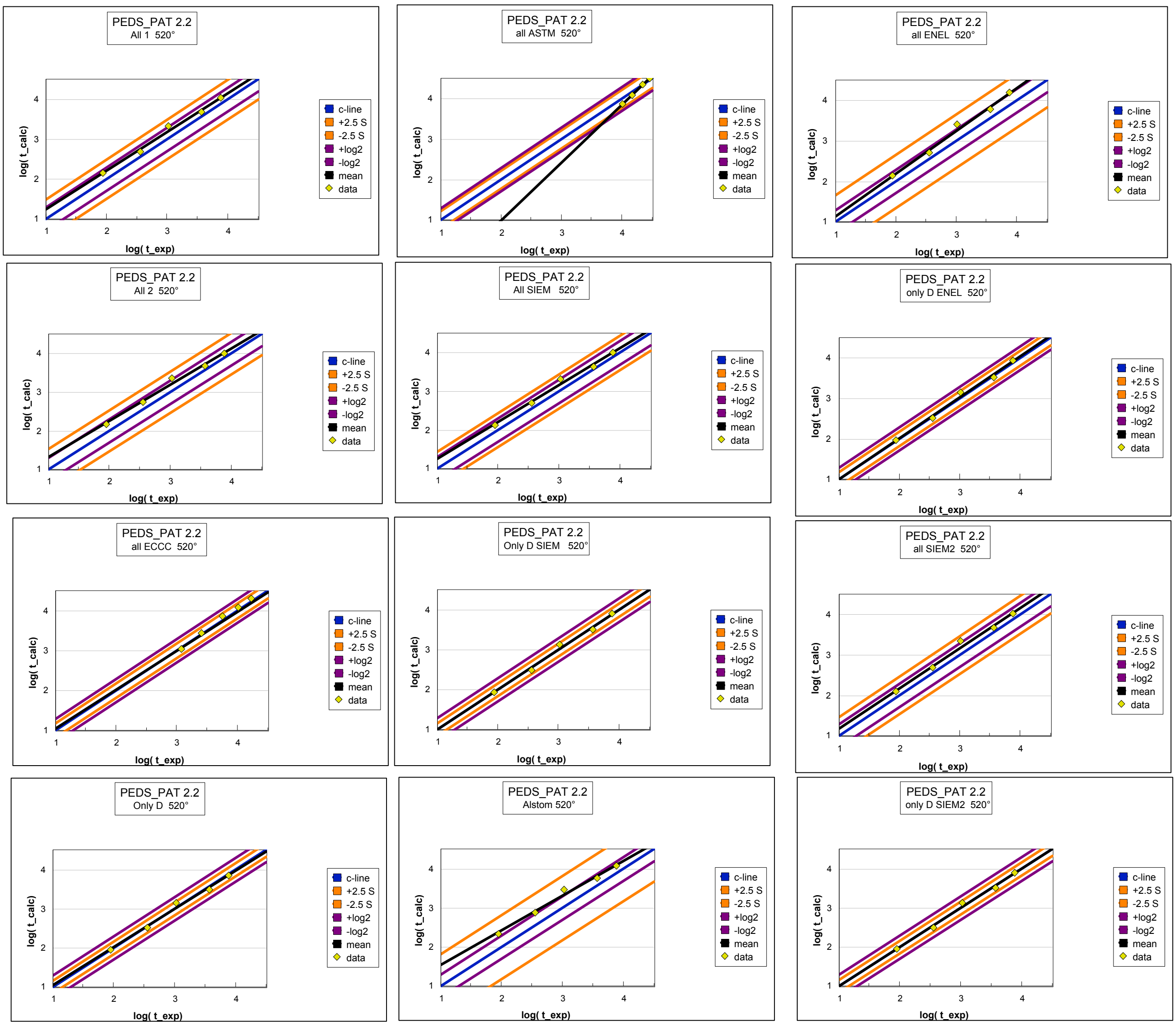

Figure 15: Check of PAT-2.2 at 520°C, basing on target component, pipe D, PE-data only.

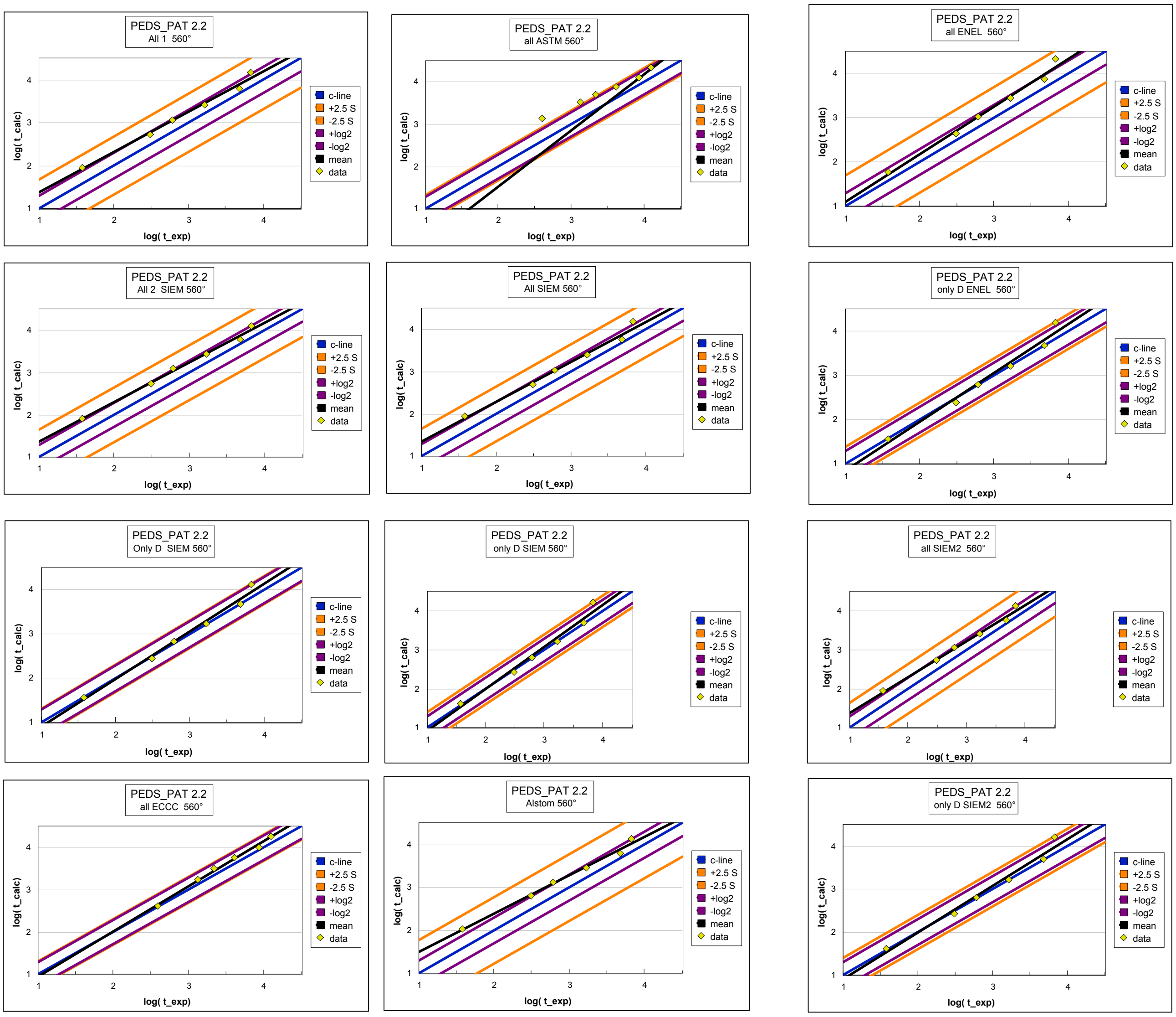

Figure 16: **Check of PAT-2.2 at 560°C, basing on target component, pipe D, PE-data only.**

Table IV: Details of results on PAT-2.1 and PAT-2.2, basing on all available PE-data.

PEDS-PAT 2.1

	Alstom	All SIEM	Only D SIEM	All 1	All2	Only D	All ECCC	All ENEL	Only D ENEL	Only D SIEM2	All SIEM2	All ASTM
points outside 2,5 $s_{[A-RLT]}$ boundaries	1	0	1	0	0	9	2	0	0	3	1	6
slope of linear regression mean line	0,85	0,84	0,89	0,85	0,86	0,89	0,95	0,99	0,95	0,89	0,88	0,87
standard deviation $s_{[A-RLT]}$	0,26	0,31	0,53	0,24	0,24	0,31	0,11	0,27	0,37	0,53	0,27	0,36
mean line contained within log2 boundaries	yes	yes	yes	yes	yes	yes	(yes)	yes	yes	yes	yes	yes

PEDS-PAT 2.2 520°

	Alstom	All SIEM	Only D SIEM	All 1	All2	Only D	All ECCC	All ENEL	Only D ENEL	Only D SIEM2	All SIEM2	All ASTM
points outside 2,5 $s_{[I-RLT]}$ boundaries	0	0	0	0	0	0	0	0	0	0	0	1
slope of linear regression mean line	0,77	0,83	0,87	0,84	0,81	0,85	0,85	0,92	0,88	0,87	0,87	1,13
standard deviation $s_{[I-RLT]}$	0,31	0,28	0,34	0,28	0,28	0,33	0,08	0,31	0,33	0,34	0,28	0,07
mean line contained within log2 boundaries	no	yes	no	yes	yes	no	yes	yes	no	no	yes	no

PEDS-PAT 2.2 560°

	Alstom	All SIEM	Only D SIEM	All 1	All2	Only D	All ECCC	All ENEL	Only D ENEL	Only D SIEM2	All SIEM2	All ASTM
points outside 2,5 $s_{[I-RLT]}$ boundaries	0	0	0	0	0	0	0	0	0	0	0	0
slope of linear regression mean line	0,88	0,93	1,09	0,93	0,93	1,08	1,07	1,07	1,1	1,09	0,92	1,33
standard deviation $s_{[I-RLT]}$	0,4	0,34	0,22	0,36	0,36	0,21	0,17	0,37	0,21	0,22	0,35	0,15
mean line contained within log2 boundaries	no	no	yes	no	no	yes	yes	no	yes	yes	no	no

PEDS-PAT 2.2 570°

	Alstom	All SIEM	Only D SIEM	All 1	All2	Only D	All ECCC	All ENEL	Only D ENEL	Only D SIEM2	All SIEM2	All ASTM
points outside 2,5 $s_{[I-RLT]}$ boundaries	0	0	0	0	0	0	0	0	0	0	0	0
slope of linear regression mean line	0,87	0,92	1,1	0,9	0,9	1,09	0,92	1,06	1,12	1,11	0,89	0,92
standard deviation $s_{[I-RLT]}$	0,21	0,23	0,34	0,22	0,21	0,34	0,09	0,24	0,36	0,34	0,23	0,07
mean line contained within log2 boundaries	yes	yes	no	yes	yes	no	yes	yes	no	no	yes	yes

PEDS-PAT 2.2 600°

	Alstom	All SIEM	Only D SIEM	All 1	All2	Only D	All ECCC	All ENEL	Only D ENEL	Only D SIEM2	All SIEM2	All ASTM
points outside 2,5 $s_{[I-RLT]}$ boundaries	0	0	0	0	1	0	0	1	0	0	0	0
slope of linear regression mean line	0,77	0,8	0,91	0,87	0,99	1,17	0,98	1,03	1,17	1,07	0,88	0,92
standard deviation $s_{[I-RLT]}$	0,4	0,35	0,28	0,22	0,23	0,44	0,14	0,34	0,5	0,44	0,25	0,23
mean line contained within log2 boundaries	no	no	no	yes	yes	no	yes	yes	no	no	yes	yes

Table V: Details of results on PAT-2.1 and PAT-2.2, basing on target component, pipe D, PE-data only.

PEDS-PAT 2.1

	Alstom	All SIEM	Only D SIEM	All 1	All2	Only D	All ECCC	All ENEL	Only D ENEL	Only D SIEM2	All SIEM2	All ASTM
Points outside 2,5 $s_{[A\text{-}RLT]}$ boundaries	0	0	0	0	0	0	0	0	0	0	0	0
slope of linear regression mean line	0.87	0.91	1	0.92	0.91	1	1.04	1.04	1.02	1	0.93	1.04
standard deviation $s_{[A\text{-}RLT]}$	0.32	0.21	0.05	0.23	0.24	0.05	0.09	0.23	0.06	0.05	0.22	0.09
mean line contained within log2 boundaries	no	(yes)	yes	yes	yes	yes	yes	no	yes	yes	yes	yes

PEDS-PAT 2.2 520°

	Alstom	All SIEM	Only D SIEM	All 1	All2	Only D	All ECCC	All ENEL	Only D ENEL	Only D SIEM2	All SIEM2	All ASTM
points outside 2,5 $s_{[I\text{-}RLT]}$ boundaries	0	0	0	0	0	0	0	0	0	0	0	0
Slope of linear regression mean line	0.88	0.96	1	0.97	0.93	0.97	0.97	1.06	1-01	1	0.96	1.43
Standard deviation $s_{[I\text{-}RLT]}$	0.33	0.18	0.07	0.2	0.21	0.07	0.08	0.27	0.07	0.07	0.19	0.09
Mean line contained within log2 boundaries	no	yes	yes	(yes)	yes	yes	yes	yes	yes	yes	yes	no

PEDS-PAT 2.2 560°

	Alstom	All SIEM	Only D SIEM	All 1	All2	Only D	All ECCC	All ENEL	Only D ENEL	Only D SIEM2	All SIEM2	All ASTM
points outside 2,5 $s_{[I\text{-}RLT]}$ boundaries	0	0	0	0	0	0	0	0	0	0	0	3
slope of linear regression mean line	0.89	0.94	1.09	0.94	0.94	1.09	1.07	1.08	1.11	1.09	0.93	1.34
standard deviation $s_{[I\text{-}RLT]}$	0.31	0.26	0.16	0.27	0.26	0.12	0.12	0.28	0.16	0.16	0.26	0.14
mean line contained within log2 boundaries	no	yes	no	yes	yes	yes	yes	no	yes	yes	yes	no

APPENDIX D

Recommendation Validation based on Creep Rupture and Strain PE-Data

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Index

1 Introduction

Residual Life Computation (CRL) is regarded being less reliable compared to the results of the on site inspection by non destructive controls, because in the majority of cases, "infinite" residual life is predicted.
The main causes for this belief are the small amount of data available from post exposure material belonging to the component under investigation but also the non appropriated assessment methods.
WG1.1 has among its goals to define methods to enhance CRL credibility, via enhancing the data set used for and via a series of post assessment tests (PATs), that on the basis of the ECCC Recommendations for virgin material confirm the reliability of the CRL.
In the past, 1998-2001, a first round robin showed, that by enhancing creep rupture data considering "similar" material, applying linear damage accumulation rules and using the PATs, all "infinite" predicting CRLs could be excluded due to objective criteria and that a credible final prediction could be made.

This third Round Robin has the aim to verify, if

- Further enhancement of experimental post exposure (PE-) data by adding the strain-time information leads to an improvement of the predicted residual life
- The actually in ECCC Recommendations Volume 5 Part III collated PATs for CRL do credibly check also the results of creep strain enhanced CRL.

2 Working Approach

The third Round Robin bases on the collation of data from a broad range of components, as shown in the following table:

Table I: Experimental Data Origin

Pipe	Pipe Origin	PE-Testing approach	Available points	Distribution	$t_{u,max}$ h
A	Power Plant	2 isotherms around T_{serv}	10	5 per isotherm	10000
B	Power Plant	2 isotherms around T_{serv}	10	5 per isotherm	11000
C	Power Plant	2 isotherms around T_{serv}	10	5 per isotherm	11000
D	Power Plant	2 isotherms around T_{serv}	10	5 per isotherm	8000
E	Power Plant	2 isotherms around T_{serv}	10	5 per isotherm	7000
F	Power Plant	2 isotherms around T_{serv}	10	5 per isotherm	11000
G	Power Plant	2 isotherms around T_{serv}	10	5 per isotherm	10000
H	Refinery	3 isostress curves around σ_{serv}	8	4, 2, 2, per isostress	4000
I	Refinery	2 isothermes above T_{serv}, material from 2 different sampling locations on the same pipe	6	3 per isotherm, 1 isotherm per sampling location	1000
J	Refinery	parametric curve around target life extension	4	-	1500
K	Refinery	1 isotherm above T_{serv}, material from two different sampling locations on the same pipe	6	3 per sampling location	3000
L	Refinery	3 isostress curves at and above σ_{serv}	18	8 or 5 per isostress line	5700
N	Power Plant	2 isotherms around T_{serv}	10	5 per isotherm	8000
O	Refinery	isotherm	3	3 points	7500
Q	Refinery	parametric	7	creep tests	1300
JAP	Power Plant	isotherm	10	Creep test	Rupture 10000 Cont. >15.000

The total set of data available to each assessors was made of all information used for the First Round Robin (only creep rupture data) enhanced by strain information for some components and by additional strain-time curves for new components (red in the following list) :

- Target component: Steam pipe of P22 (pipe D)
- Service conditions (T_{PE}, σ_{PE}, t_{u-PE}) for all components
- Information on microstructural status and structural integrity
- Available creep data
  - PE data of pipe D with strain-time curves
  - PE data from other power utility steam pipes in P22, some with strain-time curves, including new components, one with very long creep tests (>15.000 h)
  - PE data from refinery pipes serviced in similar conditions
  - virgin material creep data collated by ECCC or other reliable sources
  - virgin material creep data collated by ASTM
  - creep rupture strength as per DIN 17175 and ECCC

The next Table II shows the available service conditions and the detail of the strain-time data for each component

Table II: Details of the available creep strain data

Material	Service Temperature	Service stress	Service time	Plant	Curves	files
	° C	MPa	h			
A	538	34	144000	Power Plant Pipe	0	
B	538	34	131000	Power Plant Pipe	0	
C	538	37	130000	Power Plant Pipe	0	
D	540	38	88050	Power plant pipe	10	D-VP-520, D-VP-560
	540	38	88050	Power Plant pipe	10	D-VRC-520 D-VRC-560
E	540	37	80000	Power Plant pipe	0	
F	540	34	80000	Power Plant pipe	0	
G	540	34	80000	Power Plant pipe	0	
H	535	55	121000	Refinery pipe	0	
I	540/550	35	83000	Refinery pipe	0	
J	535	35	106000	Refinery pipe	0	
K	520/540	50/45	154000	Refinery pipe	0	
L	540	40	114000	Refinery pipe	15	L, L-40, L-55, L-70
N	540	38	ca. 150000	Power plant pipe	8	N-520, N-560
O	525	32	ca. 100000	refinery tube	7	O-3curve, O-4curve
Q	535	45	ca. 100000	refinery tube	3	Q
Jlit*	577	34	195000	power plant	8	JLit

As a total

- 147 creep rupture data points of 12 “similar components”, 109 of which also available to the first Round Robin
- testing times >10000 h (broken), >15000 h (unbroken)
- 55 creep strain curves for 7 components out of the 12.
- 8 creep strain curves for target component Pipe D

Each assessment was targeted to provide proven evidence for the two following questions:

A) Can pipe D be serviced safely for another 50.000 h in the actual service conditions?
B) When is the failure of pipe D in service conditions to be expected?

3 Assessments

During the Round Robin 13 assessments were prepared by three different assessors. They all base on MPC’s Omega Method in different modifications and using different data for the derivation of the constants:

Name	Assessment Description	Data set used
ISB_OmPoli	Omega Method following Prager’s original proposal	All PE-strain-time data
ISB_OmPara	Omega Method describing Ω parametrically	
ISB_OmRLAPoli	Like ISB_OmPoli, but the data pre-conditioned by a linear damage accumulation rule	
ISB_OmRLAPara	Like ISB_OmPara, but the data pre-conditioned by a linear damage accumulation rule	
EON	Omega method modified by EON	All PE-strain-time data
EON2		All PE-strain-time data with $T<650$°C
EON3		Virgin material from 2021 project
EON4		2021+ All PE-strain-time data at low stress
EON5		2021 + All PE-strain-time data at low stress and $T<650$°C
EON6		2021 All PE-strain-time data with $\sigma < 70$ MPa
IIS	API RP 579 Omega Method, complex Ω function	Only Pipe D strain-time data
IIS2	API RP 579 Omega Method, simple Ω function	Only Pipe D strain-time data
IIS2 ref	Like IIS2 but applying full API RP579 method	Only Pipe D strain-time data

The assessment results were made available for the present result summary via a full set of equations and all needed constants that relate stress, temperature and time to failure. Details of the available formulae are given for all assessments in the appendix.

4 Post Assessment Tests

ISB applied the Post Assessment Tests according to ECCC Recommendations Volume 5 part III, being aware that these tests were meant for assessments dealing with rupture data only. On the other hand, in CRL, no direct strain prediction is generally looked for, but strain-time information is used for an enhanced time to rupture prediction, so that the rupture data related PATs are suitable for a first guess.

ISB additionally used the PAT automation program ePAT, as prepared by ECCC WG1, but being the acceptance criteria for virgin material slightly different than for CRL, re-interpreted some of the results, mainly in PAT2.1 and 2.2, in order to comply with Volume 5 part III.
Also ePAT does not include PAT1.1b, which is relevant only to CRL. So these PATs have been done manually by ISB.
PAT 3 cannot be assessed commonly because it requires the repetition of a part of the assessment. Here data was used as far as available

As PATs need raw data for comparison, all assessments were checked against different data sets:

“all data”:	Data set including all PE-data (147 rupture points)
“limited – ltd – Data”:	Data set including just the strain-time points
“only D –all”:	Data related just to Pipe D, as being part in the original data set
“only D –ltd”:	Data related just to Pipe D, including only the strain-time data

All results of the PATs for each method and data set are included in the appendix under the appropriated assessment.
PAT 2.1 and 2.2 are also summarised in the tables at the end of the appendix.

5 Results

The following tables gives a rough overview on the results:

Table III: PAT results

PAT	T [°C]	Data set	ISB_poli	ISB_para	ISB_RLApoli	ISB_RLApara	EON	EON2	EON4	EON5	EON6	IIS	IIS2
1.1a	-	All data	Ok	(Ok)	Ok	No	Ok	Ok	No	No	Ok	(ok)	Ok
1.1a		Ltd data	Ok	(Ok)	Ok	Ok	Ok	(ok)	Ok	(ok)	Ok	ok	(ok)
1.1b	520		No	No	No	No	No	No	No	Ok	Ok	No	No
1.1b	560		No	No	No	No	No	No	Ok	Ok	Ok	No	No
1.2			Ok	No	Ok	No	ok	ok	Ok	Ok	Ok	Ok	Ok
1.3			Ok	(ok)	Ok	No	No	No	Ok	Ok	Ok	Ok	(ok)
2.1		All data	Ok	No	Ok	No	No	No	No	No	No	No	Ok
2.1		Ltd data	Ok	Ok	Ok	Ok	No	No	No	No	No	Ok	Ok
2.2	520-	OnlyD /all	Ok	Ok	Ok	Ok	No	No	No	No	No	Ok	Ok
2.2	520-	OnlyD /ltd	Ok	(ok)	Ok	Ok	Ok	(ok)	No	No	No	Ok	Ok
2.2	520-	Ltd data	Ok	Ok	Ok	Ok	No	(ok)	No	No	No	Ok	Ok
2.2	520-	All data	No	No	Ok	No	No	No	No	No	No	No	No
2.2	560-	OnlyD /all	Ok	Ok	Ok	Ok	No	No	No	No	Ok	Ok	Ok
2.2	560-	OnlyD /ltd	Ok	No	Ok	No	(ok)	Ok	No	Ok	(ok)	No	No
2.2	560-	Ltd data	(Ok)	(Ok)	Ok	Ok	Ok	(ok)	Ok	Ok	Ok	Ok	Ok
2.2	560-	All data	Ok	Ok	Ok	Ok	ok	Ok	ok	Ok	ok	Ok	Ok
3.1		Ltd data	Ok	Ok	-	-	-	-	-	-	-	-	-
3.2		Ltd data	ok	Ok	-	-	-	-	-	-	-	-	-
Total			No	No	No	No	No	No	No	No	No	No	No

No assessment is able to comply with all PATs contemporaneously. Even if considering only one type of data set, no assessment passes all PATs.
Main problems arose in passing PAT 1.1b (9 assessments failed), PAT 2.1 considering all data (8 assessments), PAT 2.2 at 520°C, considering all data (10 assessments failed)

Table IV: Overview of Results from First and Third Round Robin

CRL Assessment Name	Used CRL Method	Used data	Pipe D: further service for 50kh	Estimate of true life end [h]	
				PATs not successful	PATs succesfull
Only D, Only D, E Only D SIEM Only D SIEM2	Parametric Parametric Parametric Parametric	PE data only of Pipe D	Si Si Si Si	2.8M 32M 17M 17M	
All SIEM	Parametric	PE data of power utility steam pipes	Si	6.5M	
All2, A All1, All SIEM2, All E	Parametric PD6605 Parametric Parametric Parametric	all PE-data	Si Si Si Si Si	 800k 1.4M 1.7M 6.9M	330k
All ECCC All ASTM	LDAR based on ECCC + Parametric LDAR based on ASTM + Parametric	all PE data after suitable "assimilation" process	Si Si	 790k	200k
Omega Poli	Strain based MPC Omega Method (polynomial descr.)	all PE creep strain data	Si	2,5M	
Omega Para	strain based MPC Omega Method (parametric descr.)		Si	Na	
Omega E	Strain based modified MPC Omega method		Si	90k	
Omega E2		PE data with T < 650°C	Si	120k	
Omega E4		2021 data + low stress PE data	si	175k	
Omega E5		2021 data + low stress PE data with T<650°C	si	182k	
Omega E6		2021 data + PE data with σ < 70 MPa	si	240k	
Omega I	Strain based API RP 579 Omega method	only pipe D 520/560°C	Si	32 M	
Omega I2			Si	105 M	
Omega I2-ref	Full API RP 579		Si	152 M	na
Omega PoliLDAR	LDAR/ECCC +Omega Poli	all PE creep strain after suitable "assimilation"	Si	400k	
Omega Para LDAR	LDAR/ECCC + Omega Para		Si	Na	Na
New ASTM	ISO 6303	virgin material ASTM	Si	204k	
New ECCC	DESA	virgin material ECCC	Si		240k
New Omega E3	Strain based modified MPC Omega method	Virgin material 2021 project	Si	203k	?
IS	circolare ISPESL 15/92	creep strength acc. DIN 17175	Si	1,2M	
Original E	Limite di accettabilità	virgin ASTM + PE data pipe D	Si		>50k
Variability				Factor 1000	Factor 1,65

Being the data sets of the first and third round robin compatible, a direct comparison of the results is allowable (Table IV):

A) All assessments allow pipe D to continue service for another 50.000 h

B) Predicted rupture time is very variable (90 k to ca. 100 M hours)
C) Predicted rupture time on just creep rupture data is 200 k to 32 M, including creep strain, the range enlarges to 90 k to 100 M hours.
D) Some only on creep rupture data basing assessments comply with all the PATs
E) Methods using "enhanced" data sets are more likely to pass PATs.
F) No strain based assessment, in spite of results close to those of the assessments being successful with the PATs, passes all PATs.
G) The predicted rupture time among the PAT passing assessments is in a much closer range (200k – 330k hours).

6 Conclusions

At the moment it is felt, that the PATs as stated in Volume 5 part III are acceptable and credible.
The strain induced enhancement on prediction credibility could not be proved, but this could be due to the fact, that only one method (MPC Omega), even if in 12 different modifications, has been really tested. Other assessment method are recommended to be included as soon as possible.

ANNEX to APPENDIX D of Volume 5 Part III [issue 2]
(G. Merckling)

Detail on the Post Assessment Test Results for all Checked Assessments

<table>
<tr><td>EON2</td><td>All PE data with T<650°C</td></tr>
<tr><td>

$$\sigma = 5958{,}55\ A^{-3{,}49886}$$

$$A = T[K](2{,}8 + \log\{\Omega\})$$

$$t_u = \frac{1}{\Omega \varepsilon_0^{\bullet}}$$

</td><td>

Low stresses: σ < 73,7 MPa

$$\ln\{\varepsilon_0^{\bullet}\} = 21{,}2564 + 4{,}1687\ln\{\sigma\} - \left[\frac{86.661{,}78}{1{,}9859\,T[K]}\right]$$

High Stress:

$$\ln\{\varepsilon_0^{\bullet}\} = -8{,}6552 + 11{,}1857\ln\{\sigma\} - \left[\frac{86.661{,}78}{1{,}9859\,T[K]}\right]$$

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<tr><td>PAT1.1a – all data</td><td>PAT1.1a – limited data</td></tr>
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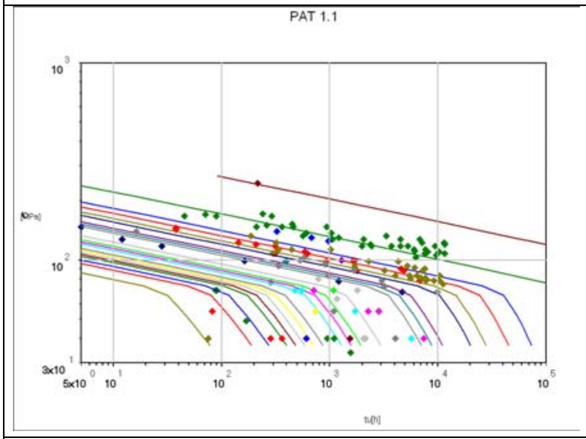

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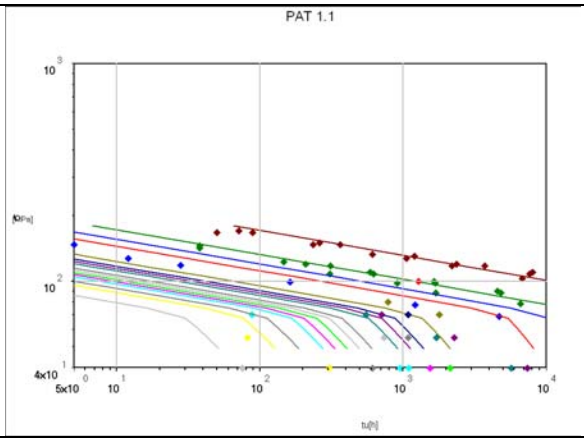

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<tr><td>PAT1.1b 520°C</td><td>PAT1.1b 560°C</td></tr>
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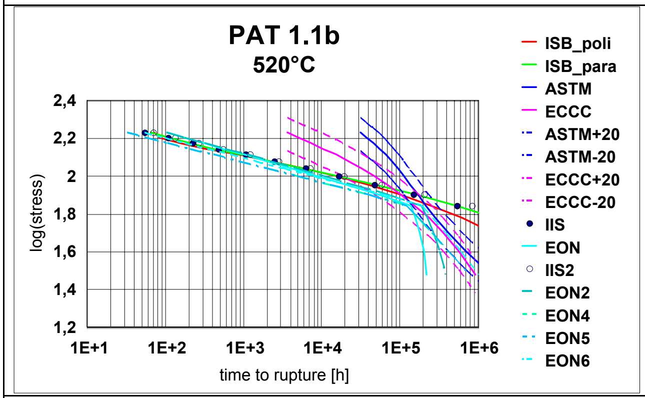

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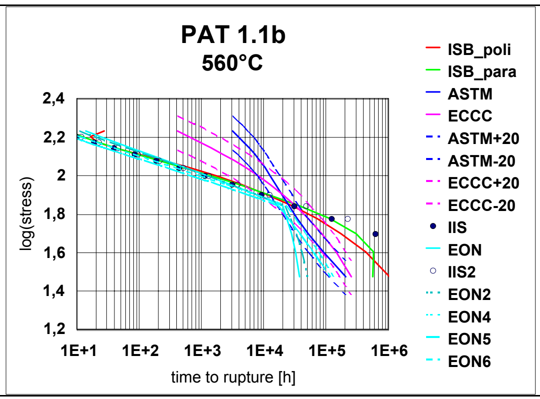

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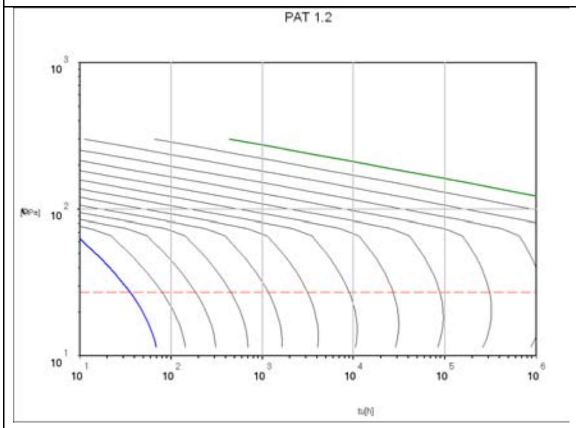

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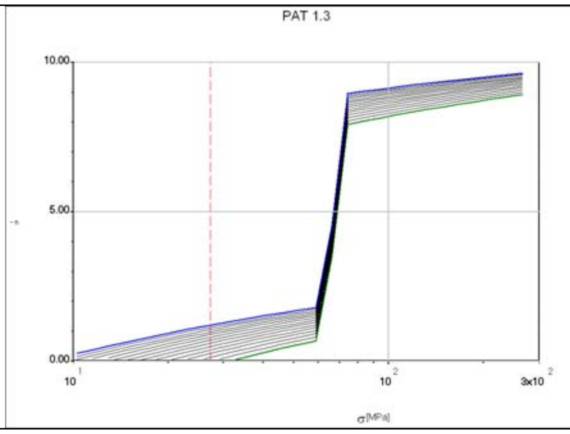

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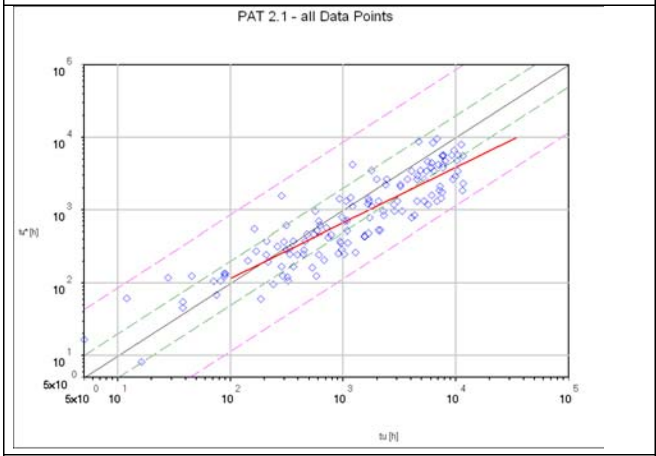
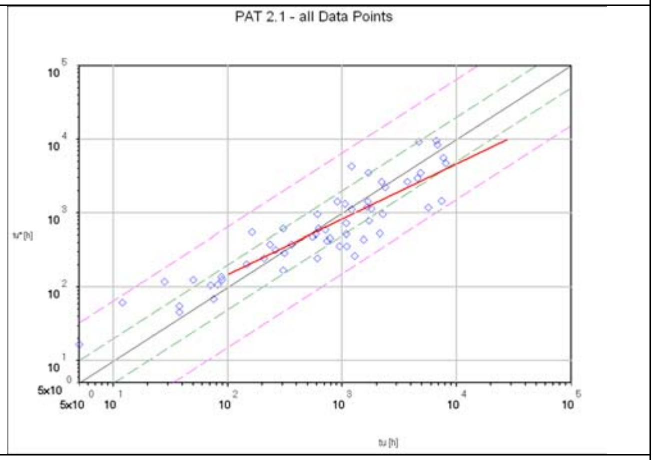
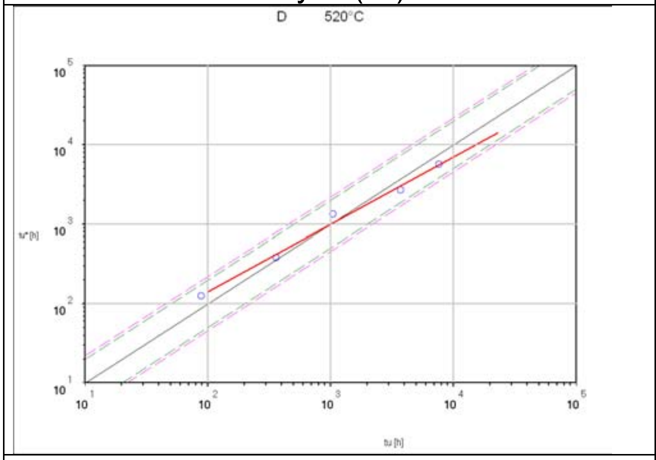
EON2



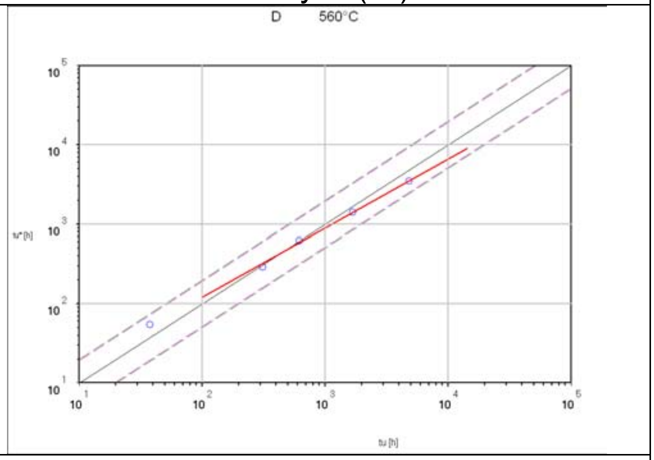
All PE data with T<650°C



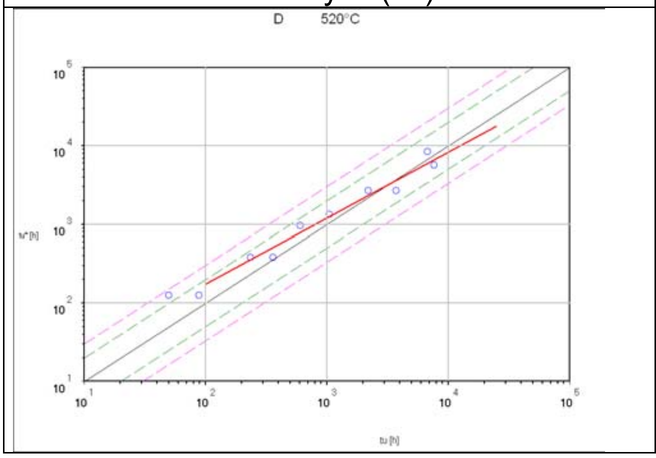
PAT2.2 520°C – only D (all)



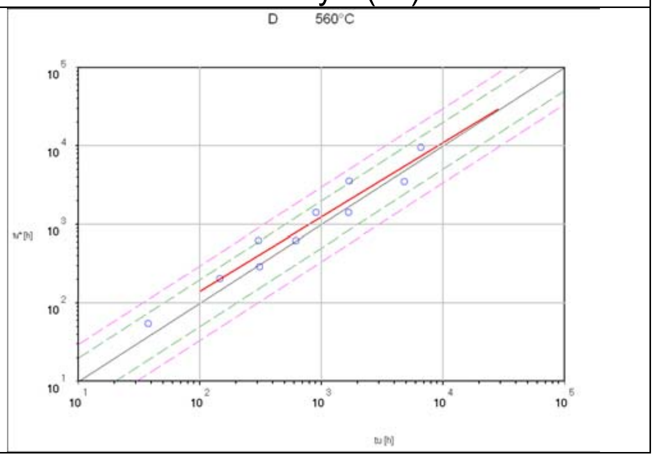
PAT 2.2 560°C – only D (all)

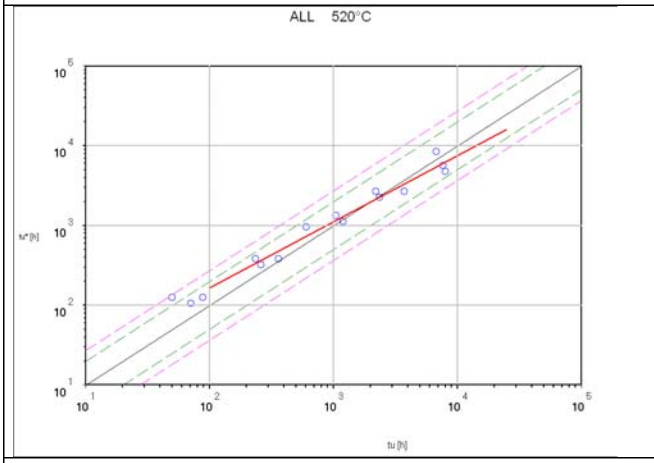
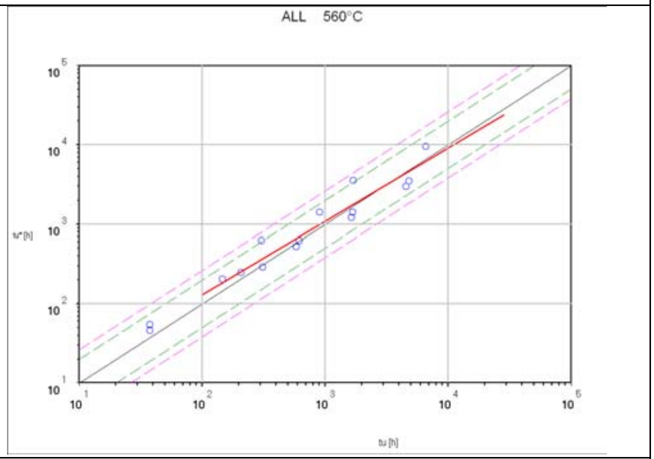
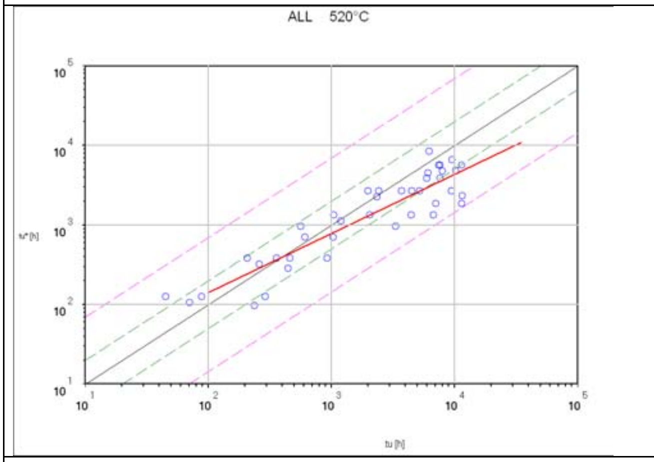
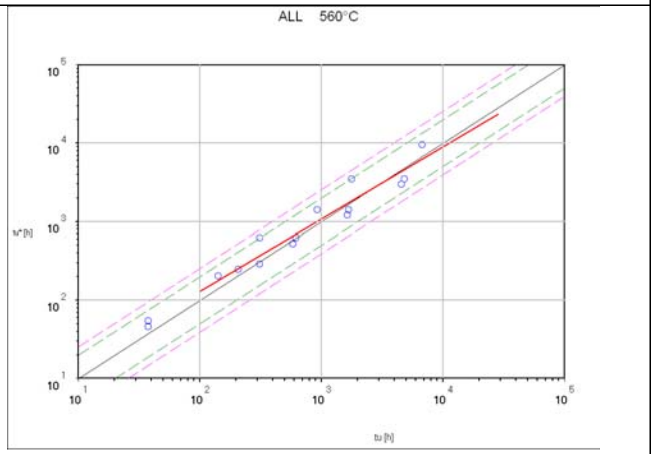


PAT2.2 – 520°C – only D (ltd)



PAT2.2 – 560°C – only D(ltd)



PAT2.2 – 520°C – ltd. data	PAT 2.2 – 560°C – ltd. data
	
PAT2.2 – 520°C – all data	PAT 2.2 – 560°C – all data
	
PAT3.1	PAT3.2
Not done	Not done

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$$\sigma = 13062647{,}91\, A^{-7{,}5544}$$

$$A = T[K](4{,}4 + \log\{\Omega\})$$

$$t_u = \frac{1}{\Omega \varepsilon_0^{\bullet}}$$

</td><td>

Low stresses: σ < 73,7 MPa

$$\ln\{\varepsilon_0^{\bullet}\} = 21{,}2564 + 4{,}1687 \ln\{\sigma\} - \left[\frac{86.661{,}78}{1{,}9859\, T[K]}\right]$$

High Stress:

$$\ln\{\varepsilon_0^{\bullet}\} = -8{,}6552 + 11{,}1857 \ln\{\sigma\} - \left[\frac{86.661{,}78}{1{,}9859\, T[K]}\right]$$

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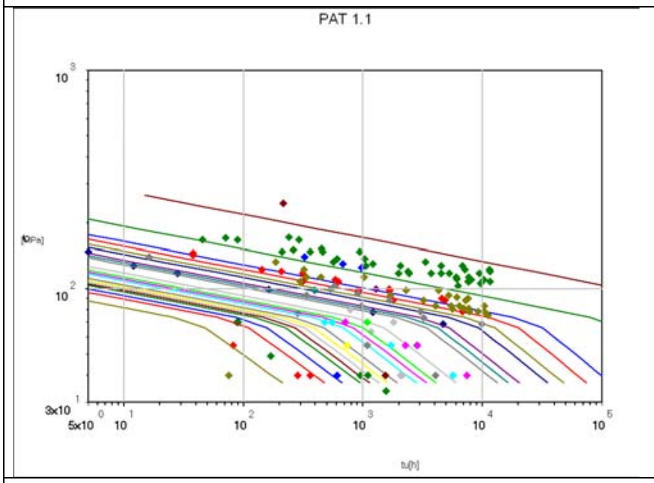
<tr><td></td><td></td></tr>
<tr><td>PAT1.1a – all data</td><td>PAT1.1a – limited data</td></tr>
<tr><td>



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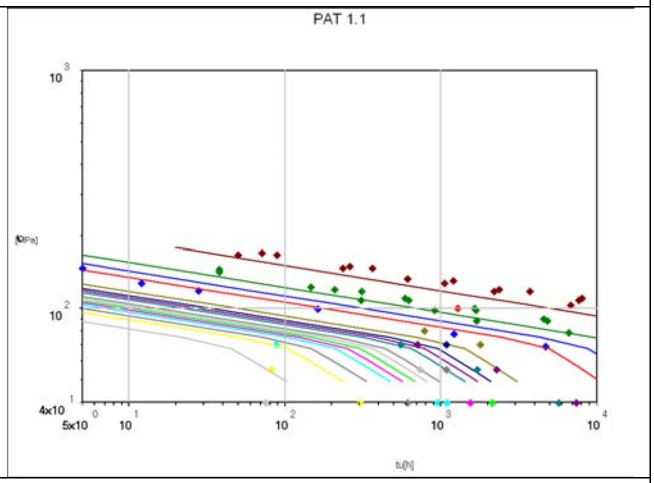

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<tr><td>PAT1.1b 520°C</td><td>PAT1.1b 560°C</td></tr>
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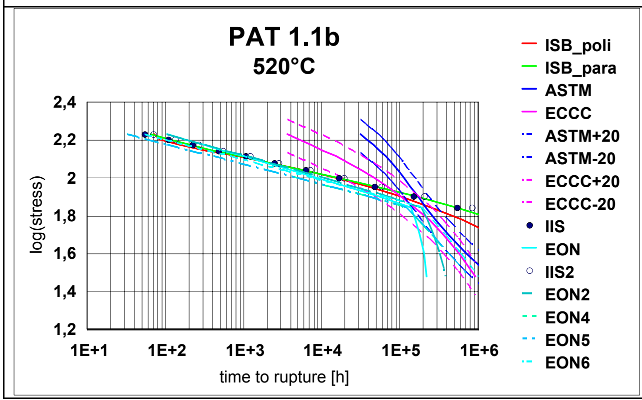

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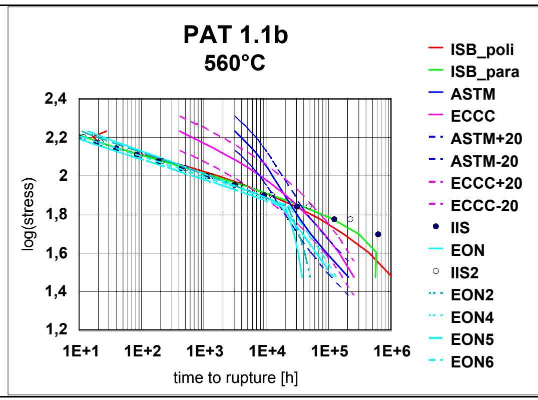

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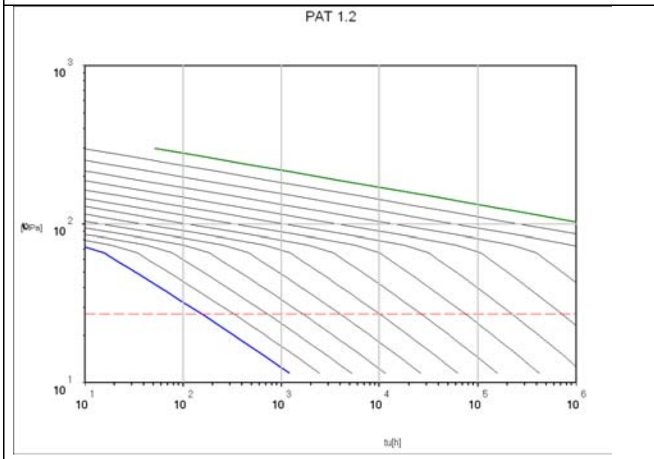
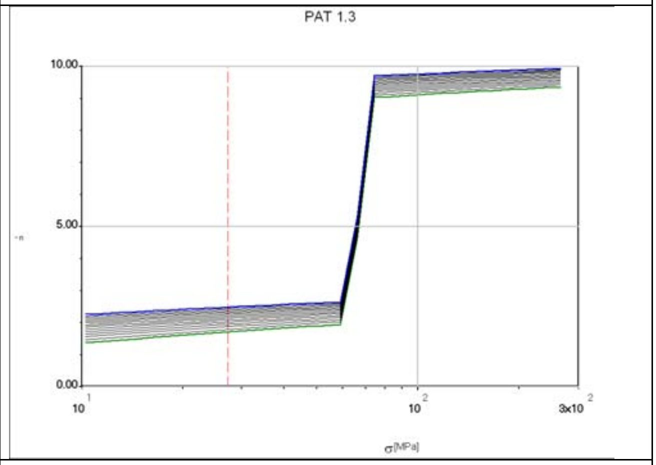
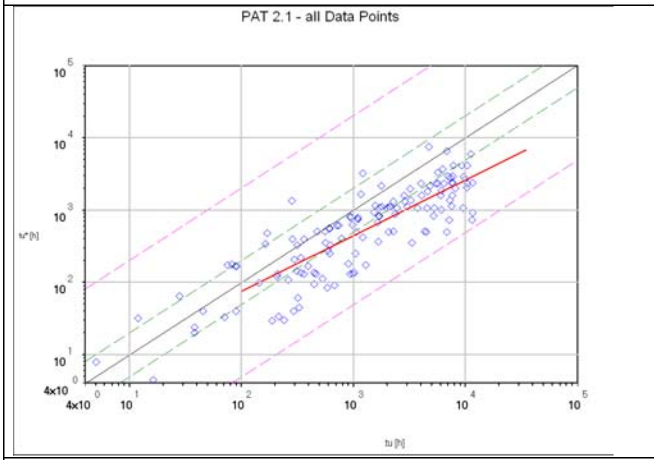
PAT1.2



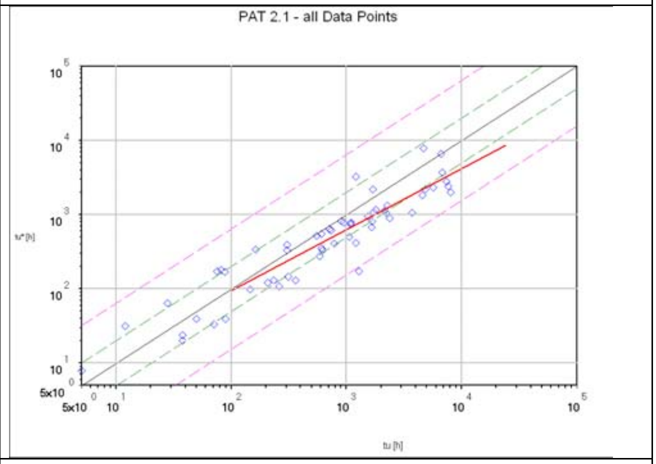
PAT1.3



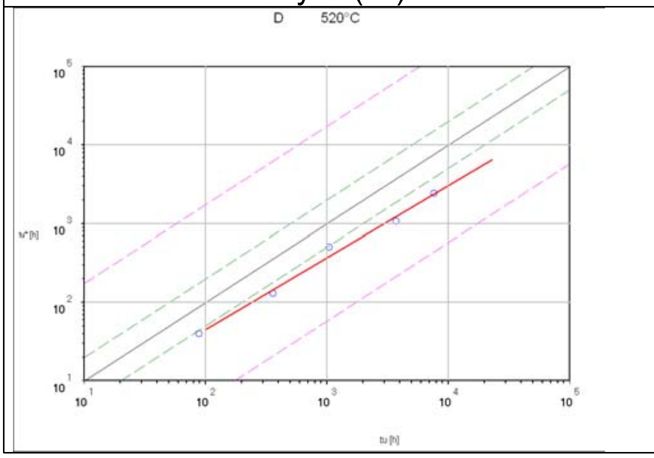
PAT2.1 – all data



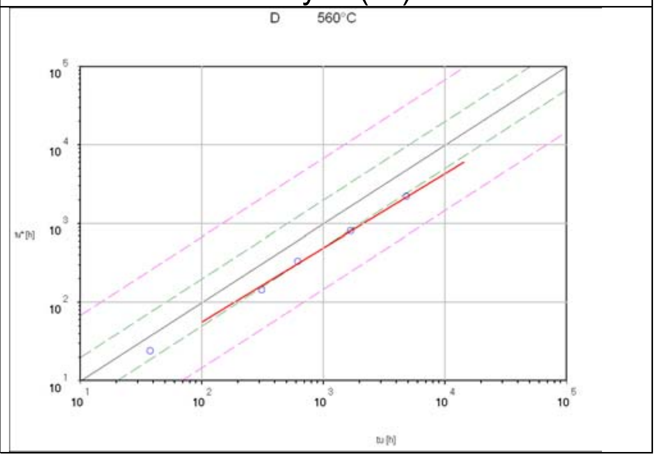
PAT 2.1 – ltd. data

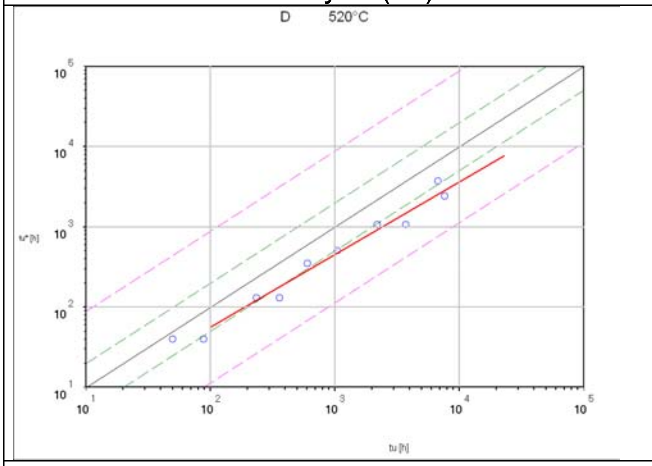
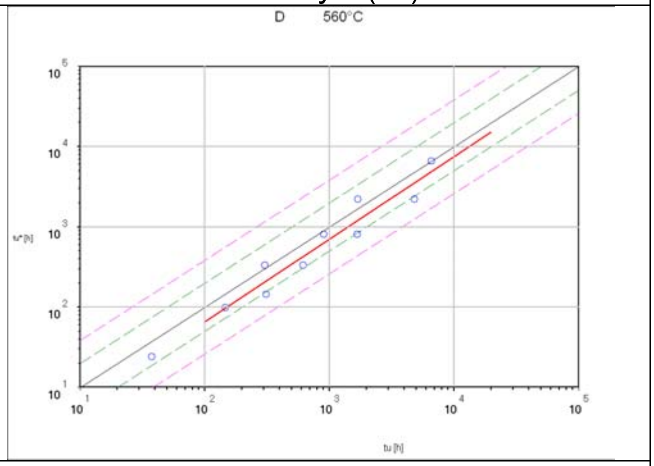
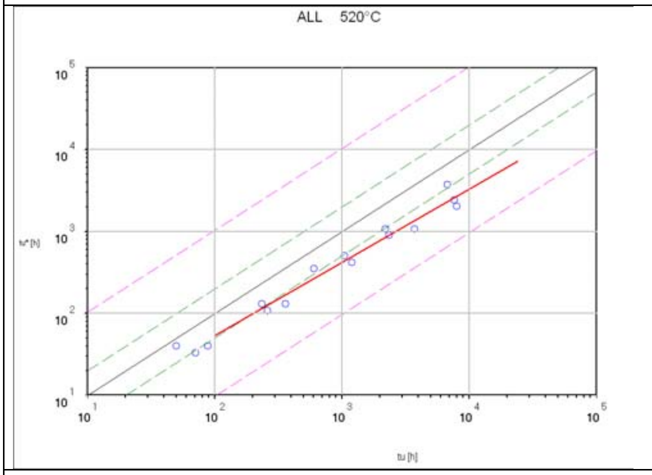
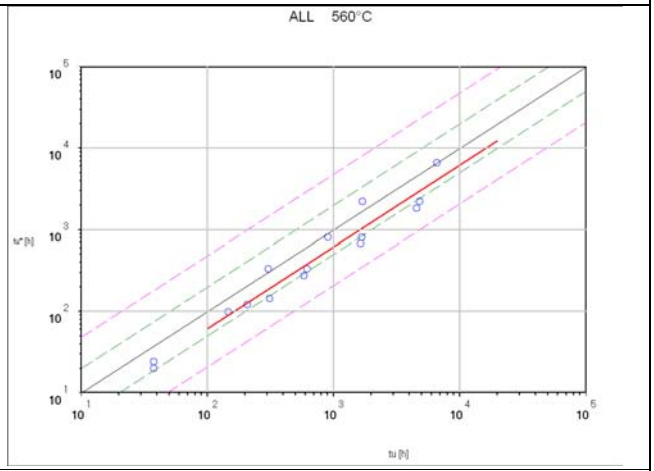
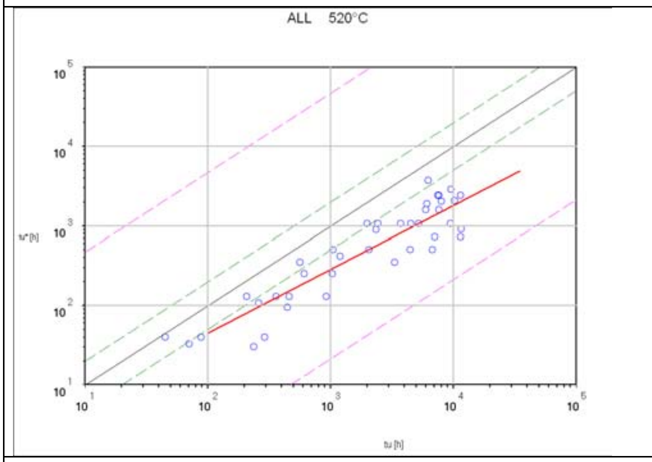
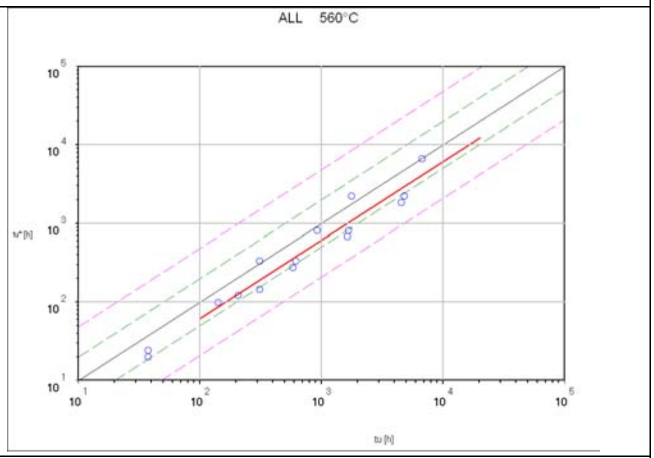


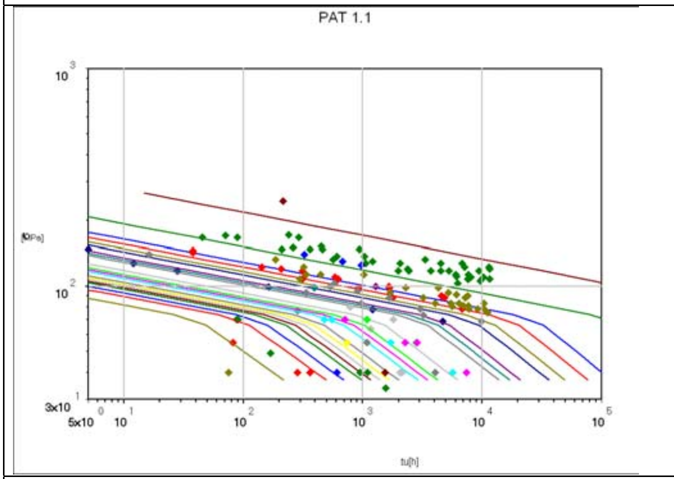
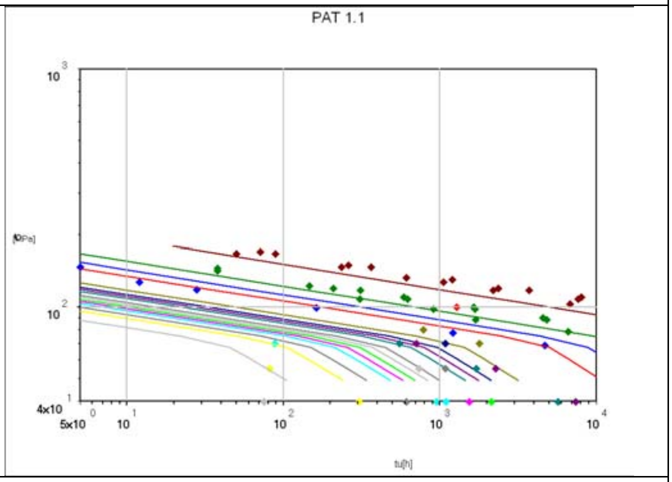
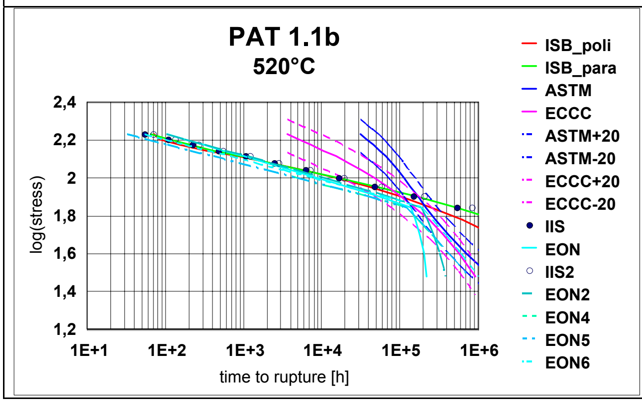
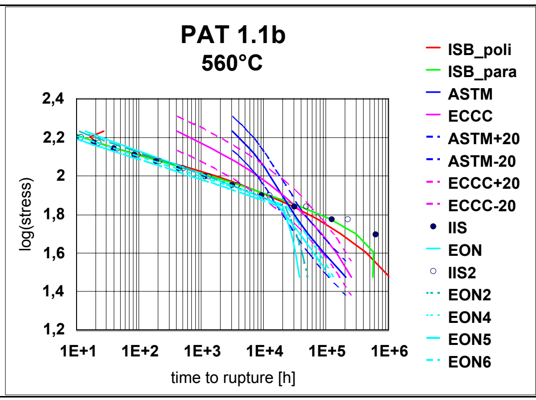
PAT2.2 520°C – only D (all)



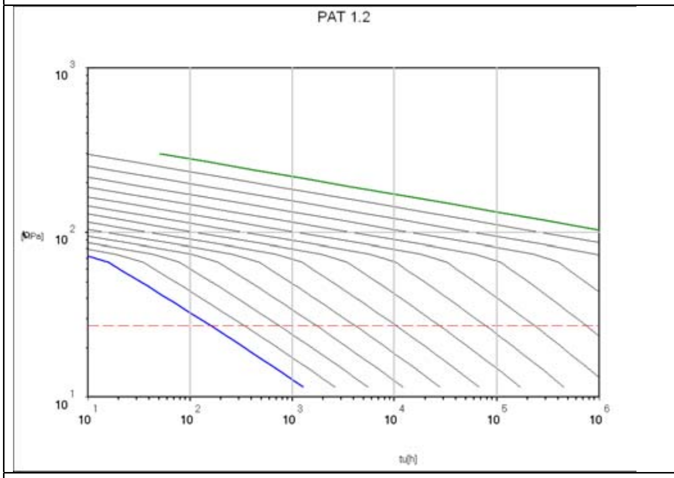
PAT 2.2 560°C – only D (all)



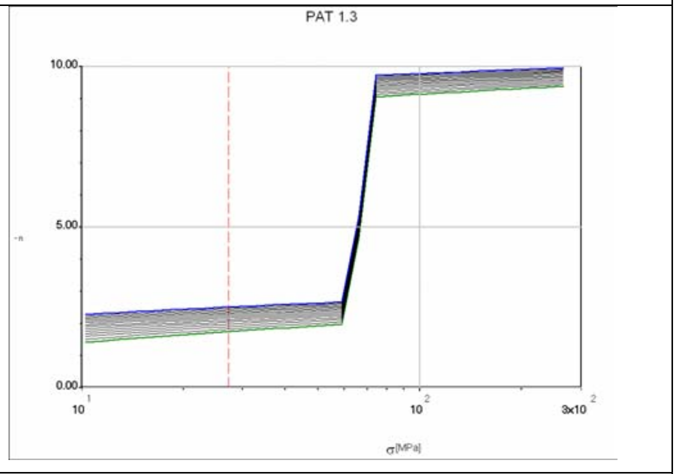
PAT2.2 – 520°C – only D (ltd)	PAT2.2 – 560°C – only D(ltd)
	
PAT2.2 – 520°C – ltd. data	PAT 2.2 – 560°C – ltd. data
	
PAT2.2 – 520°C – all data	PAT 2.2 – 560°C – all data
	
PAT3.1	PAT3.2
Not done	Not done

EON5	2021 data + low stress PE data with T<650°C
$\sigma = 15085728\, A^{-7,64926}$ $A = T[K](4{,}4 + \log\{\Omega\})$ $t_u = \frac{1}{\Omega \dot{\varepsilon}_0}$	Low stresses: σ < 73,7 MPa $\ln\{\dot{\varepsilon}_0\} = 21{,}2564 + 4{,}1687 \ln\{\sigma\} - \left[\frac{86.661{,}78}{1{,}9859\, T[K]}\right]$ High Stress: $\ln\{\dot{\varepsilon}_0\} = -8{,}6552 + 11{,}1857 \ln\{\sigma\} - \left[\frac{86.661{,}78}{1{,}9859\, T[K]}\right]$
PAT1.1a – all data	PAT1.1a – limited data
	
PAT1.1b 520°C	PAT1.1b 560°C
	

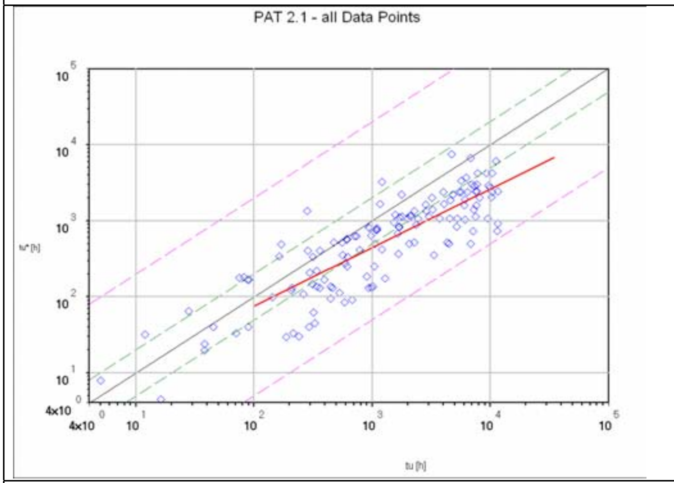
PAT1.2



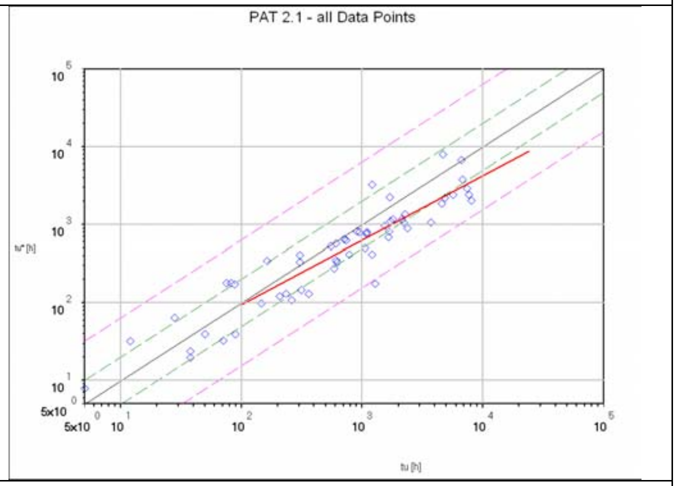
PAT1.3



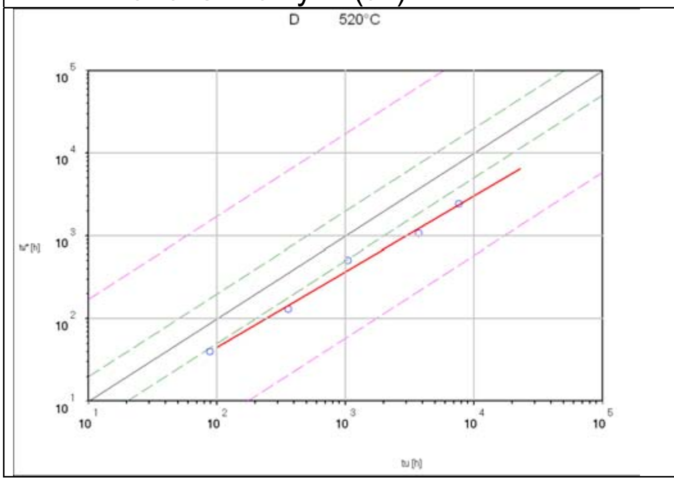
PAT2.1 – all data



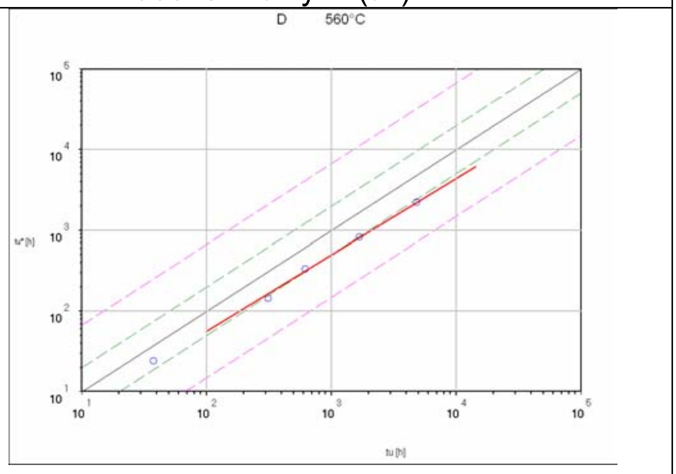
PAT 2.1 – ltd. data

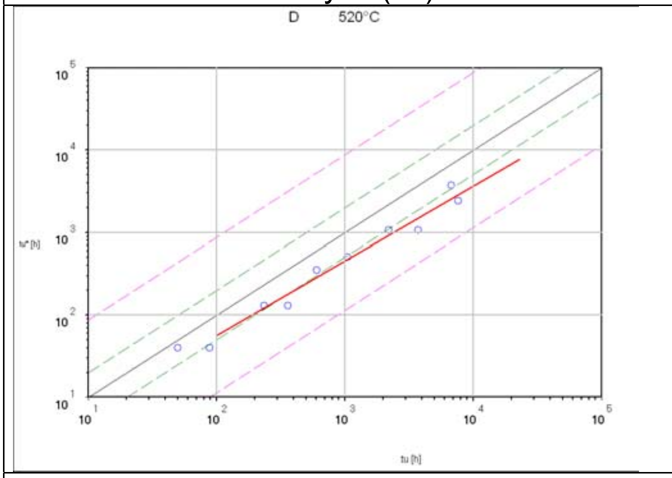
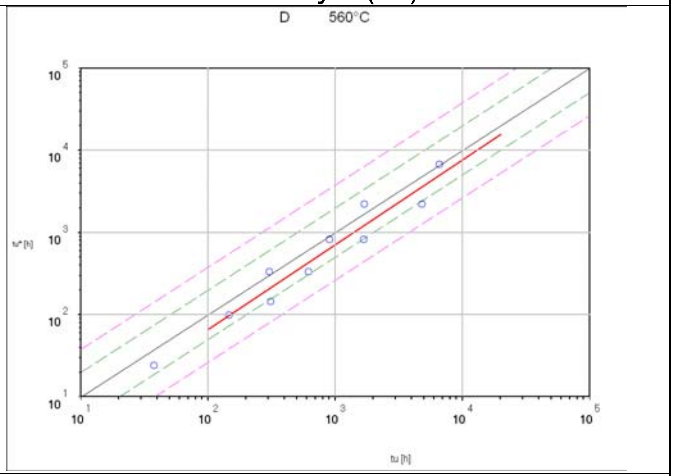
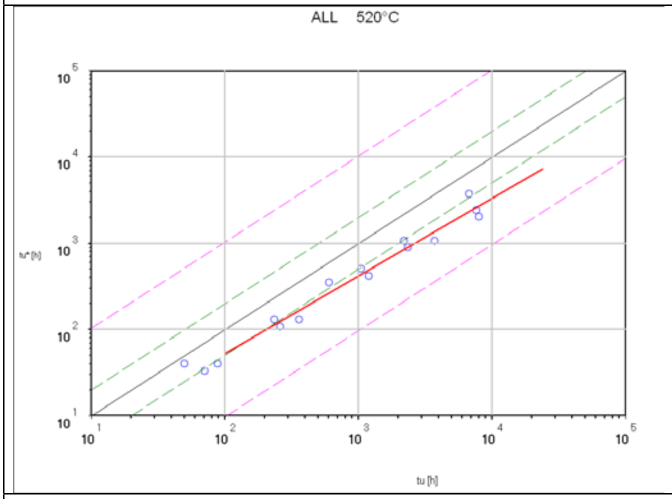
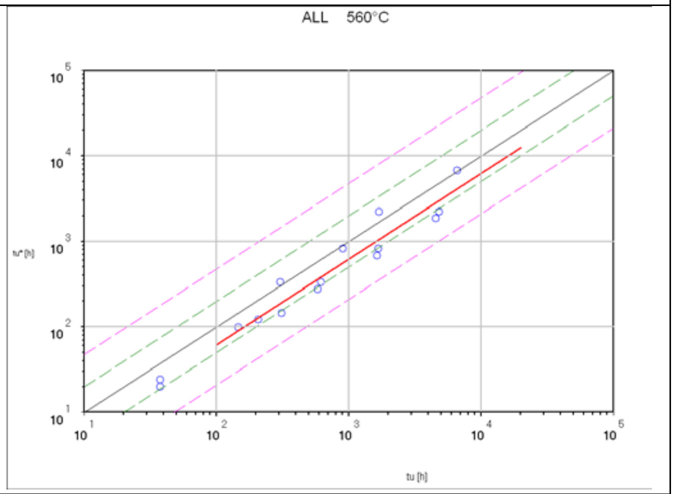
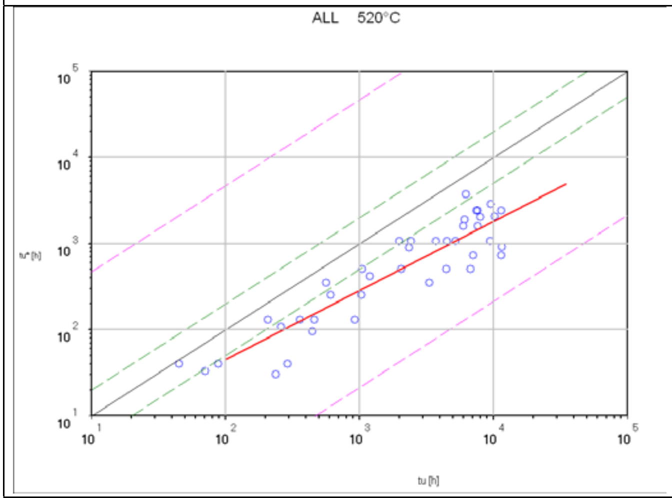
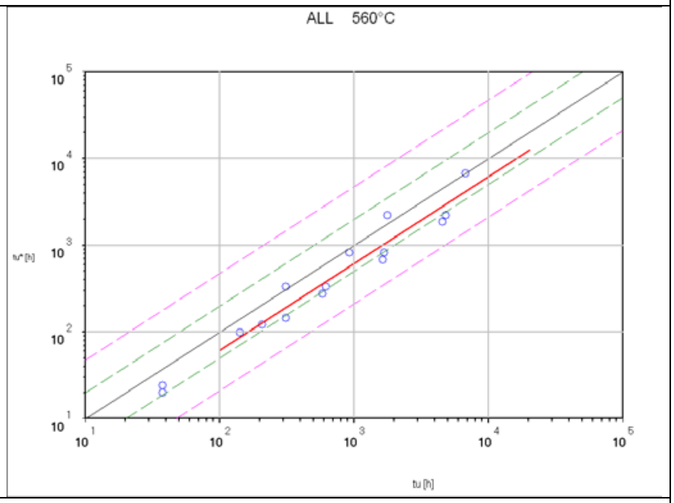


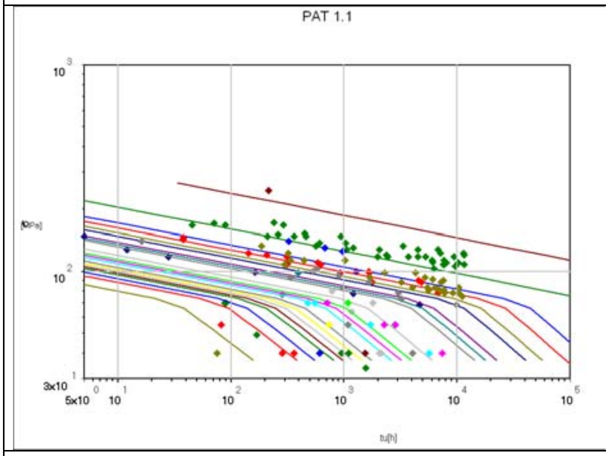
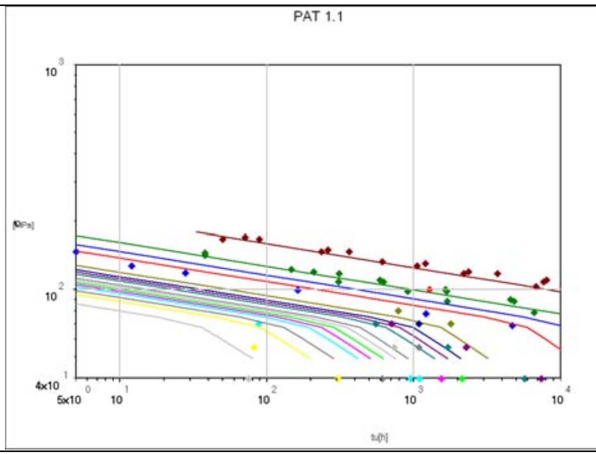
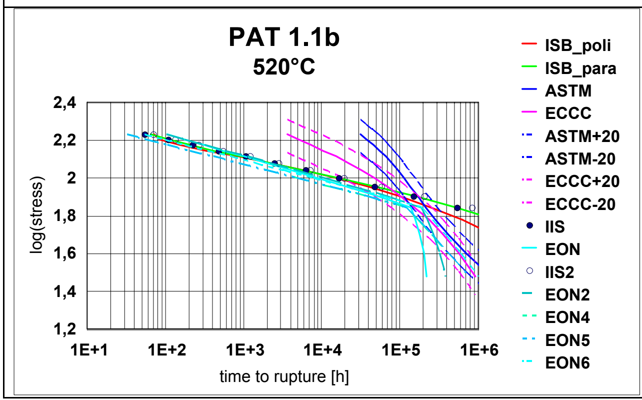
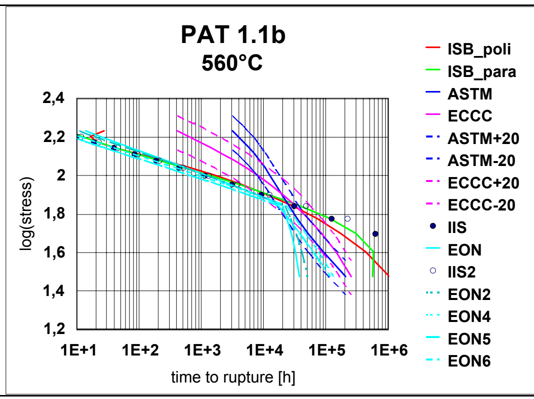
PAT2.2 520°C – only D (all)

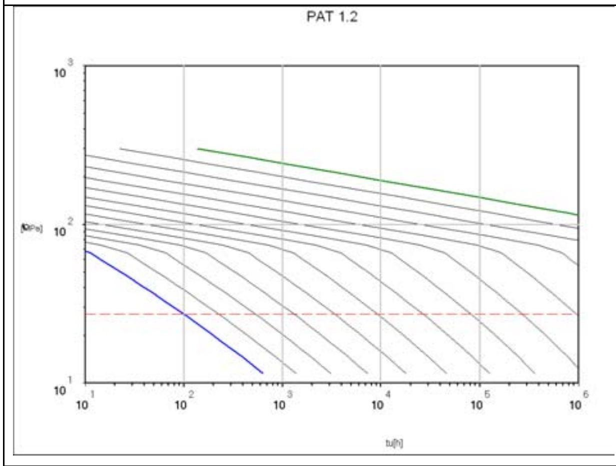
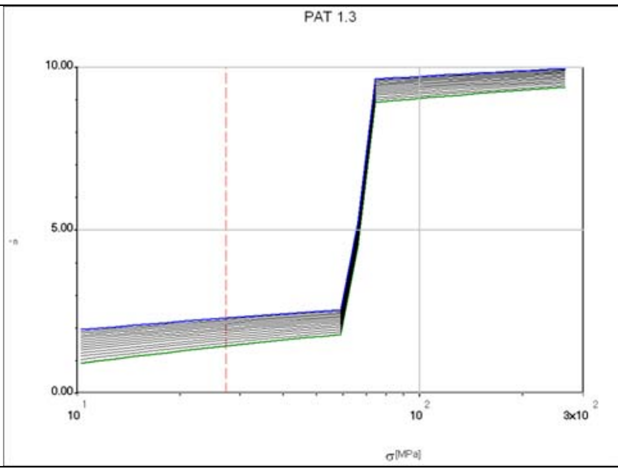
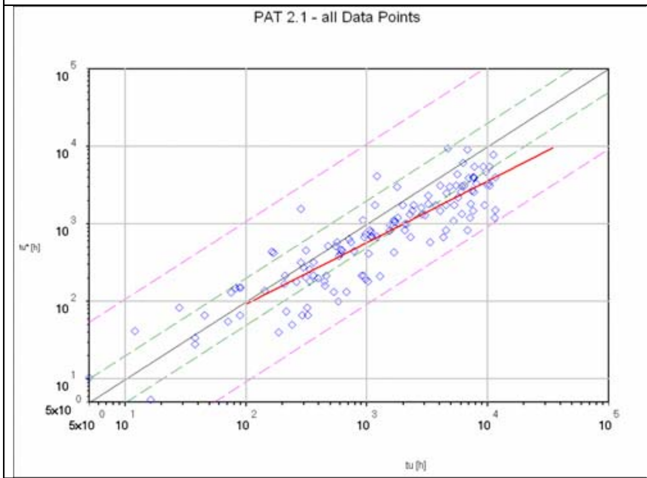
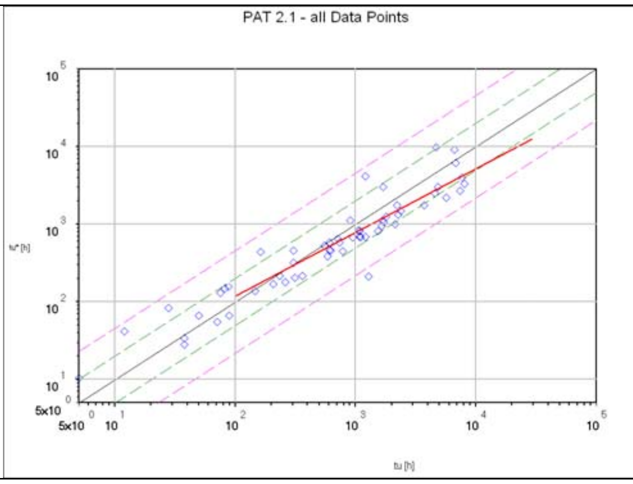
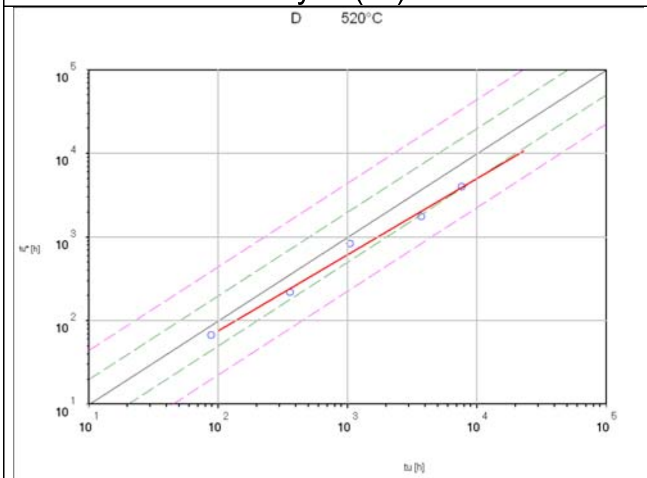
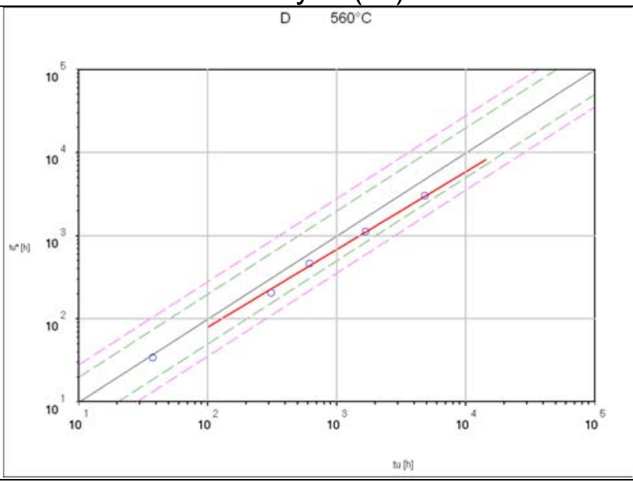


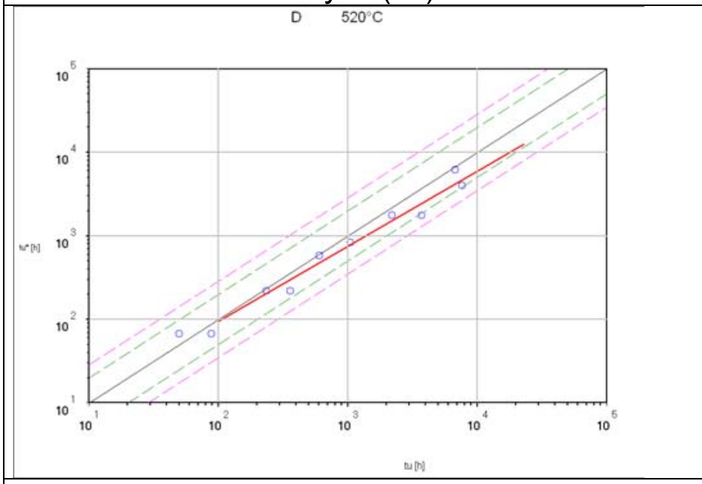
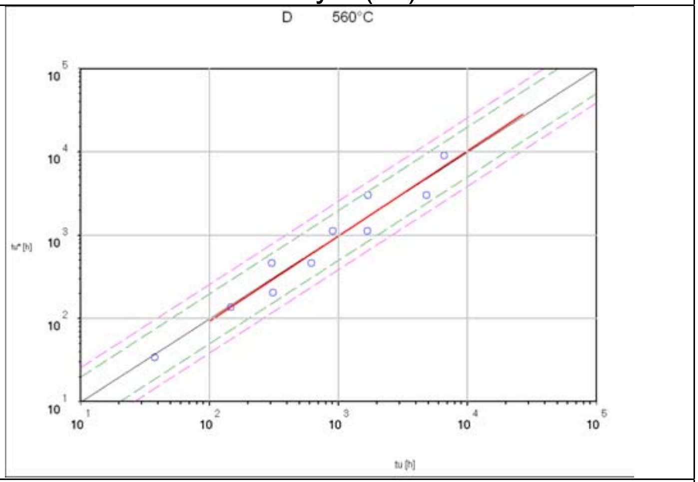
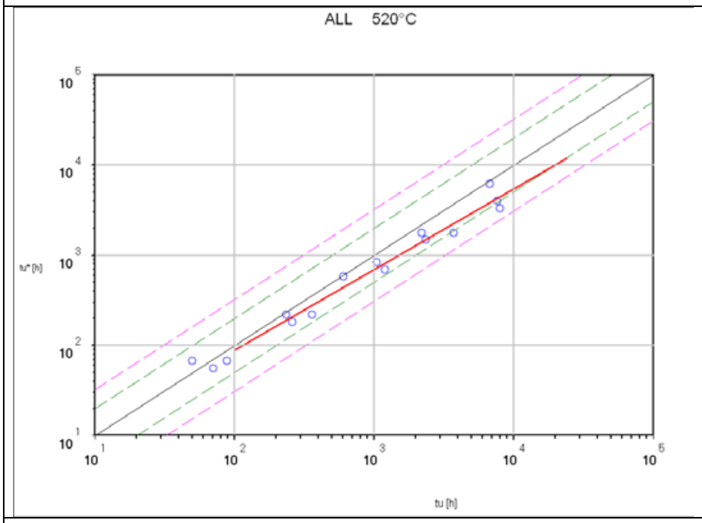
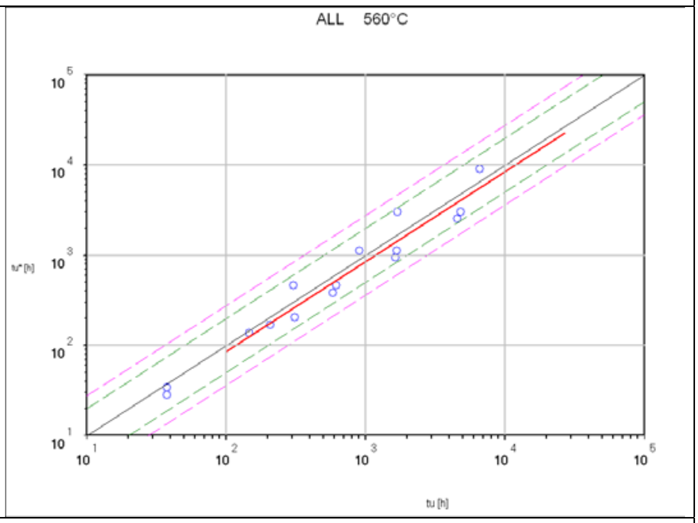
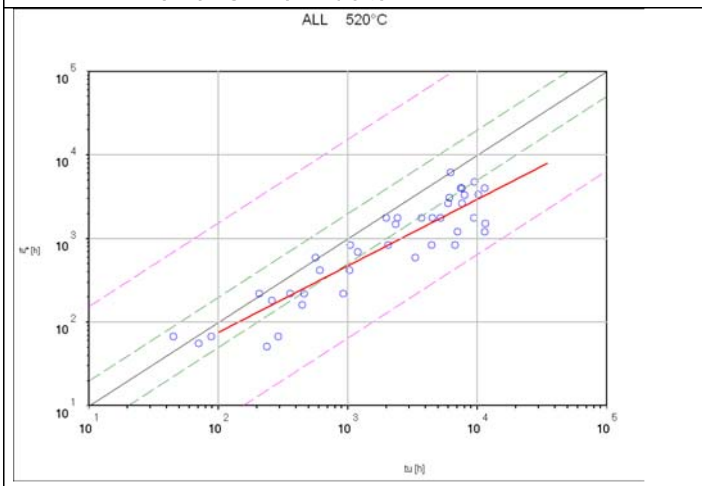
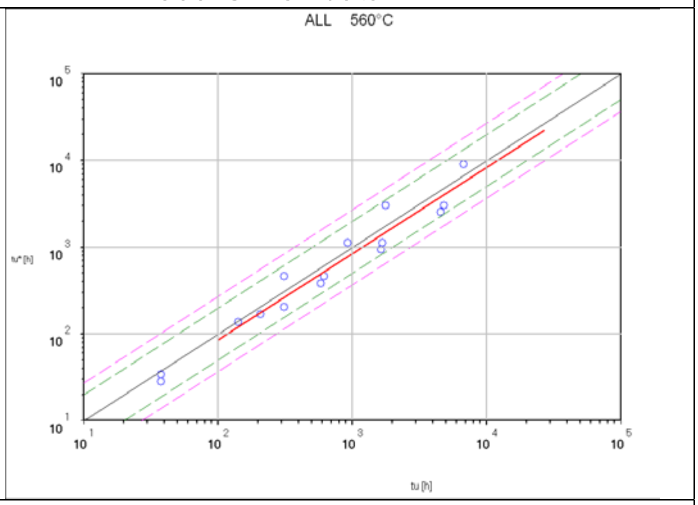
PAT 2.2 560°C – only D (all)

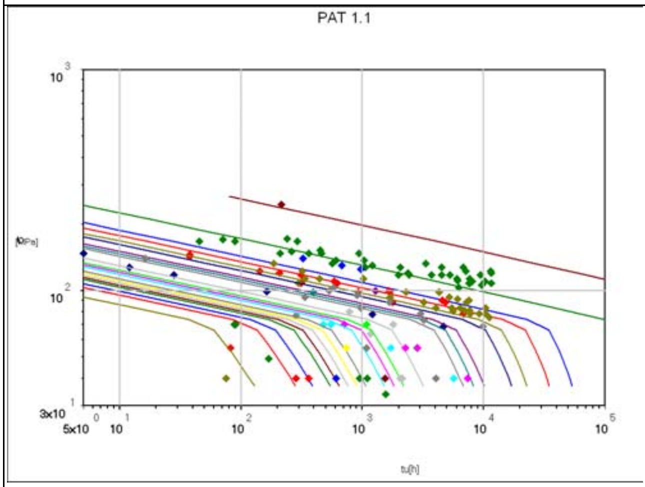
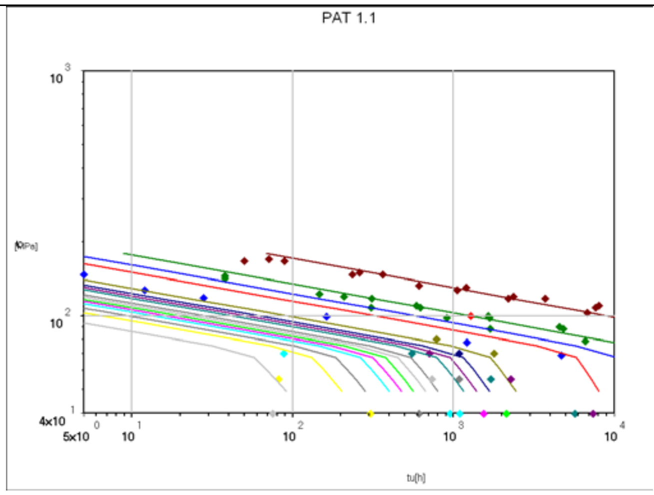
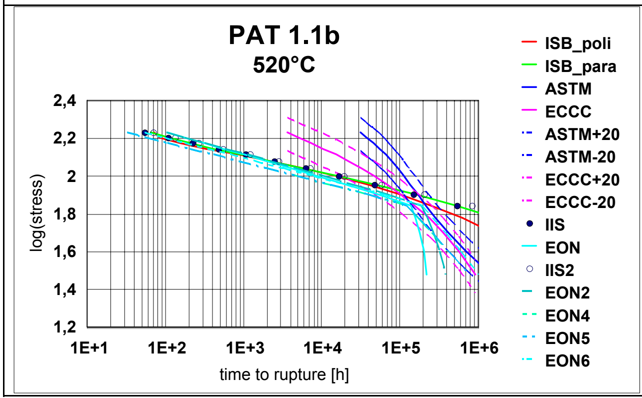
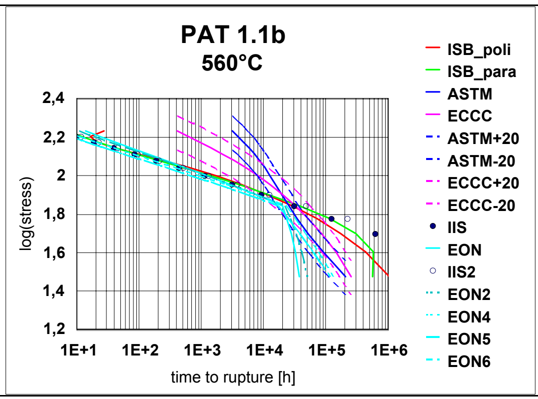


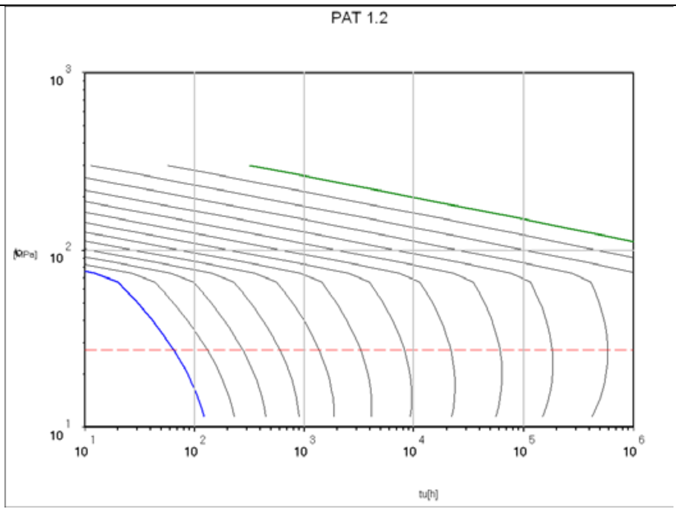
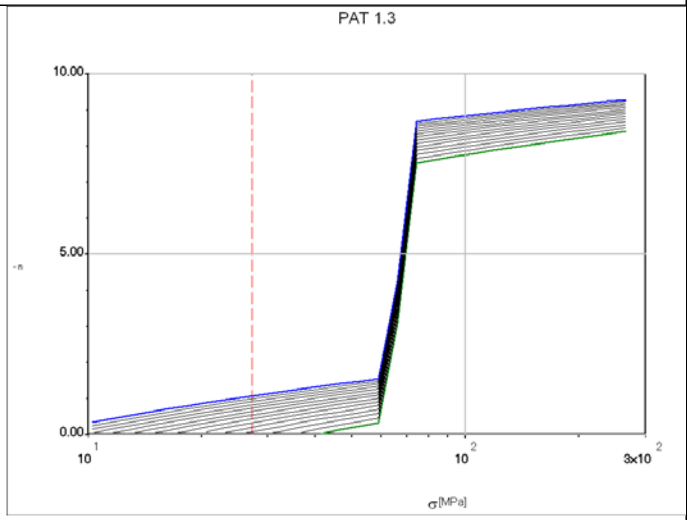
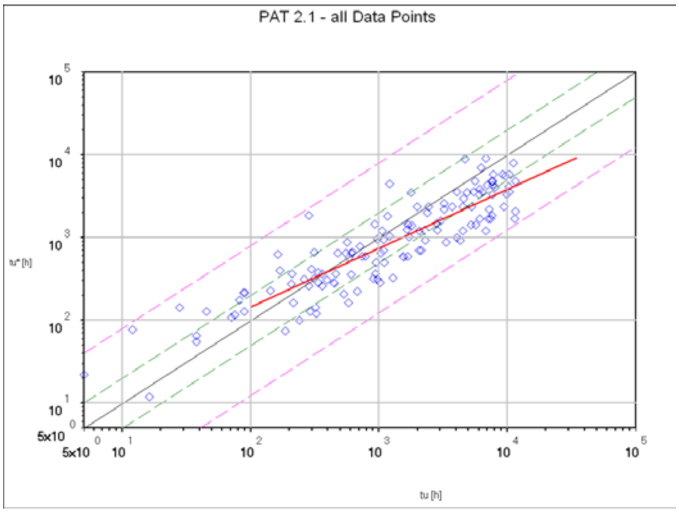
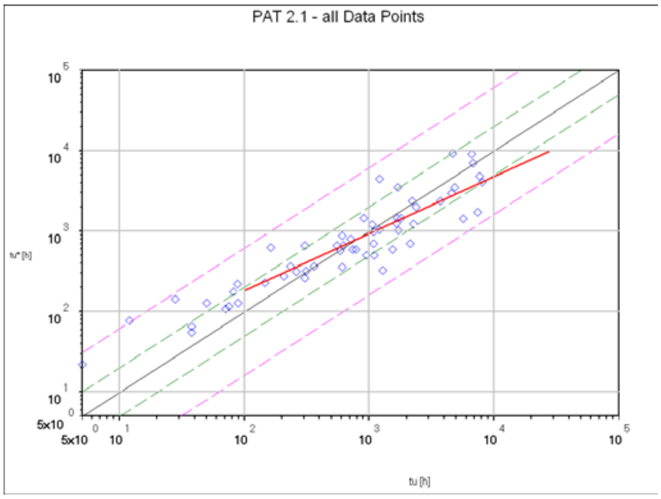
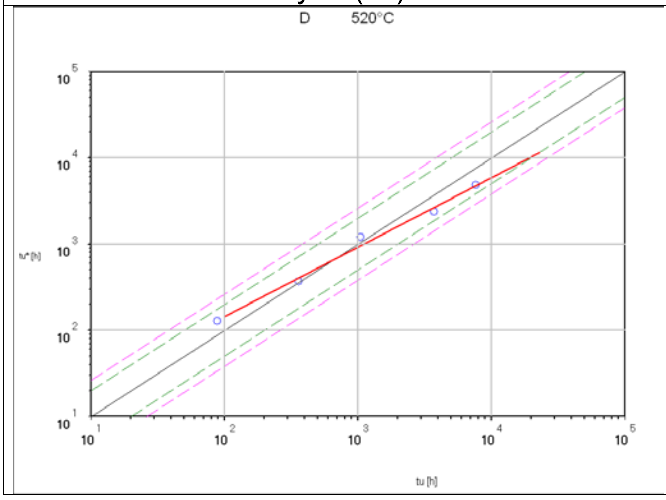
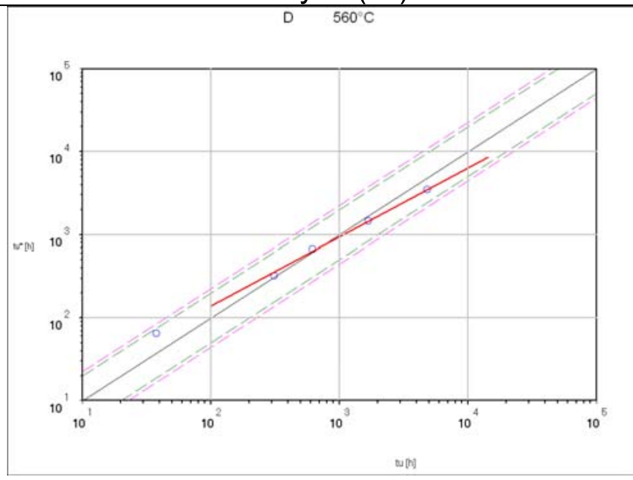
PAT2.2 – 520°C – only D (ltd)	PAT2.2 – 560°C – only D(ltd)
	
PAT2.2 – 520°C – ltd. data	PAT 2.2 – 560°C – ltd. data
	
PAT2.2 – 520°C – all data	PAT 2.2 – 560°C – all data
	
PAT3.1	PAT3.2
Not done	Not done

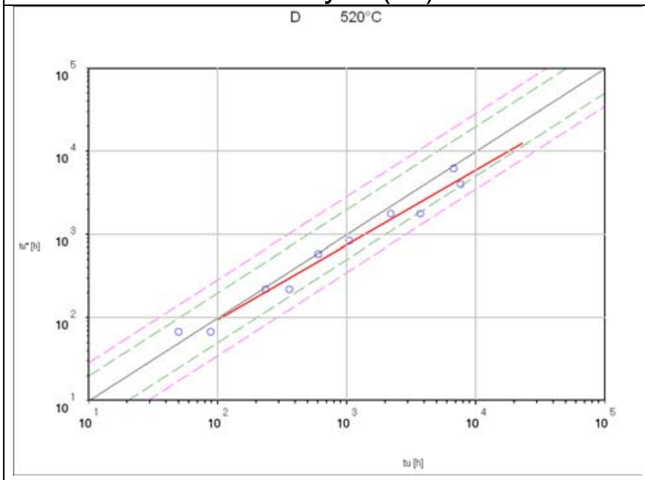
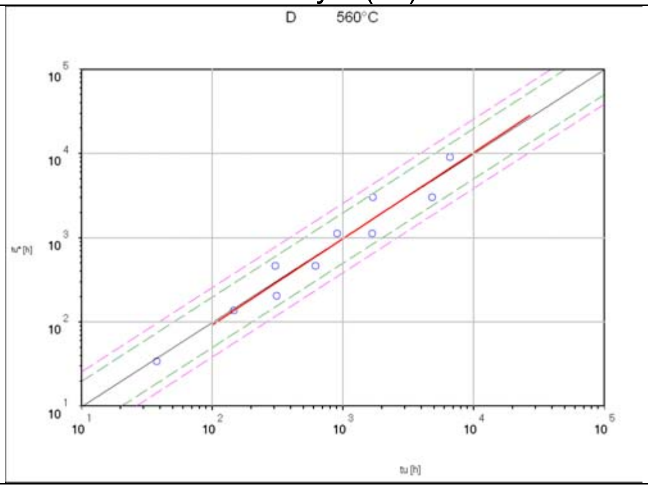
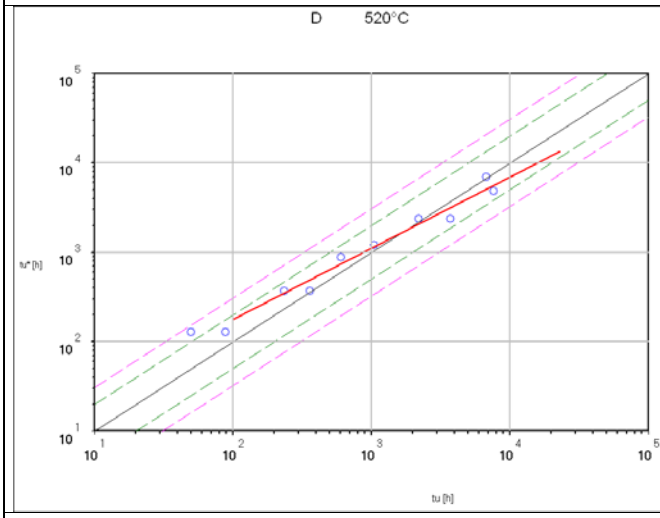
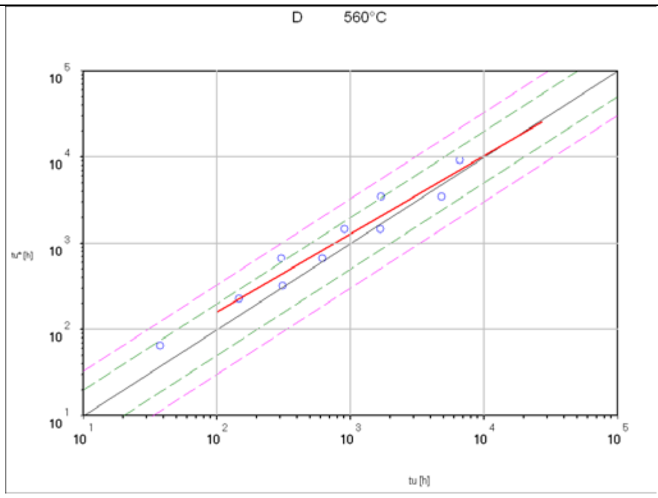
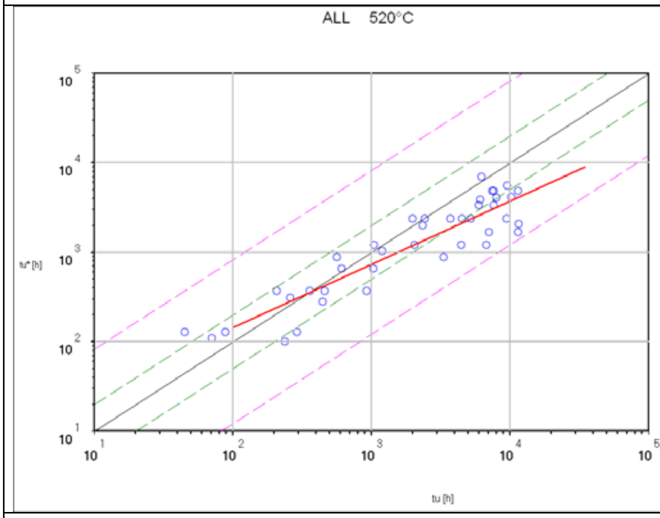
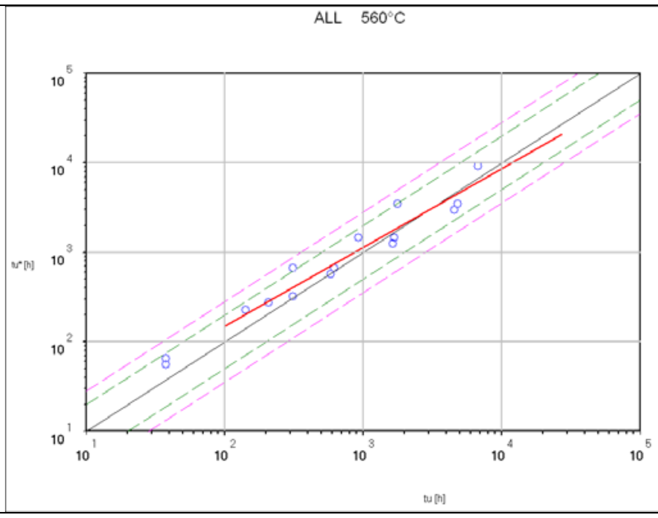
EON6	2021 data + All PE data with σ<70 MPa
$\sigma = 100427{,}11\, A^{-5{,}45002}$ $A = T[K](3{,}1 + \log\{\Omega\})$ $t_u = \dfrac{1}{\Omega \dot{\varepsilon}_0}$	Low stresses: σ < 73,7 MPa $\ln\{\dot{\varepsilon}_0\} = 21{,}2564 + 4{,}1687 \ln\{\sigma\} - \left[\dfrac{86.661{,}78}{1{,}9859\, T[K]}\right]$ High Stress: $\ln\{\dot{\varepsilon}_0\} = -8{,}6552 + 11{,}1857 \ln\{\sigma\} - \left[\dfrac{86.661{,}78}{1{,}9859\, T[K]}\right]$
PAT1.1a – all data	PAT1.1a – limited data
	
PAT1.1b 520°C	PAT1.1b 560°C
	

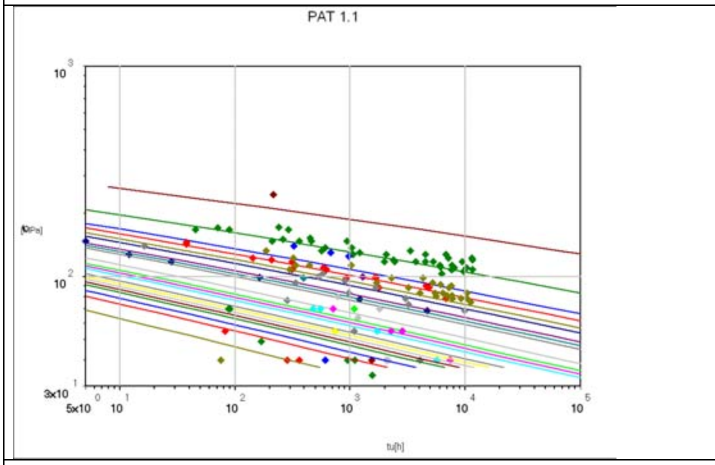
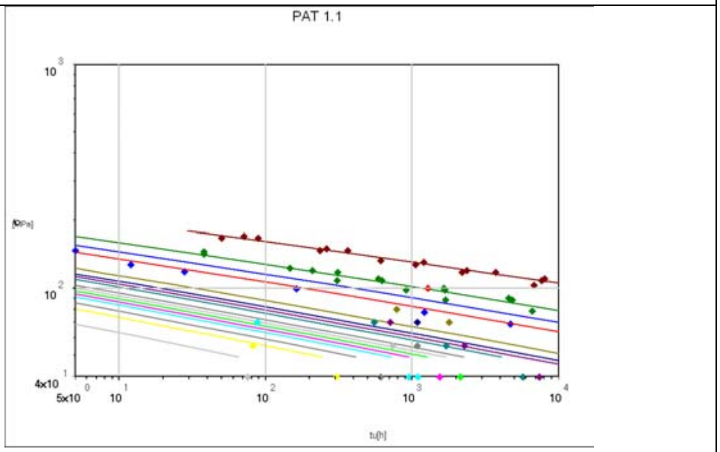
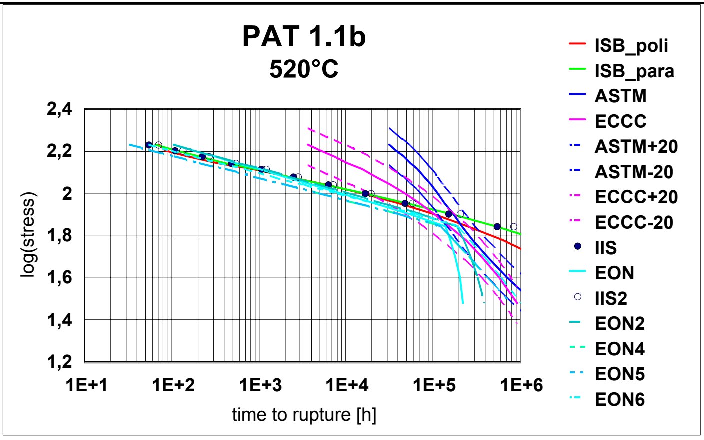
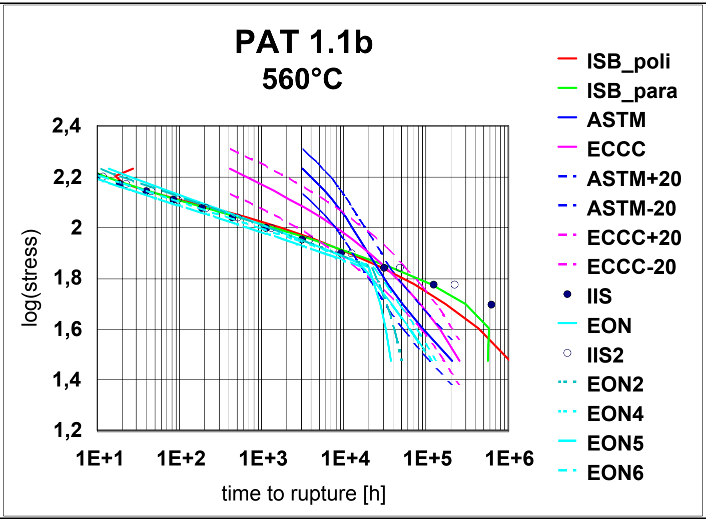
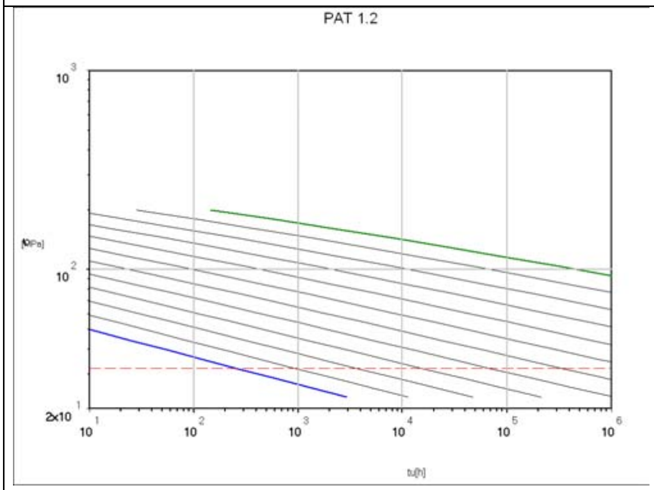
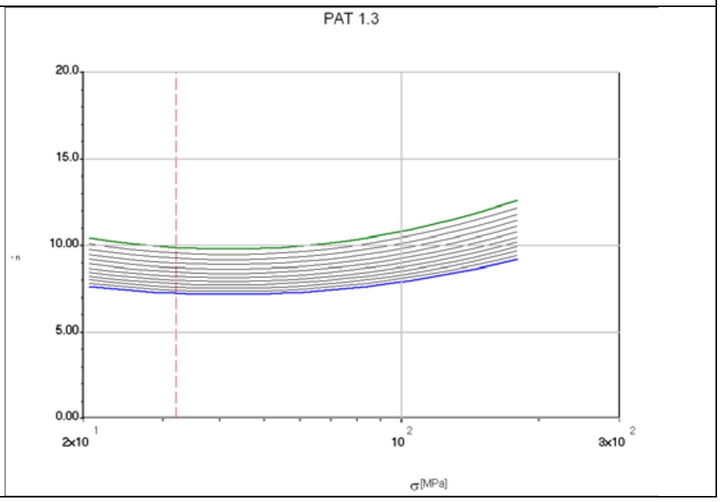
PAT1.2	PAT1.3
	
PAT2.1 – all data	PAT 2.1 – ltd. data
	
PAT2.2 520°C – only D (all)	PAT 2.2 560°C – only D (all)
	

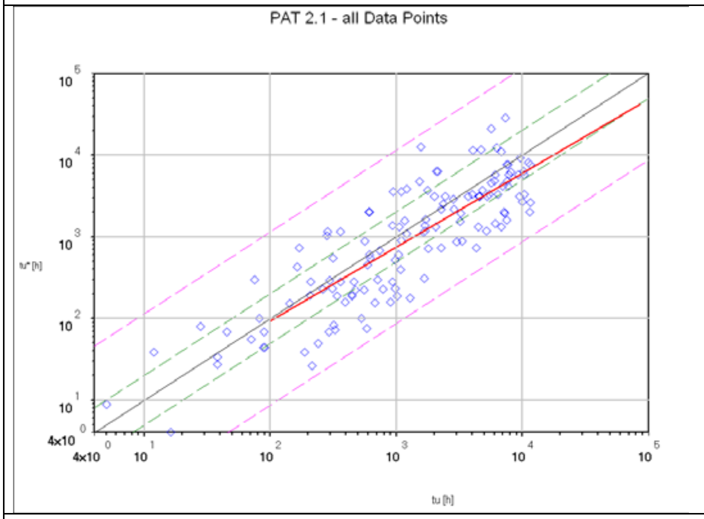
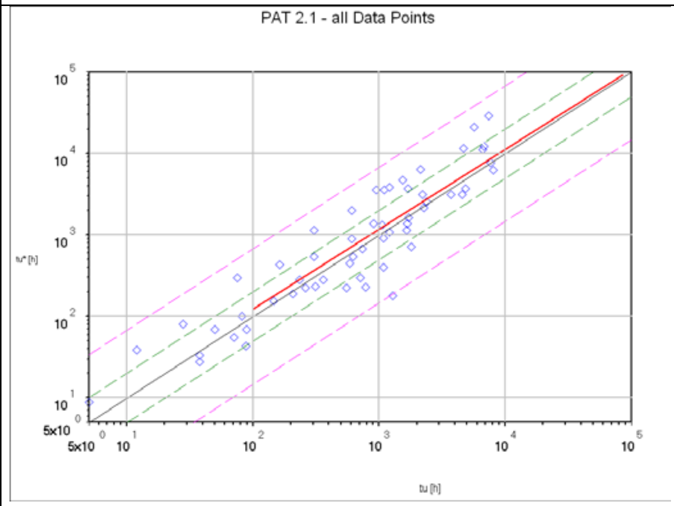
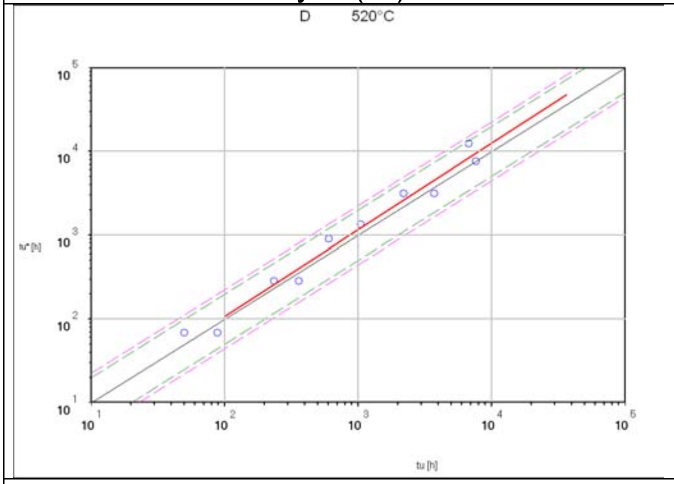
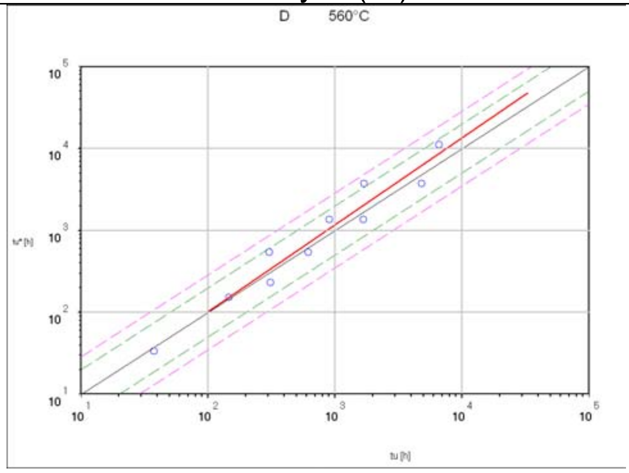
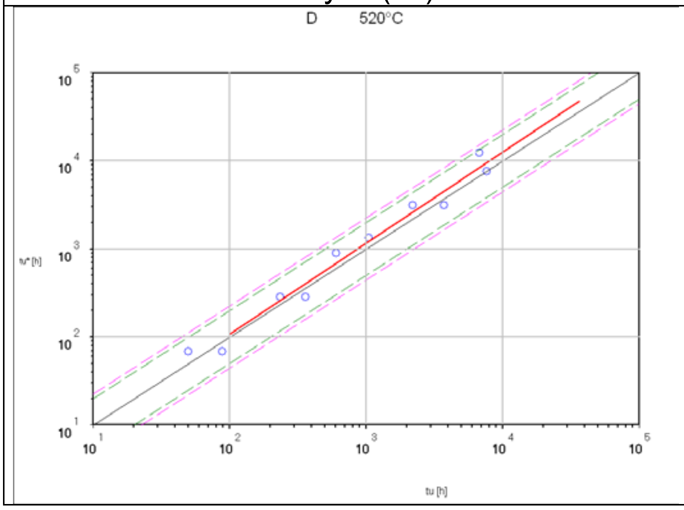
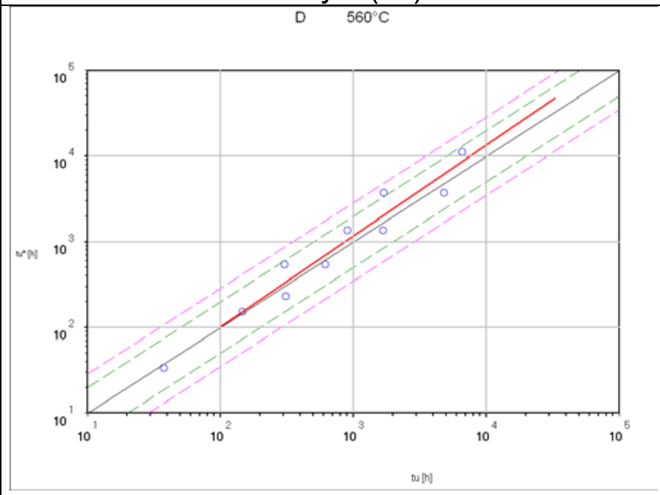
PAT2.2 – 520°C – only D (ltd)	PAT2.2 – 560°C – only D(ltd)
	
PAT2.2 – 520°C – ltd. data	PAT 2.2 – 560°C – ltd. data
	
PAT2.2 – 520°C – all data	PAT 2.2 – 560°C – all data
	
PAT3.1	PAT3.2
Not done	Not done

EON	All PE data
$\sigma = 153542{,}99\ A^{-4{,}63607}$ $A = T[K](4{,}8 + \log\{\Omega\})$ $t_u = \dfrac{1}{\Omega \dot{\varepsilon}_0}$	Low stresses: σ < 73,7 MPa $\ln\{\dot{\varepsilon}_0\} = 21{,}2564 + 4{,}1687 \ln\{\sigma\} - \left[\dfrac{86.661{,}78}{1{,}9859\,T[K]}\right]$ High Stress: $\ln\{\dot{\varepsilon}_0\} = -8{,}6552 + 11{,}1857 \ln\{\sigma\} - \left[\dfrac{86.661{,}78}{1{,}9859\,T[K]}\right]$
PAT1.1a – all data	PAT1.1a – limited data
	
PAT1.1b 520°C	PAT1.1b 560°C
	

PAT1.2	PAT1.3
	
PAT2.1 – all data	PAT 2.1 – ltd. data
	
PAT2.2 520°C – only D (all)	PAT 2.2 560°C – only D (all)
	

PAT2.2 – 520°C – only D (ltd)	PAT2.2 – 560°C – only D(ltd)
	
PAT2.2 – 520°C – ltd. data	PAT 2.2 – 560°C – ltd. data
	
PAT2.2 – 520°C – all data	PAT 2.2 – 560°C – all data
	
PAT3.1	PAT3.2
Not done	Not done

IIS	Only Pipe D (limited Data)
$\log\{\sigma\} = -1{,}85 + \frac{1}{T[K]}\left(\begin{array}{l}-1019{,}97+1182{,}7\log\{\sigma\} \\ -8567{,}98\log^2\{\sigma\}+1738{,}9\log^3\{\sigma\}\end{array}\right)$ $t_u = \frac{1}{\Omega \dot{\varepsilon}_0}$	$\log\{\dot{\varepsilon}_0\} = -21{,}858 + \frac{1}{T[K]}\left(40657{,}538 - 9530{,}618\log\{\sigma\}\right)$
PAT1.1a – all data	PAT1.1a – limited data
	
PAT1.1b 520°C	PAT1.1b 560°C
	
PAT1.2	PAT1.3
	

PAT2.1 – all data	PAT 2.1 – ltd. data
	
PAT2.2 520°C – only D (all)	**PAT 2.2 560°C – only D (all)**
	
PAT2.2 – 520°C – only D (ltd)	**PAT2.2 – 560°C – only D(ltd)**
	

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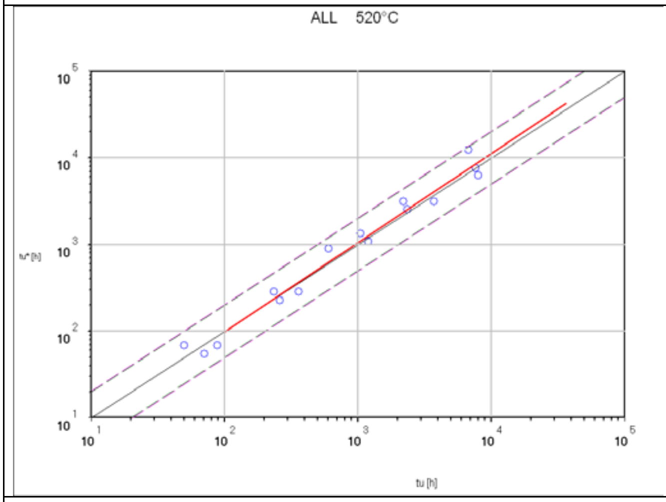
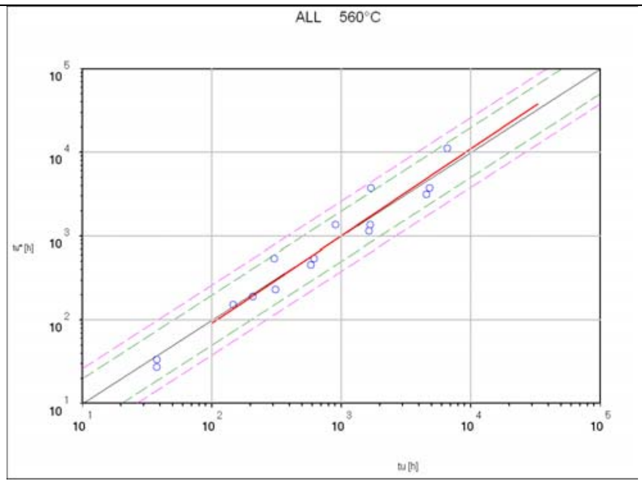
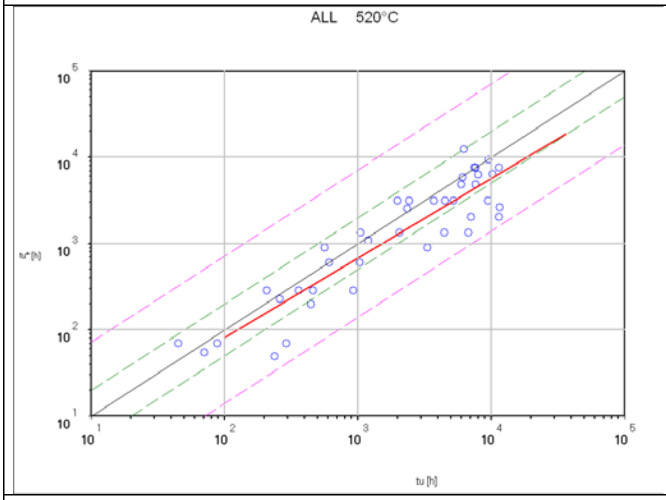
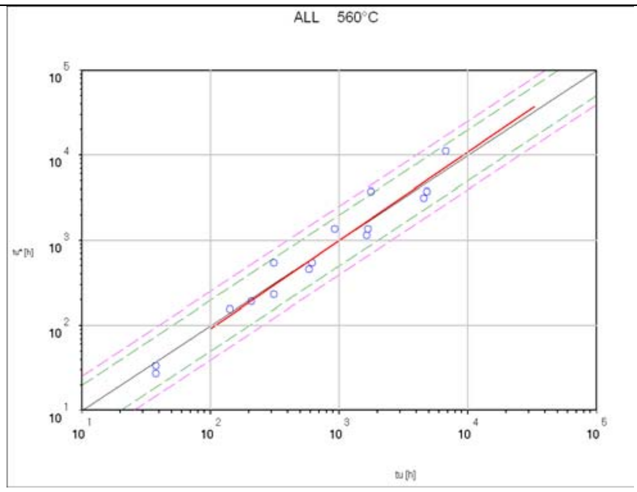
<tr><td>
</td><td>
</td></tr>
<tr><td>PAT2.2 – 520°C – all data</td><td>PAT 2.2 – 560°C – all data</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>PAT3.1</td><td>PAT3.2</td></tr>
<tr><td>Not done</td><td>Not done</td></tr>
</table>

IIS2

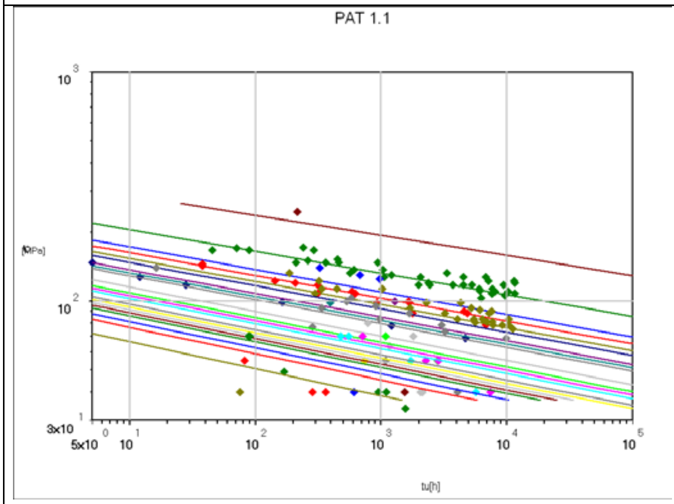
$$\log\{\sigma\} = -1{,}85 + \frac{1}{T[K]}\left(40380{,}2 - 824{,}38\log\{\sigma\}\right)$$

$$t_u = \frac{1}{\Omega \varepsilon_0^{\bullet}}$$

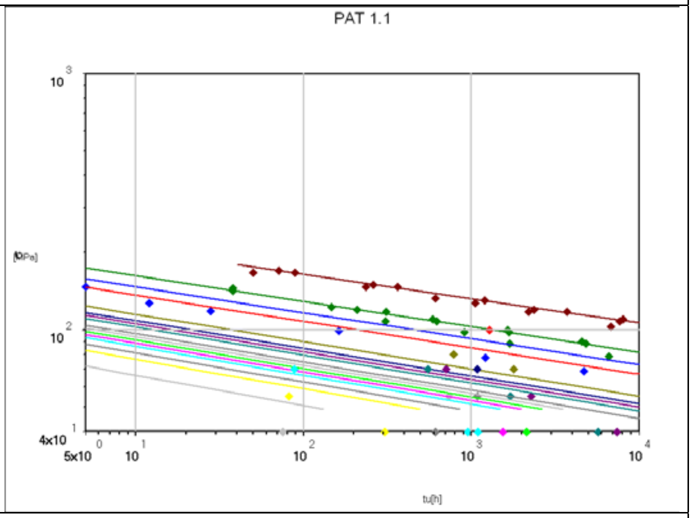
Only Pipe D (limited data)

$$\log\{\varepsilon_0^{\bullet}\} = -21{,}86 + \frac{1}{T[K]}\left(40058{,}3 - 9199{,}5\log\{\sigma\}\right)$$

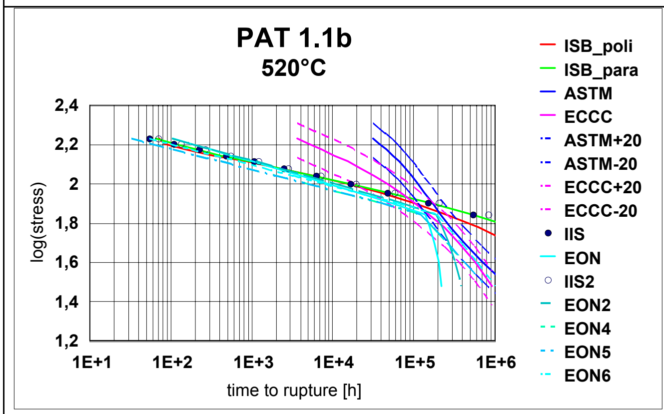
PAT1.1a – all data



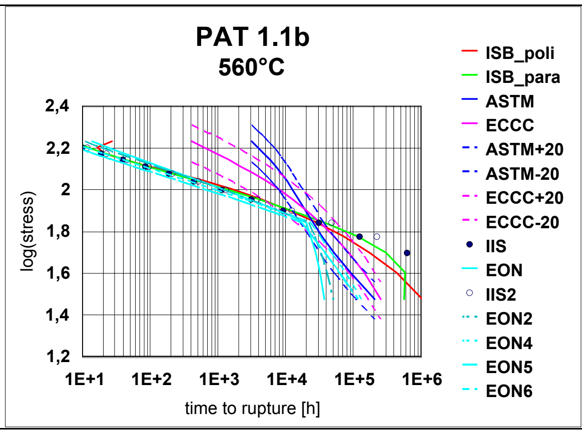
PAT1.1a – limited data



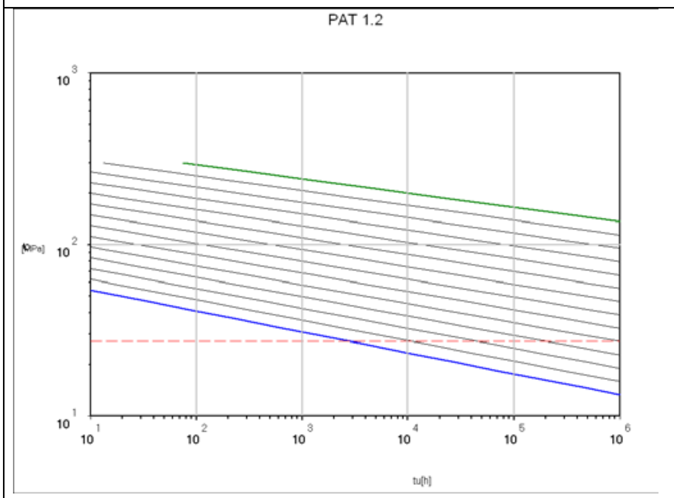
PAT1.1b 520°C



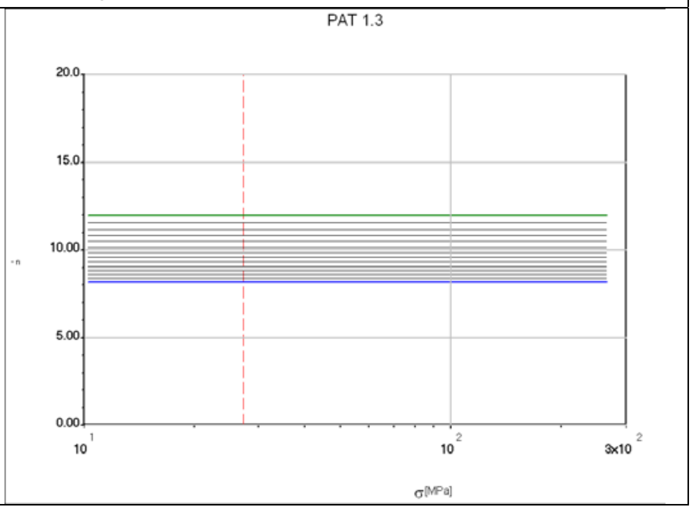
PAT1.1b 560°C



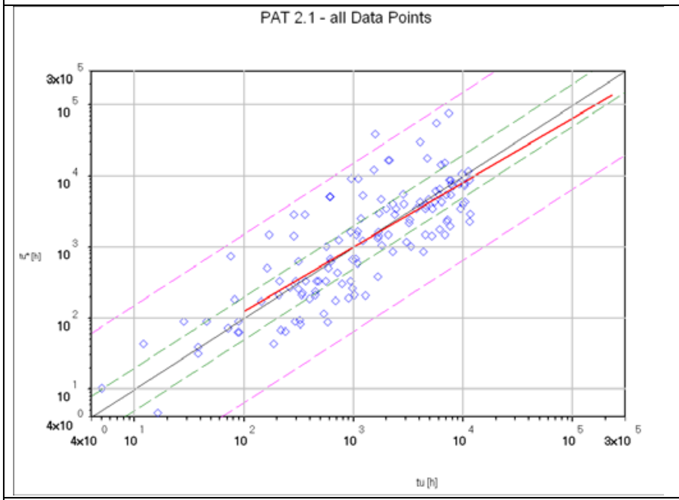
PAT1.2



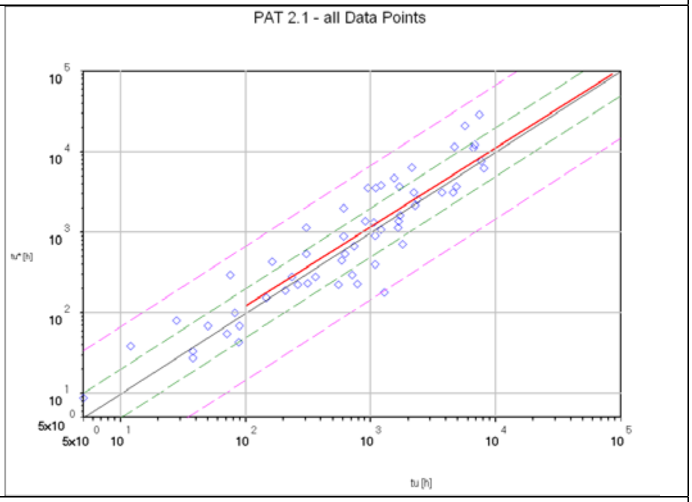
PAT1.3



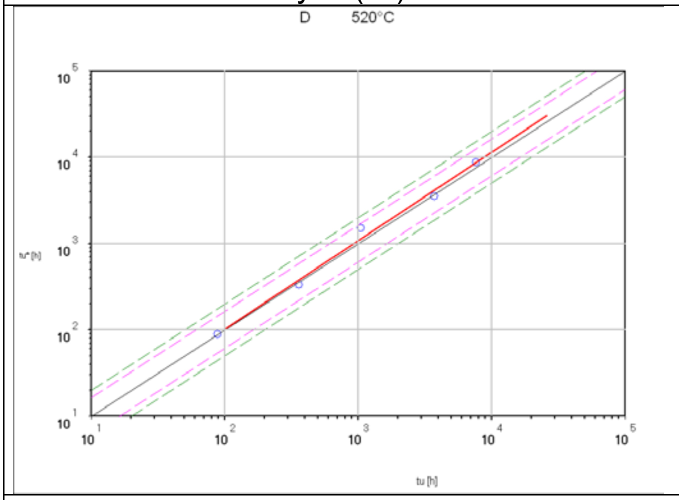
PAT2.1 – all data



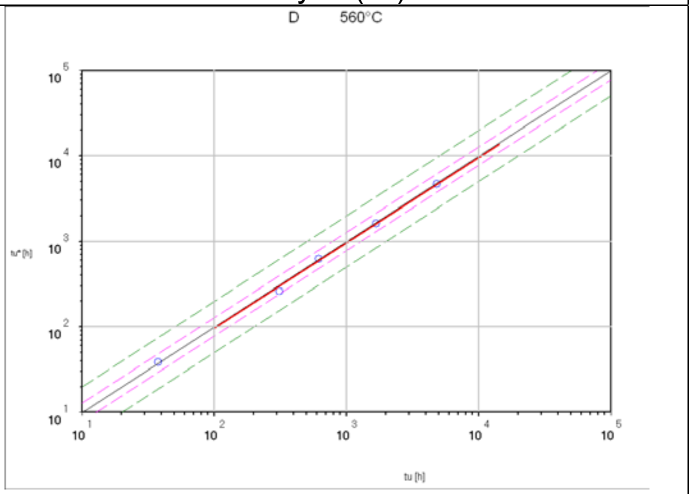
PAT 2.1 – ltd. data



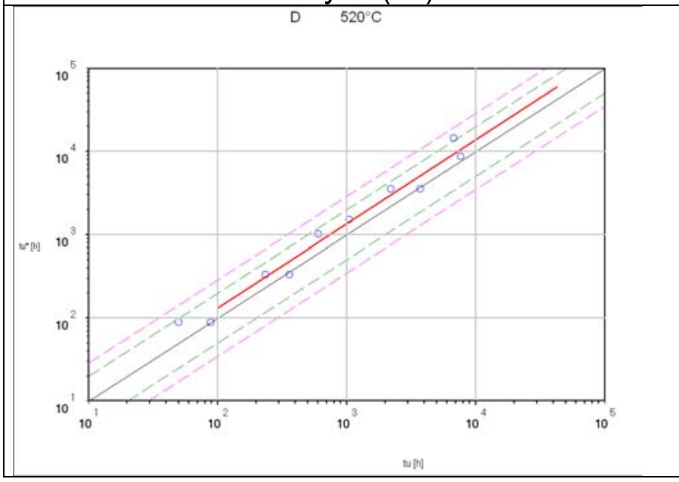
PAT2.2 520°C – only D (all)



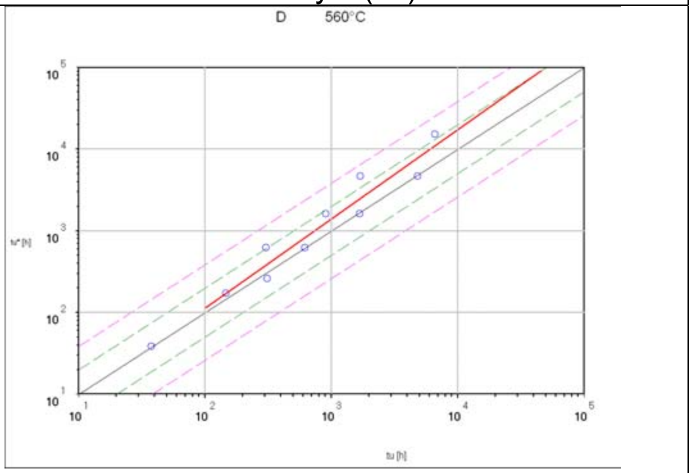
PAT 2.2 560°C – only D (all)

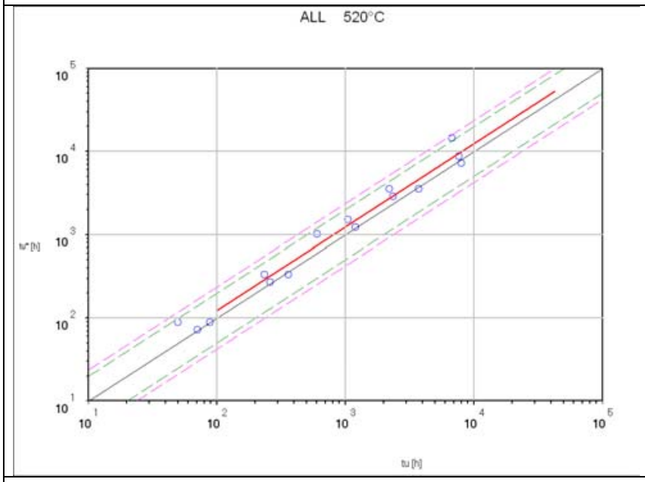
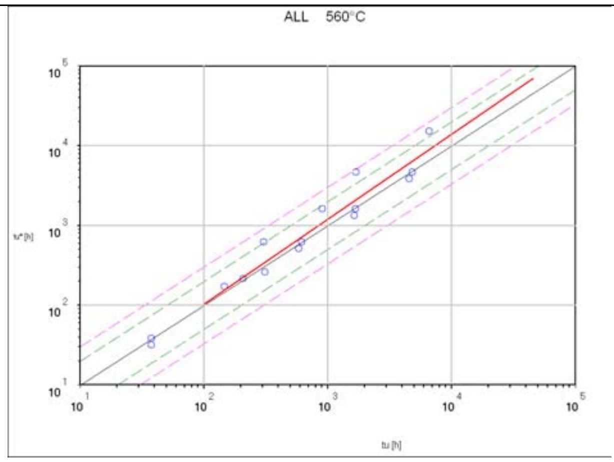
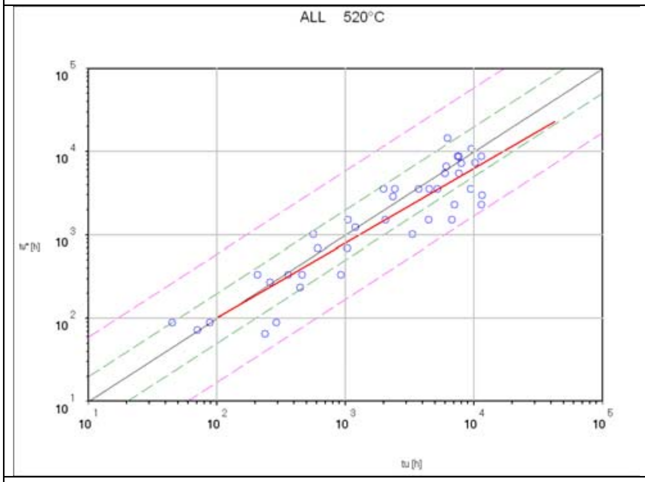
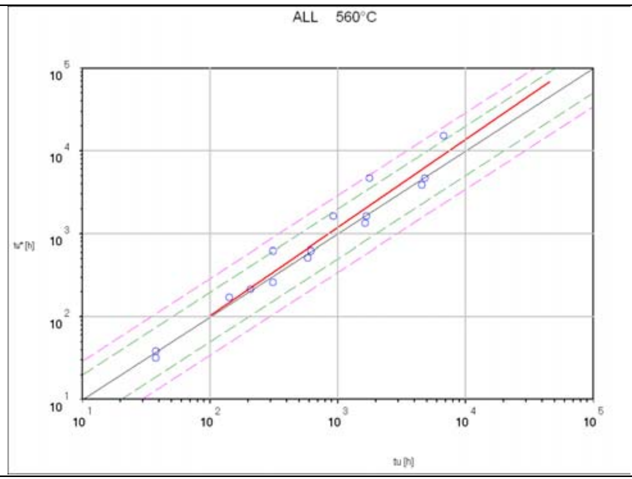


PAT2.2 – 520°C – only D (ltd)



PAT2.2 – 560°C – only D(ltd)



PAT2.2 – 520°C – ltd. data	PAT 2.2 – 560°C – ltd. data
	
PAT2.2 – 520°C – all data	PAT 2.2 – 560°C – all data
	
PAT3.1	PAT3.2
Not done	Not done

ISB - OmPoli	All PE data

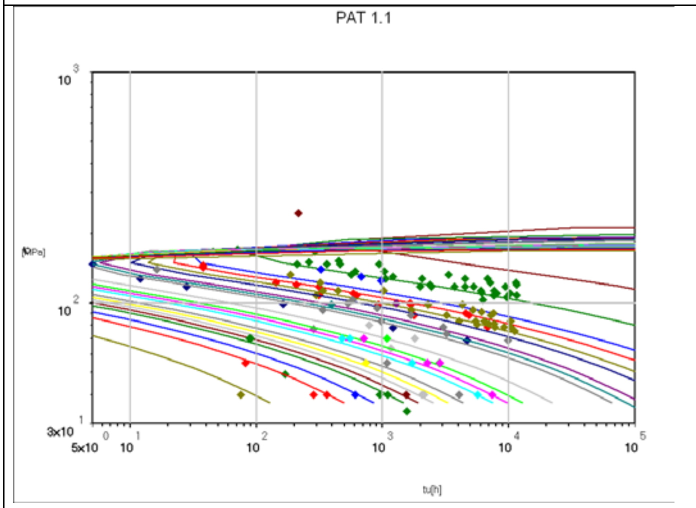
$$t_R = \left(\frac{1}{\Omega \varepsilon_0^{\bullet}} \right)$$

$$\Omega = a_0 + a_1 T[K] + a_2 \sigma + a_3 (T\sigma)^m$$

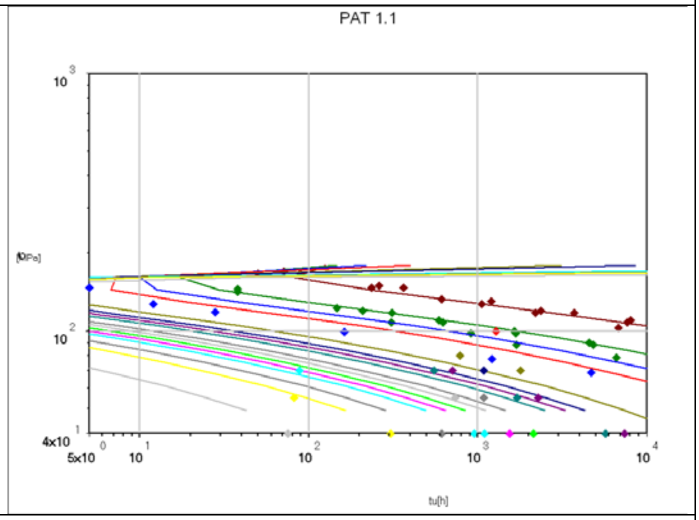
$$\varepsilon_0^{\bullet} = b_0 + b_1 T[K] + b_2 \sigma + b_3 (T\sigma)^p$$

		POLI_ just PE		
Om_a0	Om_a1	Om_a2	Om_a3	Om_m
2,089	-0,00031069	-0,01108	8,549E-023	4,28137
Isr_b0	Isr_b1	Isr_b2	Isr_b3	ISR_p
-26,912	0,023877	0,049766	-1,8389E-052	10,0929

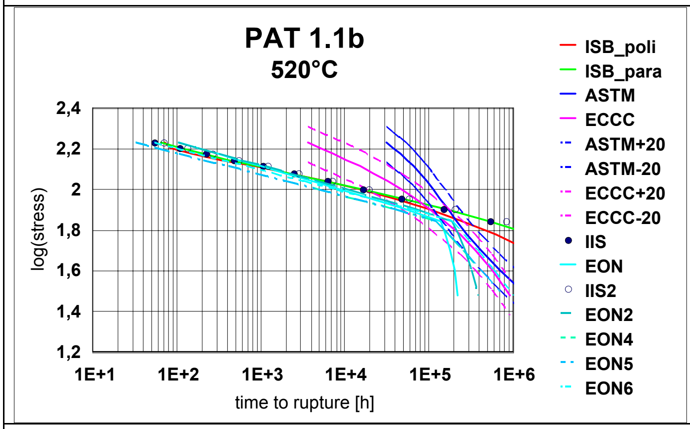
PAT1.1a – all data



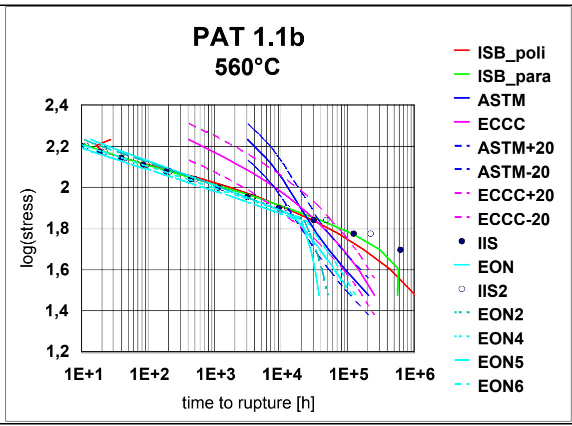
PAT1.1a – limited data



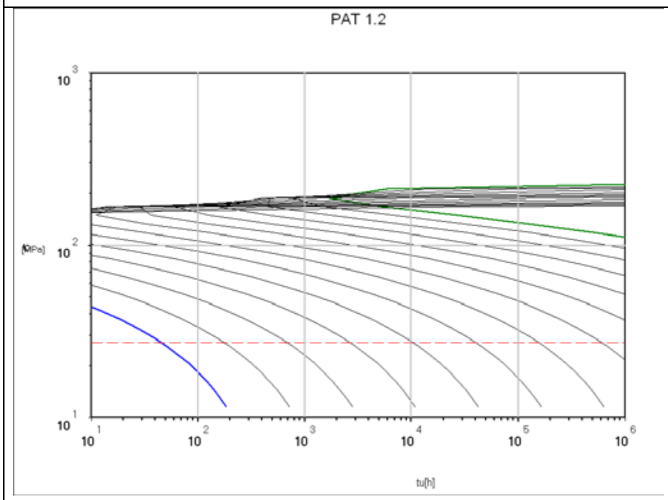
PAT1.1b 520°C



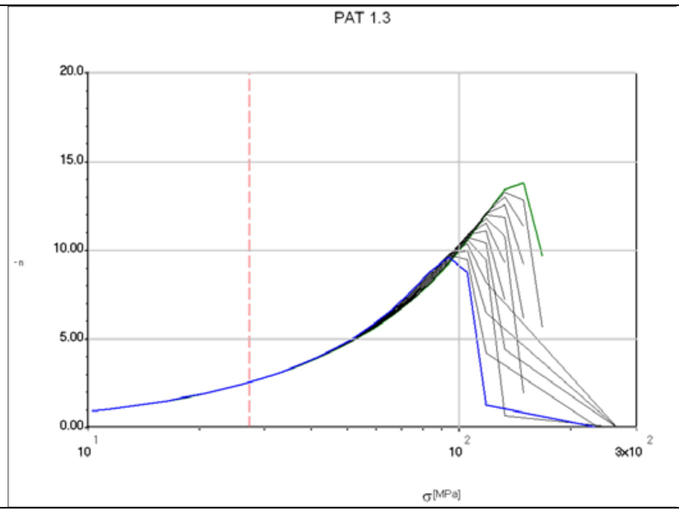
PAT1.1b 560°C

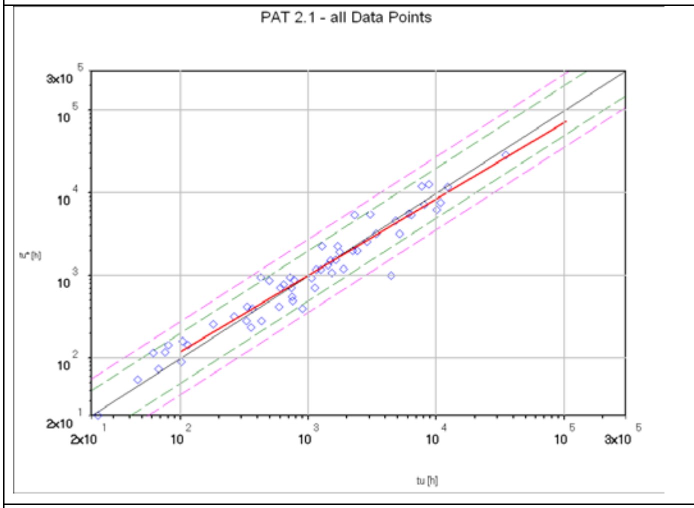
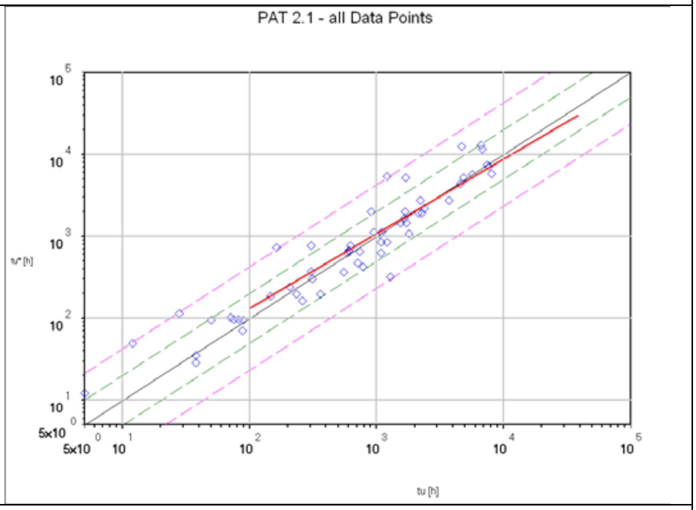
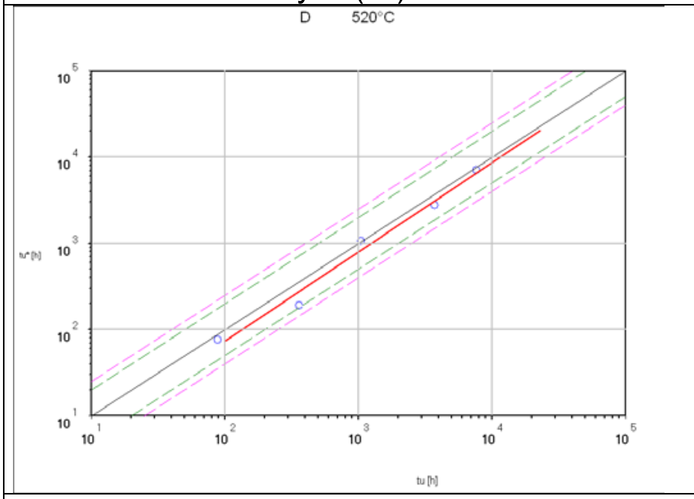
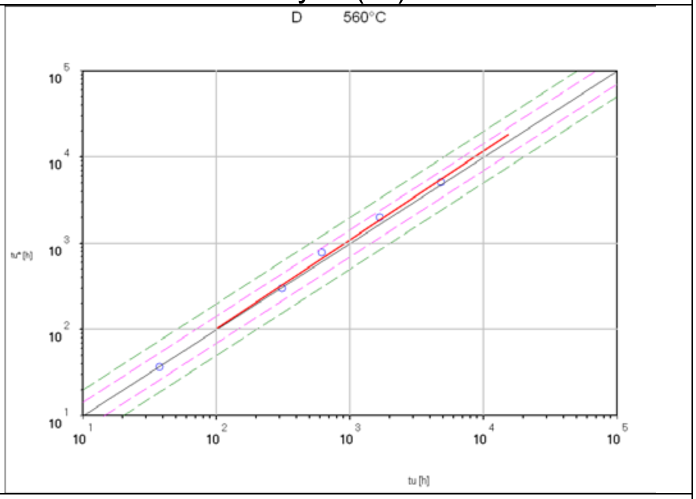
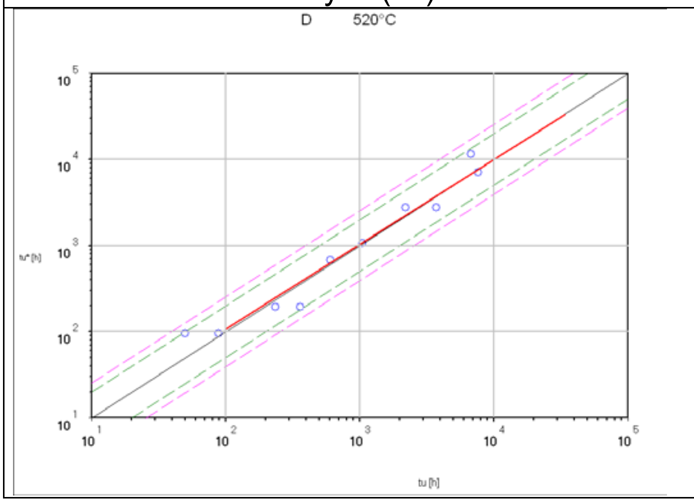
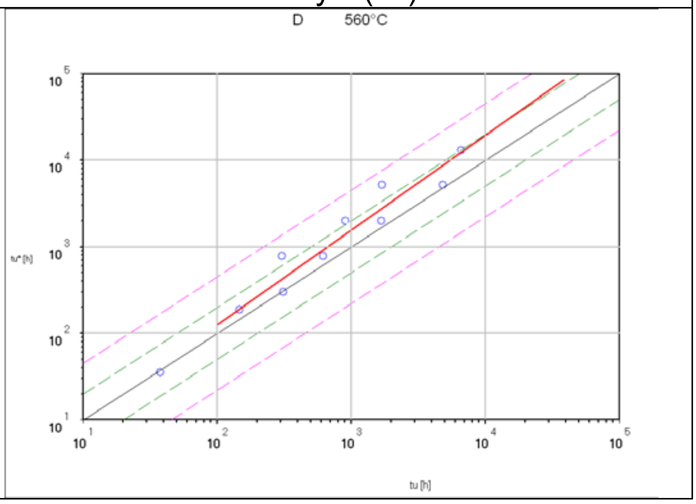


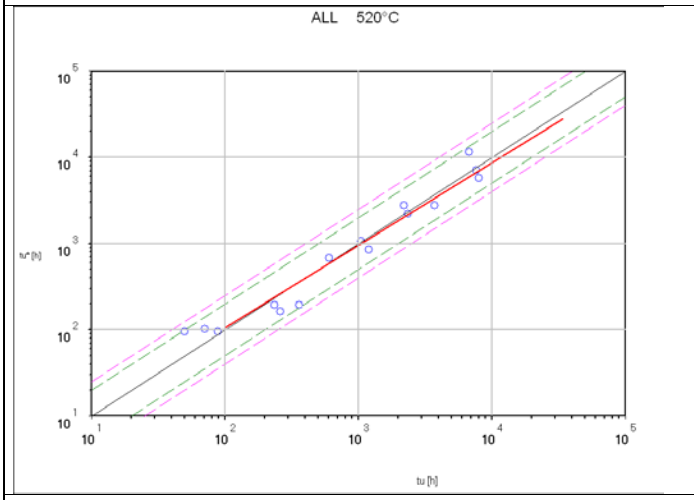
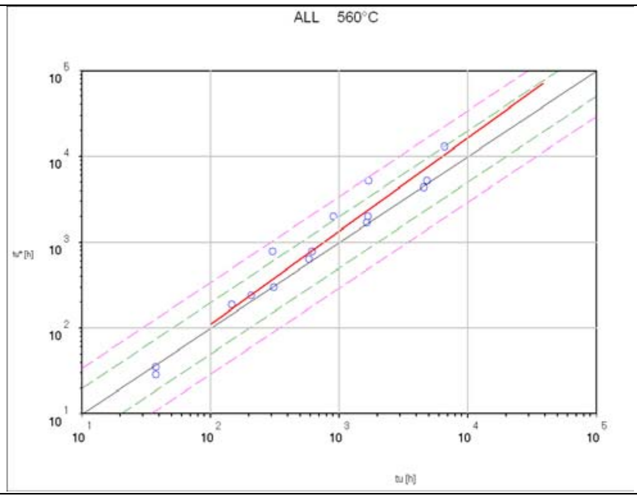
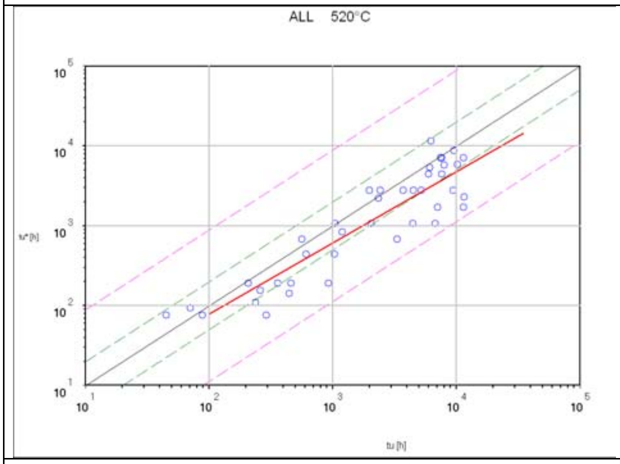
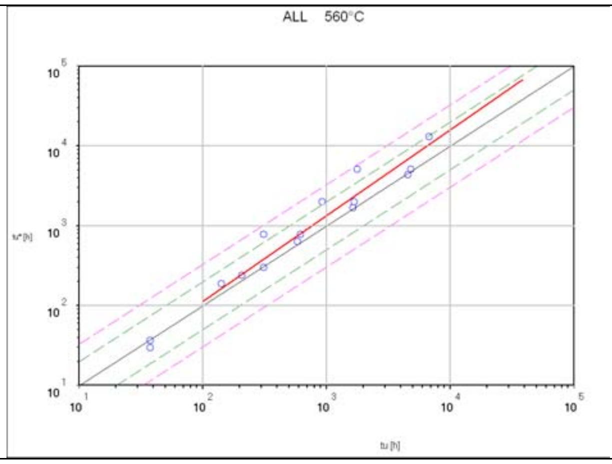
PAT1.2



PAT1.3



PAT2.1 – all data	PAT 2.1 – ltd. data
	
PAT2.2 520°C – only D (all)	PAT 2.2 560°C – only D (all)
	
PAT2.2 – 520°C – only D (ltd)	PAT2.2 – 560°C – only D(ltd)
	

PAT2.2 – 520°C – ltd. data	PAT 2.2 – 560°C – ltd. data
	
PAT2.2 – 520°C – all data	PAT 2.2 – 560°C – all data
	
PAT3.1	PAT3.2
Passed	passed

ISB - OmPara

$$t_R = \left(\frac{1}{\Omega \varepsilon_0^{\bullet}} \right)$$

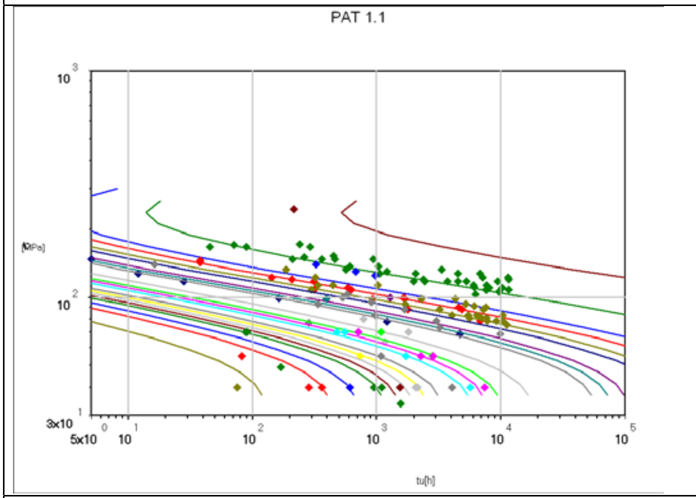
$$T[K](C + \log(\Omega)) = \sum_{i=0}^{4} a_i \log(\sigma)^i$$

$$T[K](C_2 + \log(\varepsilon_0^{\bullet})) = \sum_{i=0}^{4} b_i \log(\sigma)^i$$

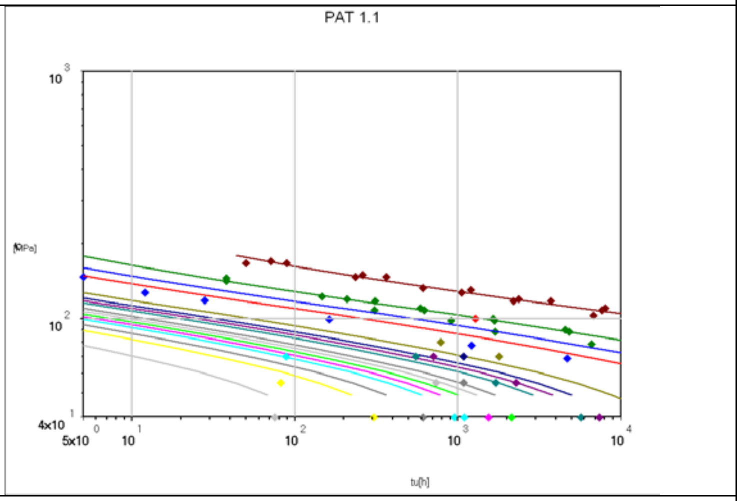
All PE data

		PARA_just PE			
Om_a0	Om_a1	Om_a2	Om_a3	Om_a4	Om_C
-720,4796	1303,1773	-783,7007	160,0782	-0,0907	9,4500
isr_b0	Isr_b1	Isr_b2	Isr_b3	Isr_b4	Isr_C2
709,8512	-1298,6892	765,3342	-152,4619	0,0772	-29,4941

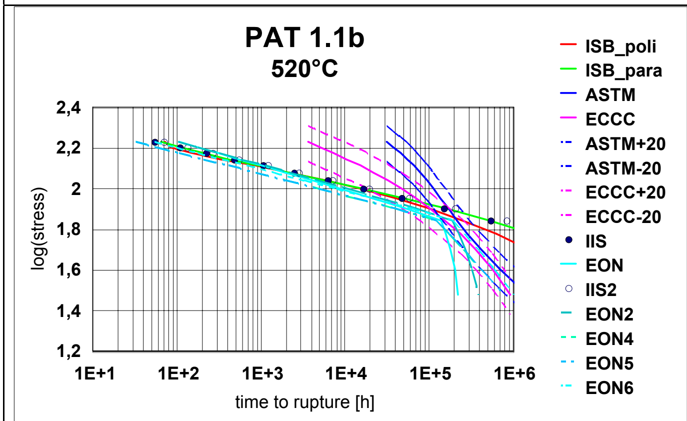
PAT1.1a – all data



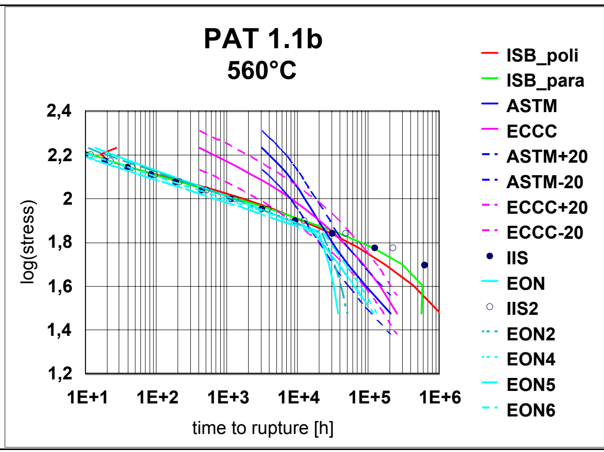
PAT1.1a – limited data

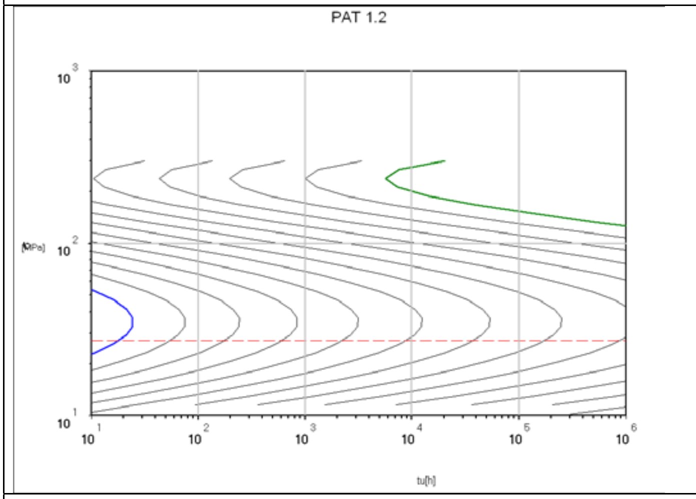
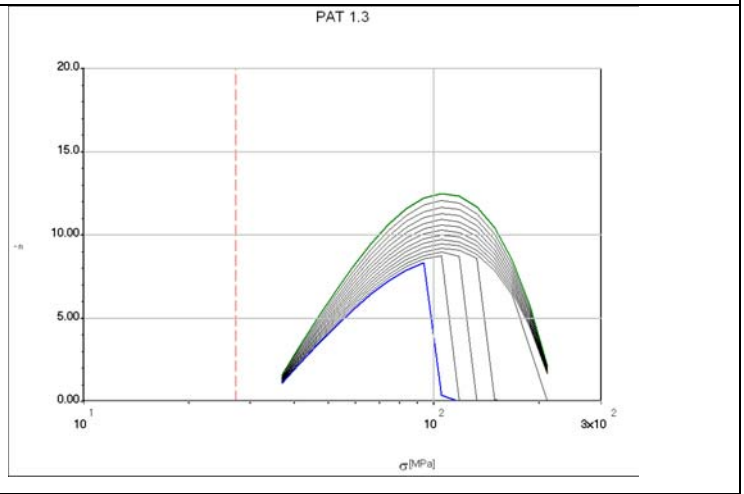
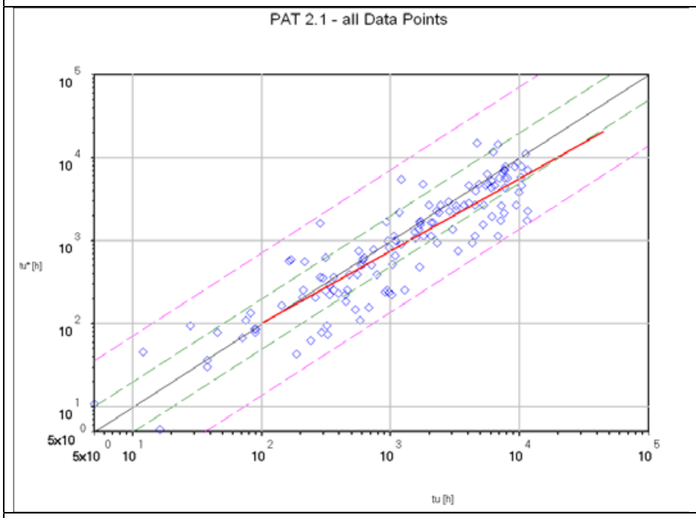
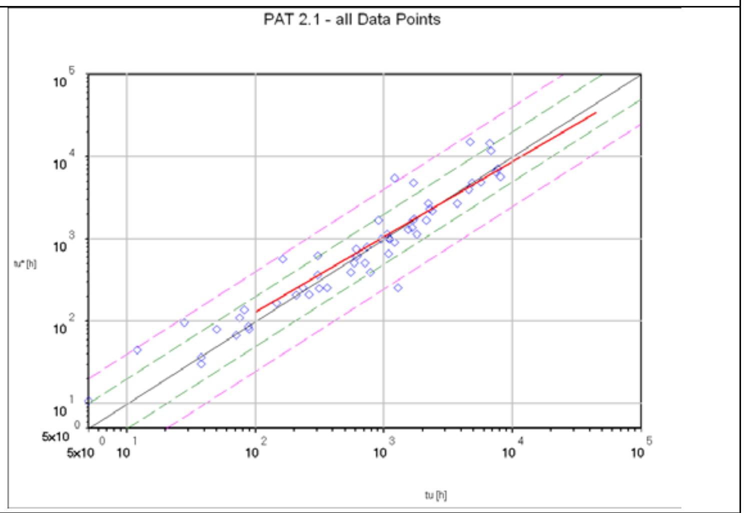
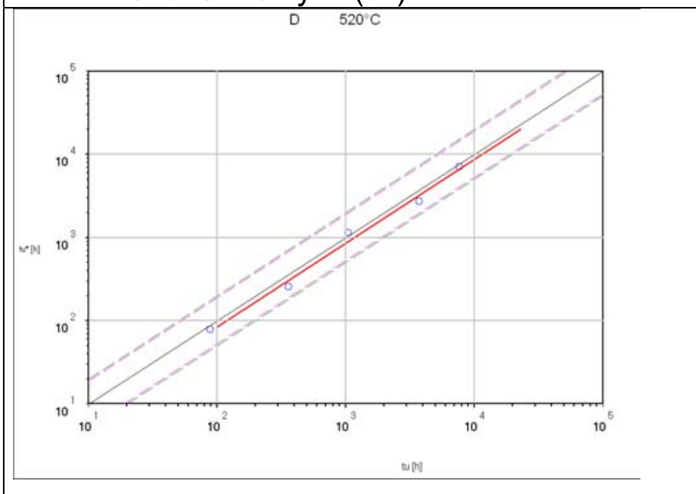
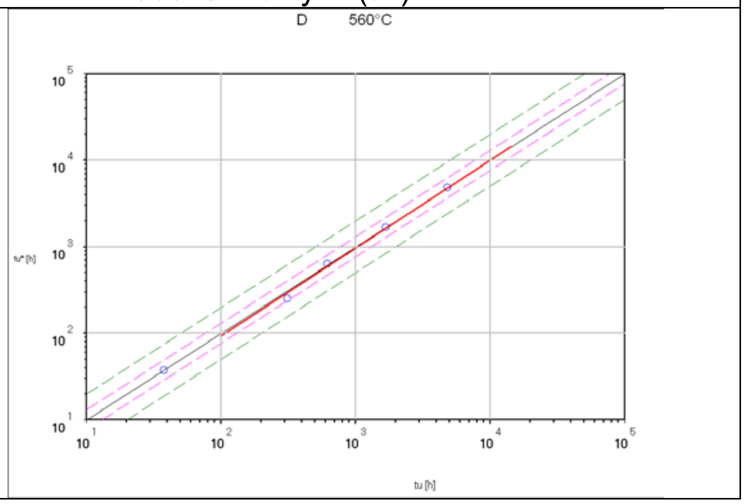


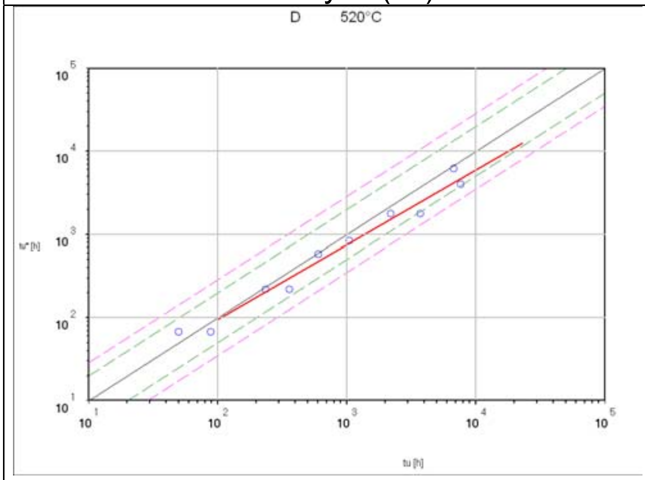
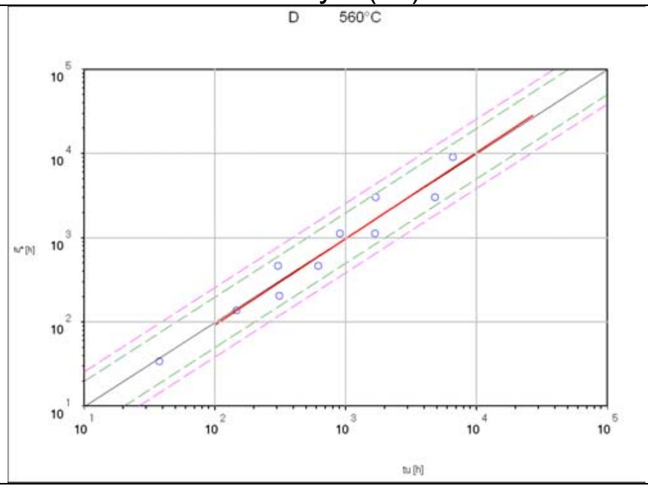
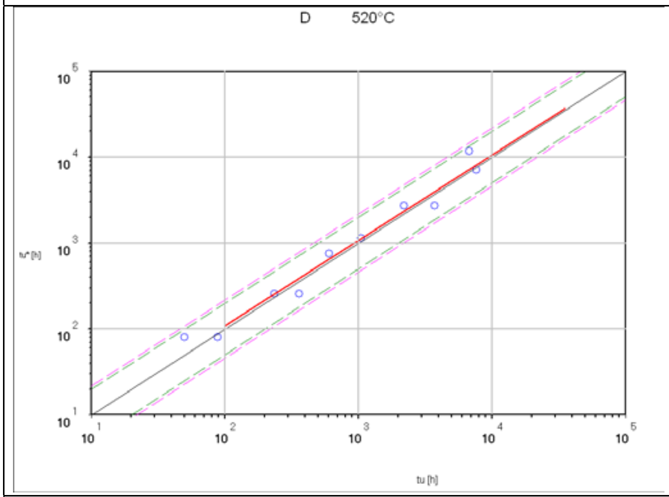
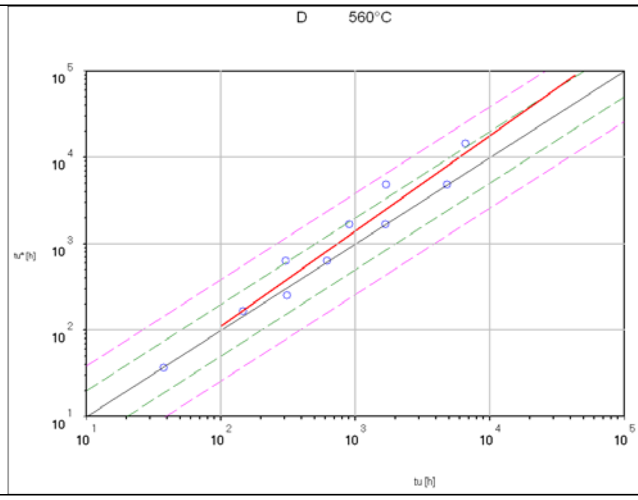
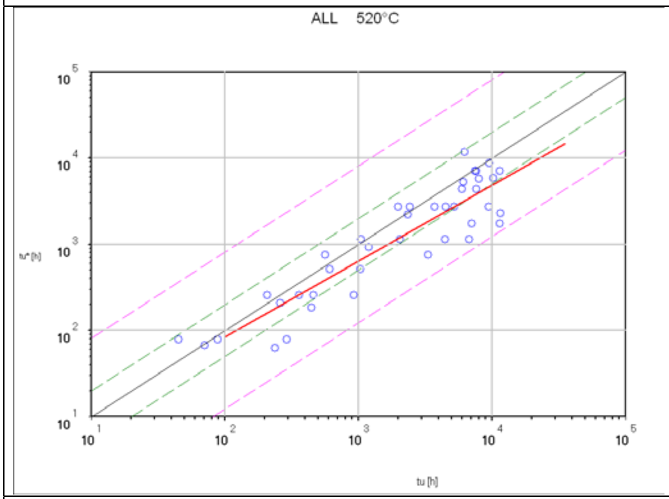
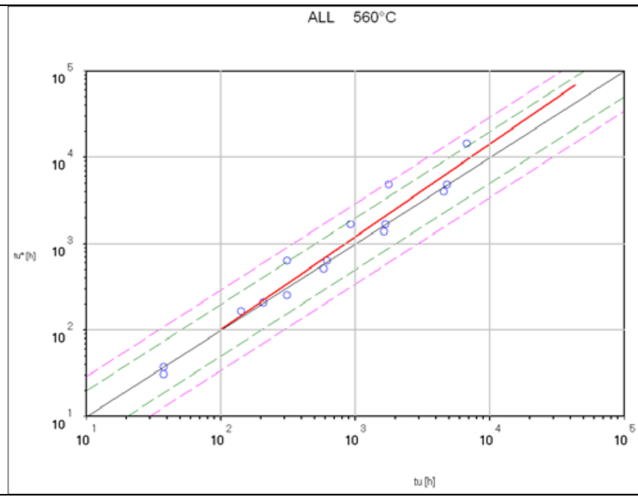
PAT1.1b 520°C



PAT1.1b 560°C



PAT1.2	PAT1.3
	
PAT2.1 – all data	PAT 2.1 – ltd. data
	
PAT2.2 520°C – only D (all)	PAT 2.2 560°C – only D (all)
	

PAT2.2 – 520°C – only D (ltd)	PAT2.2 – 560°C – only D(ltd)
	
PAT2.2 – 520°C – ltd. data	PAT 2.2 – 560°C – ltd. data
	
PAT2.2 – 520°C – all data	PAT 2.2 – 560°C – all data
	
PAT3.1	PAT3.2
Passed	passed

ISB-OmRLAPoli

All PE data – corrected by linear damage accumulation rule

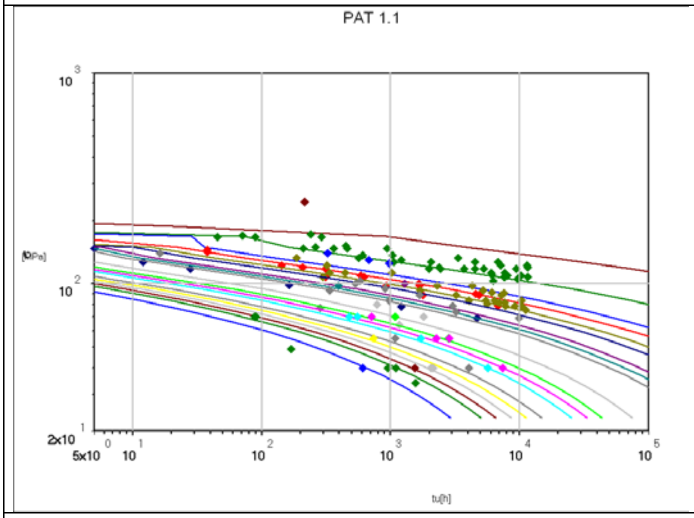
$$t_R = \left(\frac{1}{\Omega \varepsilon_0^{\bullet}}\right)$$

$$\Omega = a_0 + a_1 T[K] + a_2\sigma \ + a_3 (T\sigma)^m$$

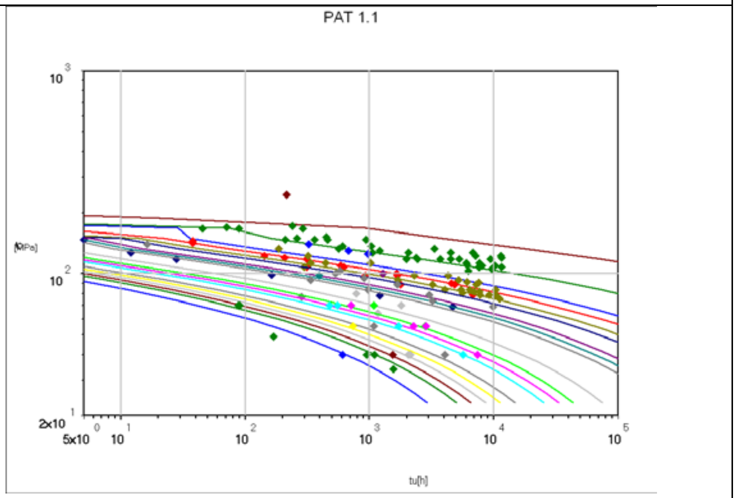
$$\varepsilon_0^{\bullet} = b_0 + b_1 T[K] + b_2\sigma \ + b_3 (T\sigma)^p$$

		POLI_ adapt		
Om_a0	Om_a1	Om_a2	Om_a3	Om_m
2,514	-0,0007689	-0,011279	2,699E-028	5,3396
Isr_b0	Isr_b1	Isr_b2	Isr_b3	ISR_p
-26,2048	0,0231875	0,048132	-1,8003E-52	10,0929

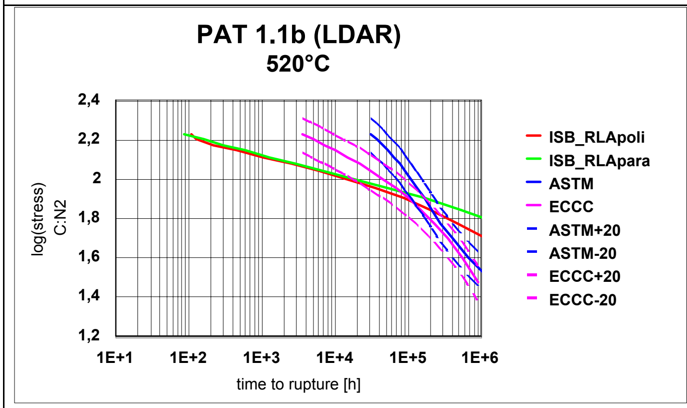
PAT1.1a – all data



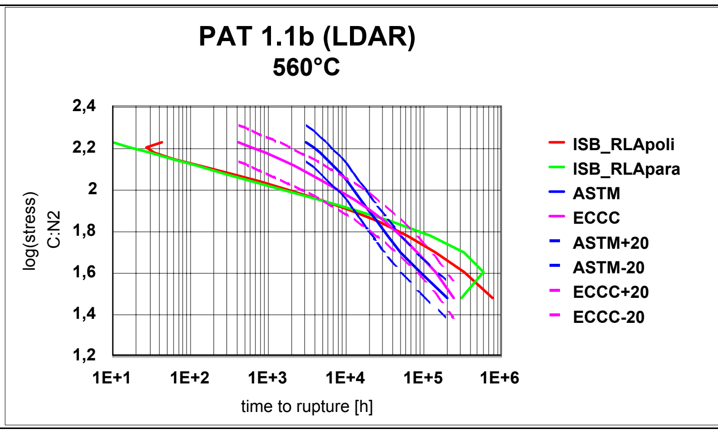
PAT1.1a – limited data



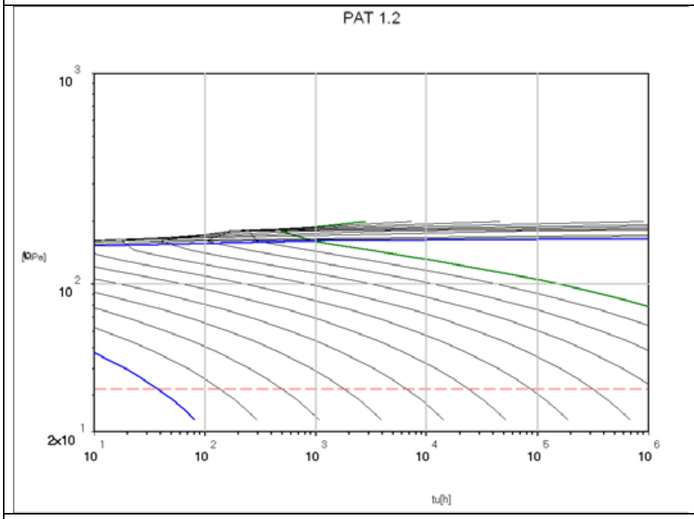
PAT1.1b 520°C



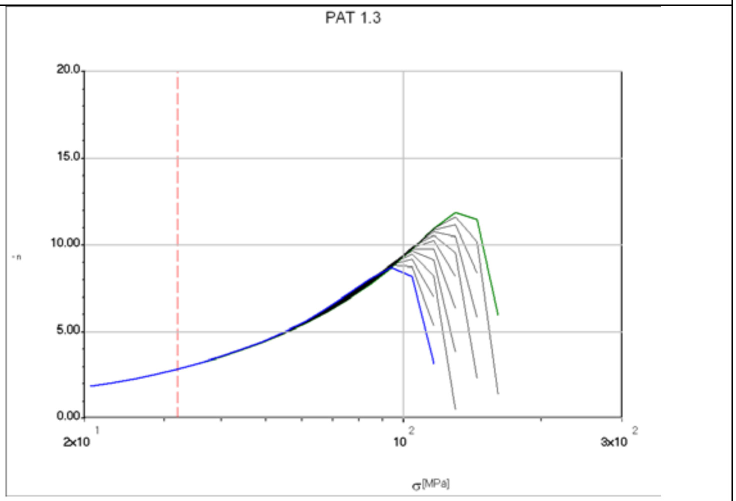
PAT1.1b 560°C



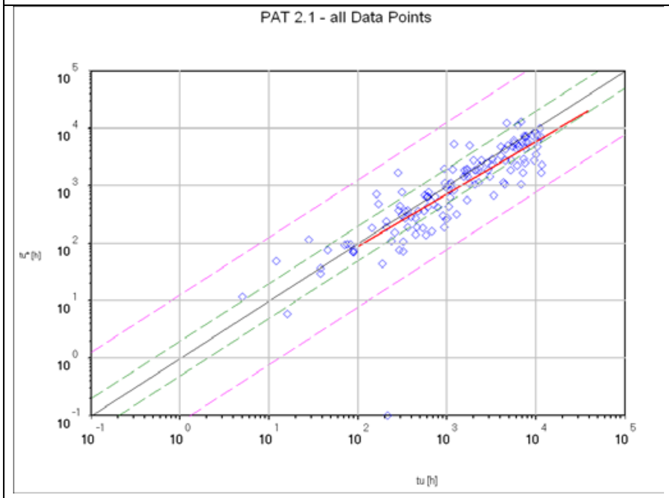
PAT1.2



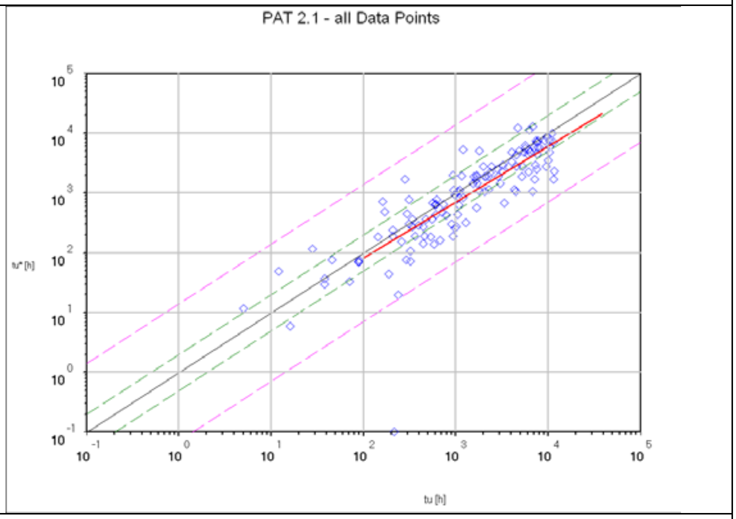
PAT1.3



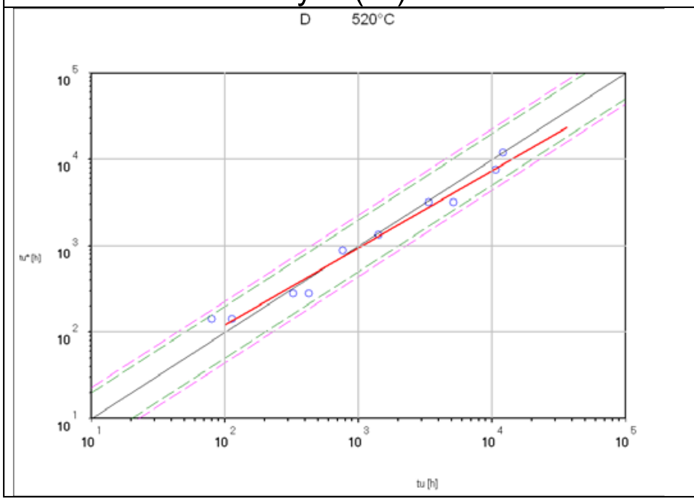
PAT2.1 – all data



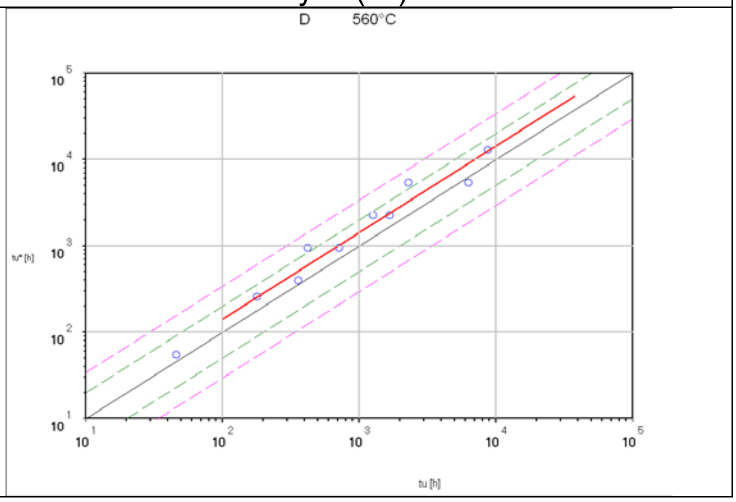
PAT 2.1 – ltd. data

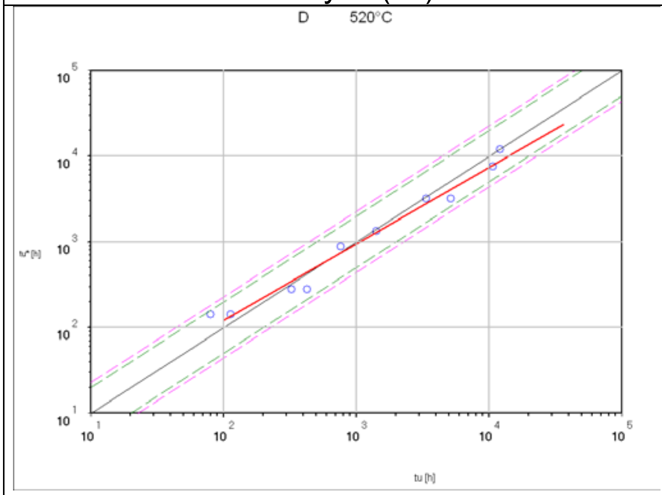
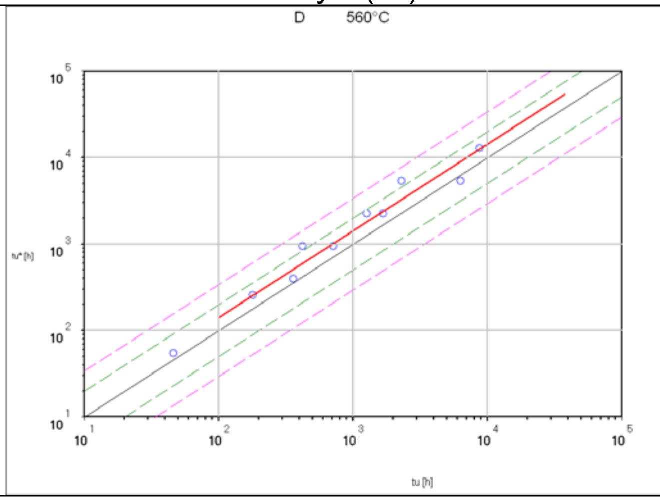
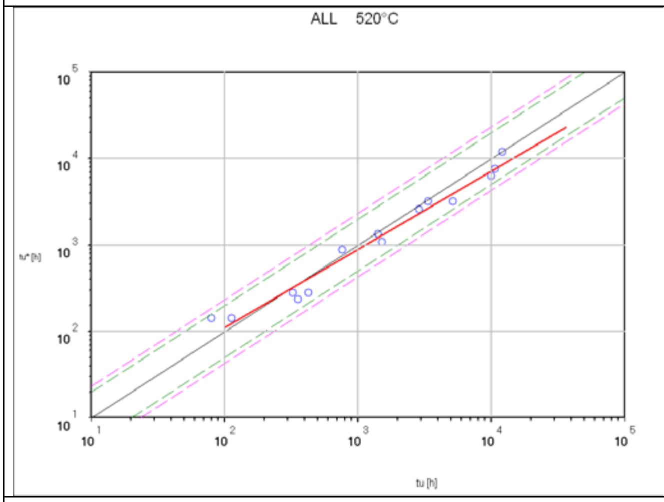
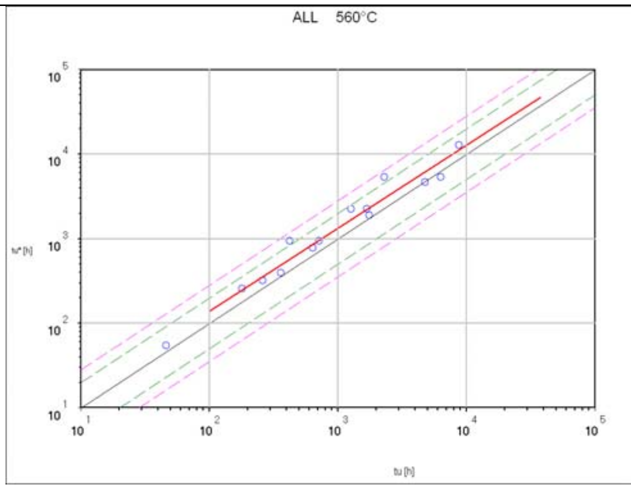
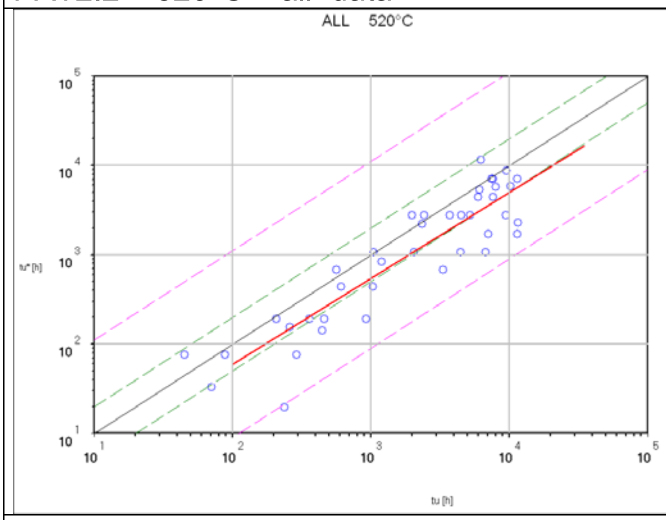
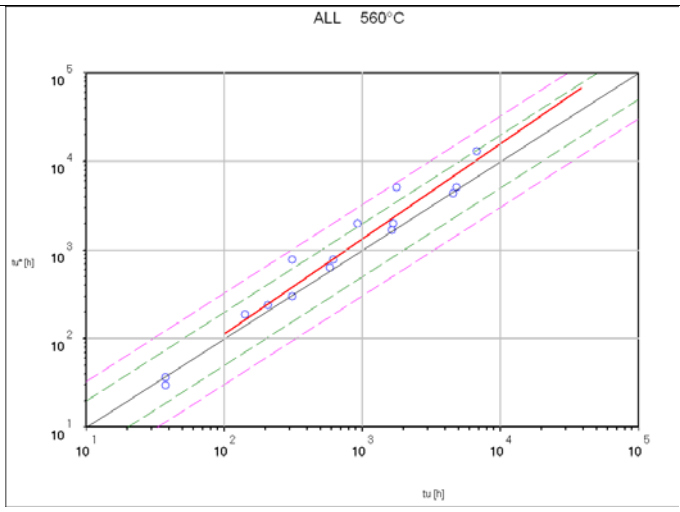


PAT2.2 520°C – only D (all)



PAT 2.2 560°C – only D (all)



PAT2.2 – 520°C – only D (ltd)	PAT2.2 – 560°C – only D(ltd)
	
PAT2.2 – 520°C – ltd. data	PAT 2.2 – 560°C – ltd. data
	
PAT2.2 – 520°C – all data	PAT 2.2 – 560°C – all data
	
PAT3.1	PAT3.2
Not done	Not done

ISB - OmRLAPara

All PE data – corrected by linear damage accumulation rule

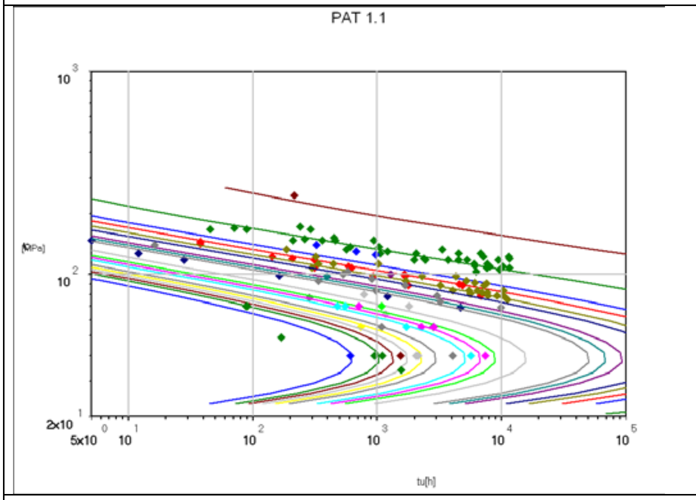
$$t_R = \left(\frac{1}{\Omega \varepsilon_0^{\bullet}} \right)$$

$$T[K](C + \log(\Omega)) = \sum_{i=0}^{4} a_i \log(\sigma)^i$$

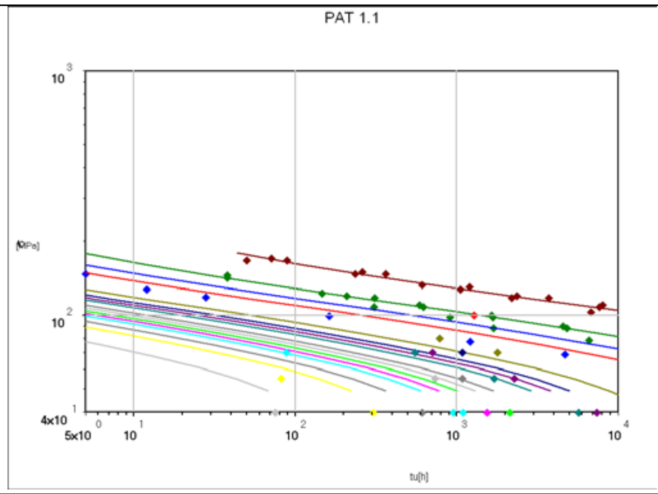
$$T[K](C_2 + \log(\varepsilon_0^{\bullet})) = \sum_{i=0}^{4} b_i \log(\sigma)^i$$

		PARA_adapt			
Om_a0	Om_a1	Om_a2	Om_a3	Om_a4	Om_C
-665,8188	1202,8285	-721,3212	146,8476	-0,082	9,45
isr_a0	Isr_a1	Isr_a2	Isr_a3	Isr_a4	Isr_C
764,5120	-1399,038	827,7138	-165,693	0,0863	-29,49

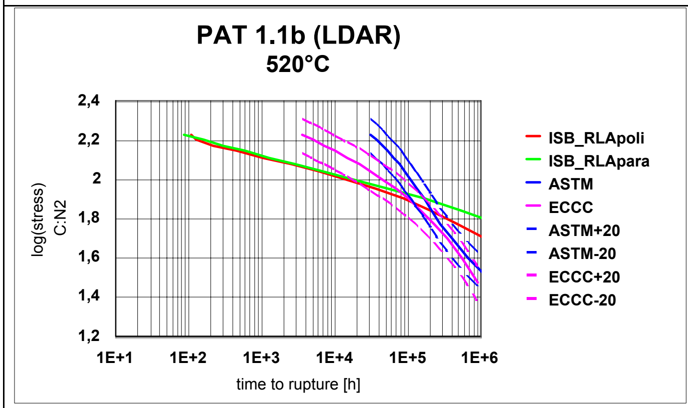
PAT1.1a – all data



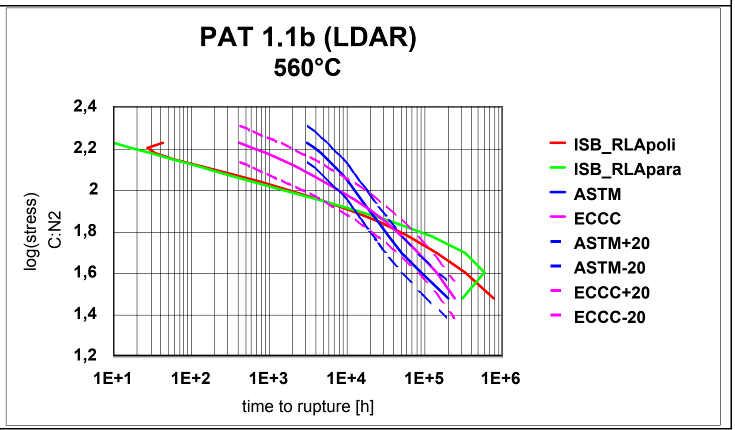
PAT1.1a – limited data

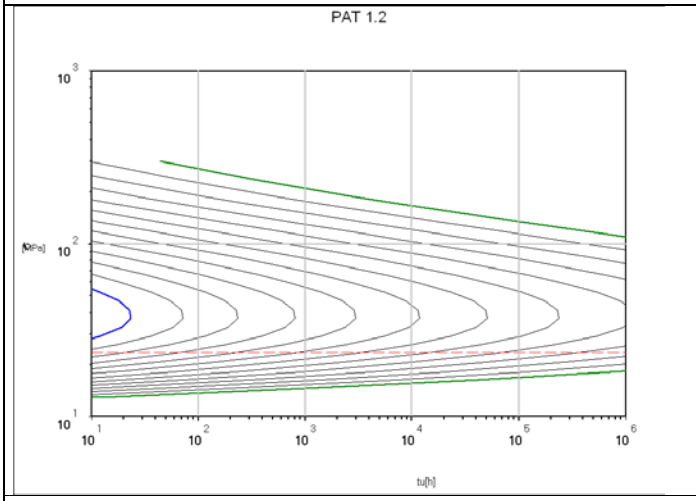
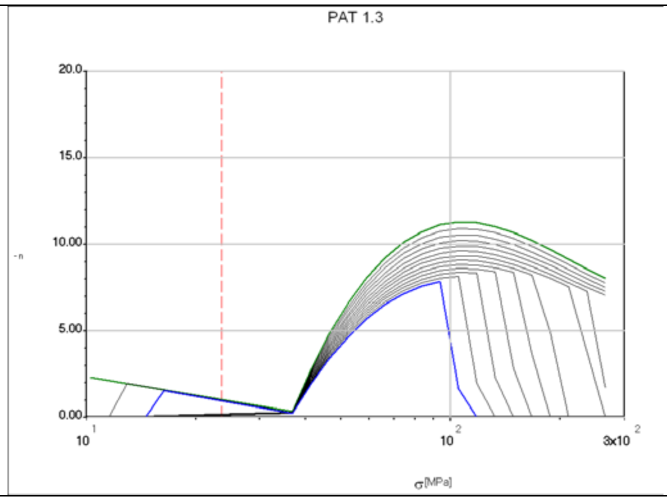
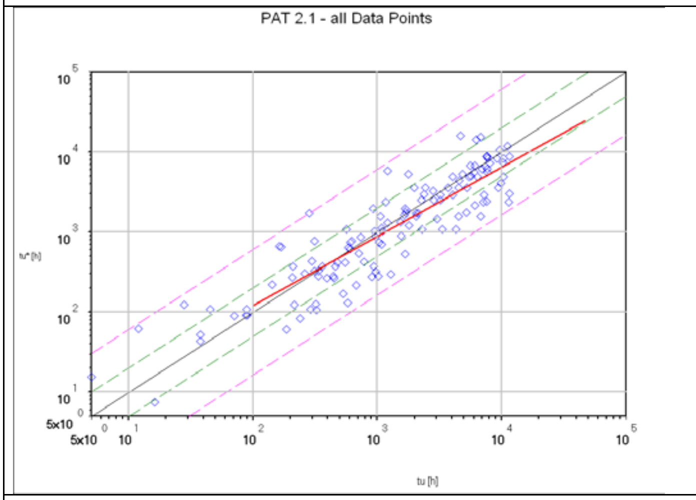
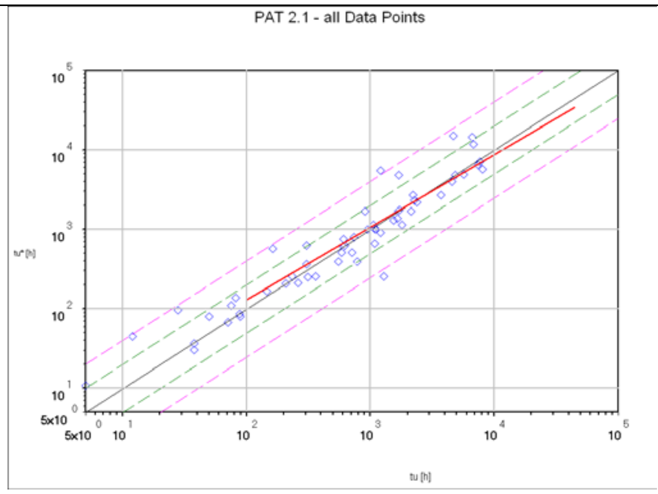
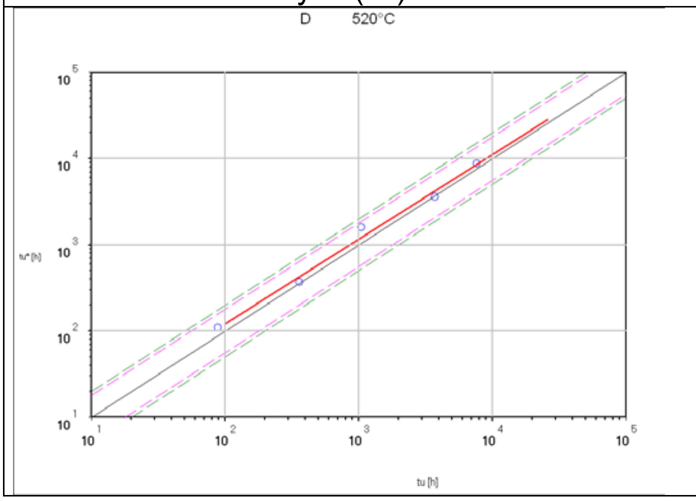
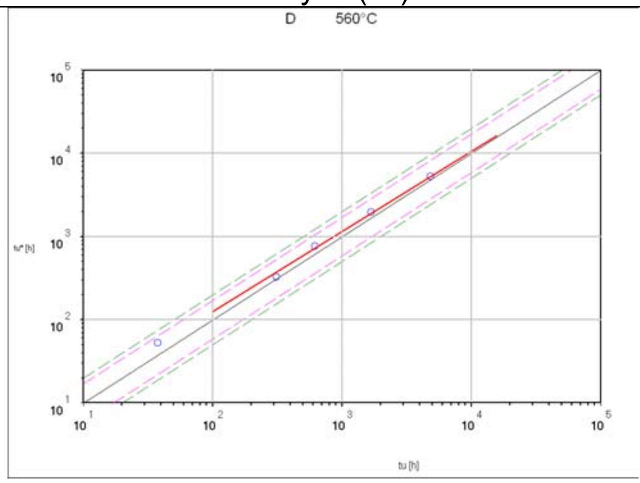


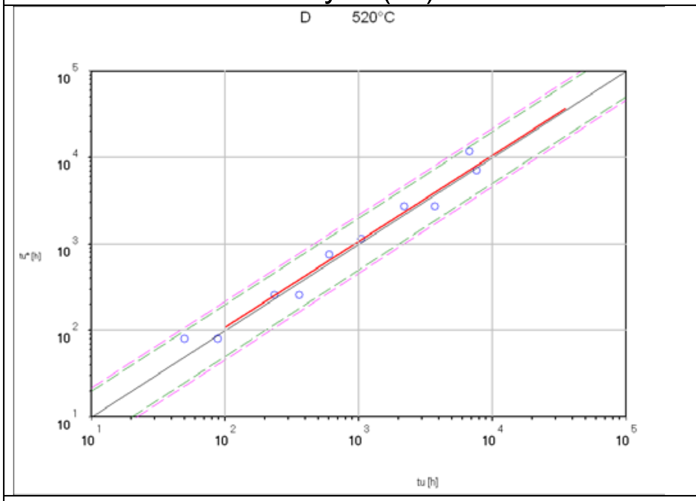
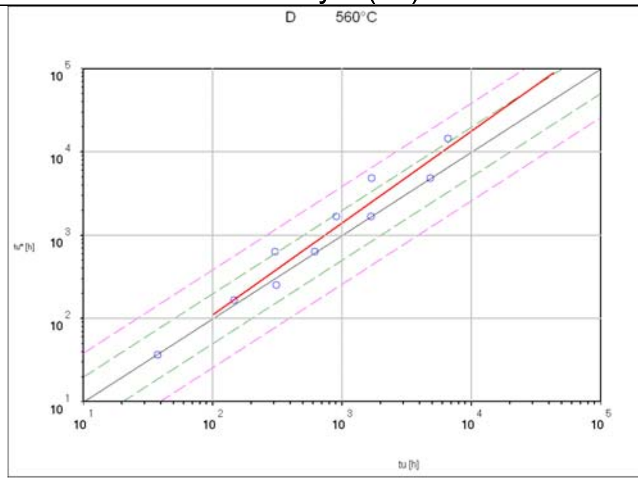
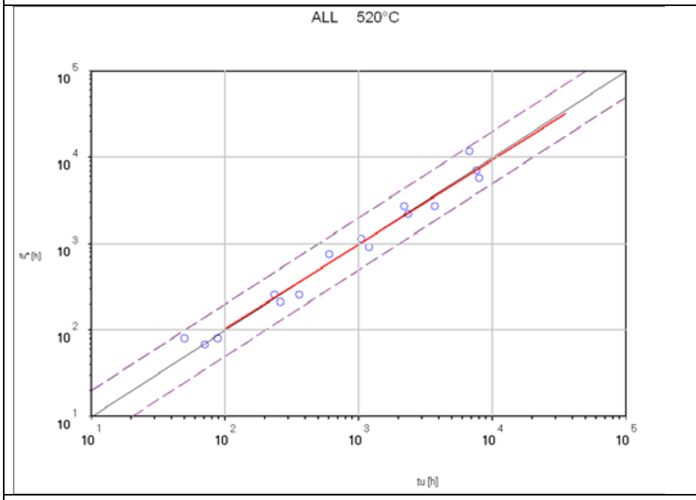
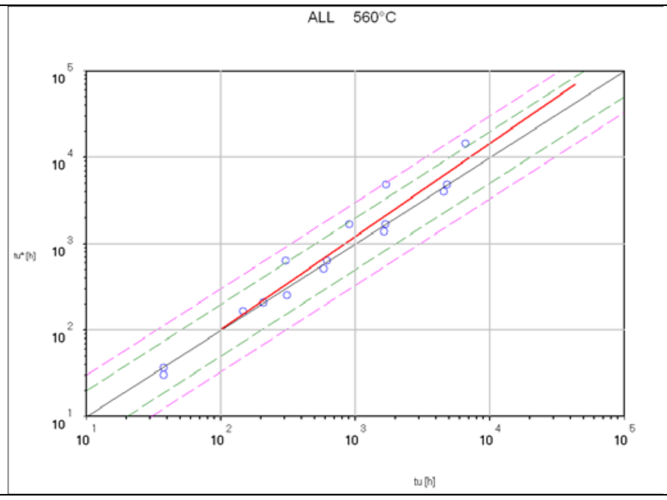
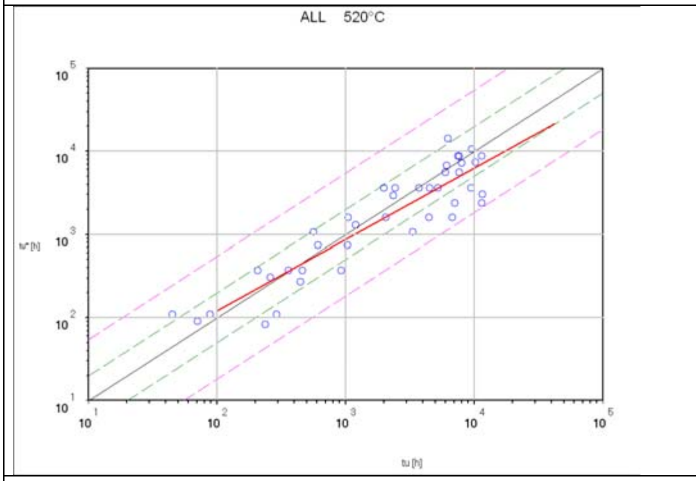
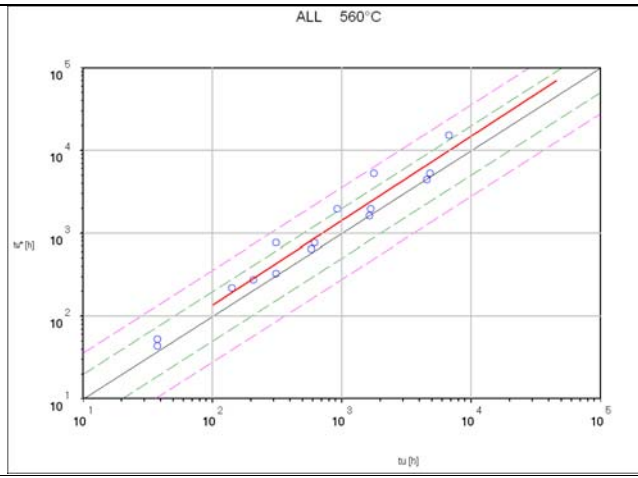
PAT1.1b 520°C



PAT1.1b 560°C



PAT1.2	PAT1.3
	
PAT2.1 – all data	PAT 2.1 – ltd. data
	
PAT2.2 520°C – only D (all)	PAT 2.2 560°C – only D (all)
	

PAT2.2 – 520°C – only D (ltd)	PAT2.2 – 560°C – only D(ltd)
	
PAT2.2 – 520°C – ltd. data	PAT 2.2 – 560°C – ltd. data
	
PAT2.2 – 520°C – all data	PAT 2.2 – 560°C – all data
	
PAT3.1	PAT3.2
Not done	Not done

	PAT	T	Data set	ISB_poli	ISB_para	ISB_RLApoli	ISB_RLApara	EON	EON2	EON4	EON5	EON6	IIS	IIS2
s_{arlt}	2.1	-	All PE	0,442	0,343	0,459	0,314	0,362	0,375	0,521	0,520	0,413	0,423	0,473
Z	2.1	-	All PE	12,7	7,2	14,0	6,1	8,0	8,7	20,1	20,0	10,8	11,4	15,2
Outliers	2.1	-	All PE	ok	Ok	ok	Ok	ok	Ok	Ok	Ok	Ok	Ok	Ok
slope	2.1	-	All PE	0,97	0,869	0,931	0,860	**0,709**	**0,761**	**0,770**	**0,771**	0,790'	0,906	0,905
Regr. limits	2.1	-	All PE	ok	**No**	ok	**No**	**no**	**no**	**no**	**No**	**No**	ok	ok
s_{arlt}	2,1	-	Ltd.PE	0,253	0,241	0,177	0,241	0,315	0,327	0,324	0,323	0,263	0,332	0,464
Z	2,1	-	Ltd.PE	4,3	4	2,8	4	6,1	6,6	6,5	6,4	4,5	6,8	14,5
Outliers	2,1	-	Ltd.PE	ok	Ok	ok	Ok	ok	Ok	Ok	Ok	Ok	Ok	Ok
Slope	2,1	-	Ltd.PE	0,907	0,914	0,924	0,914	**0,707**	**0,745**	0,819	0,821	0,817	0,98	1,014
Regr. limits	2,1	-	Ltd.PE	ok	Ok	ok	Ok	**No**	**no**	**No**	**no**	**no**	ok	ok

	PAT	T [°C]	Data set	ISB_poli	ISB_para	ISB_RLApoli	ISB_RLApara	EON	EON2	EON4	EON5	EON6	IIS	IIS2
s_{arlt}	2.2	520-	Only D (all)	0,162	0,111	0,142	0,101	0,168	0,136	0,495	0,494	0,259	0,142	0,085
Z	2.2	520-	Only D (all)	2,5	1,9	2,3	1,8	2,6	2,2	17,3	17,2	4,4	2,3	1,6
Outliers	2.2	520-	Only D (all)	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	ok	Ok
slope	2.2	520-	Only D (all)	0,982	1,004	0,893	0,979	0,806	0,846	0,913	0,915	0,910	1,034	1,023
Regr. limits	2.2	520-	Only D (all)	ok	ok	ok	Ok	**no**	**No**	**No**	**No**	**No**	ok	Ok
s_{arlt}	2.2	560-	Only D (all)	0,262	0,046	0,212	0,092	0,141	0,113	0,334	0,331	0,179	0,150	0,042
Z	2.2	560-	Only D (all)	4,5	1,3	3,4	1,7	2,3	1,9	6,8	6,7	2,8	2,4	1,3
Outliers	2.2	560-	Only D (all)	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
Slope	2.2	560-	Only D (all)	1,092	1,014	1	0,960	0,827	0,864	0,938	0,940	0,933	0,971	0,996
Regr. limits	2.2	560-	Only D (all)	**no**	ok	ok	ok	**no**	**no**	**no**	**no**	ok	ok	ok

	PAT	T [°C]	Data set	ISB_poli	ISB_para	ISB_RLApoli	ISB_RLApara	EON	EON2	EON4	EON5	EON6	IIS	IIS2
s_{arlt}	2.2	520-	Only D (ltd)	0,162	0,135	0,142	0,096	0,207	O,192	0,378	0,377	0,181	0,142	0,184
Z	2.2	520-	Only D (ltd)	2,5	2,2	2,3	1,7	3,3	3,0	8,8	8,8	2,8	2,3	2,9
Outliers	2.2	520-	Only D (ltd)	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
slope	2.2	520-	Only D (ltd)	0,982	0,992	0,893	0,952	0,903	0,835	0,902	0,904	0,898	1,034	1,010
Regr. limits	2.2	520-	Only D (ltd)	Ok	Ok	Ok	Ok	Ok	Ok	**No**	**No**	**No**	Ok	Ok
s_{arlt}	2.2	560-	Only D (ltd)	0,07	0,235	0,212	0,186	0,150	0,189	0,372	0,232	0,216	0,150	0,233
Z	2.2	560-	Only D (ltd)	1,5	3,9	3,4	2,9	2,4	3,0	8,5	3,8	3,5	2,4	3,8
Outliers	2.2	560-	Only D (ltd)	ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
Slope	2.2	560-	Only D (ltd)	1,038	1,103	1,000	1,041	0,819	0,943	0,928	1,030	0,923	0,971	1,092
Regr. limits	2.2	560-	Only D (ltd)	Ok	**no**	ok	**no**	**no**	ok	**No**	Ok	**no**	Ok	**no**

	PAT	T [°C]	Data set	ISB_poli	ISB_para	ISB_RLApoli	ISB_RLApara	EON	EON2	EON4	EON5	EON6	IIS	IIS2
s_{arlt}	2.2	520-	Ltd. data	0,156	0,123	0,147	0,094	0,185	0,174	0,406	0,405	0,204	0,123	0,150
Z	2.2	520-	Ltd. data	2,5	2,0	2,3	1,7	2,9	2,7	10,4	10,3	3,2	2,0	2,4
Outliers	2.2	520-	Ltd. data	ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
slope	2.2	520-	Ltd. data	0,955	0,979	0,901	0,946	0,790	0,828	0,894	0,897	0,891	1,028	1,000
Regr. limits	2.2	520-	Ltd. data	Ok	Ok	Ok	Ok	**No**	Ok	**No**	**No**	**No**	Ok	Ok
s_{arlt}	2.2	560-	Ltd. data	0,214	0,193	0,180	0,155	0,185	0,167	0,273	0,271	0,176	0,167	0,191
Z	2.2	560-	Ltd. data	3,4	3,0	2,8	2,4	2,9	2,6	4,8	4,8	2,8	2,6	3,0
Outliers	2.2	560-	Ltd. data	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
Slope	2.2	560-	Ltd. data	1,083	1,078	0,980	1,019	0,881	0,920	1,001	1,003	0,995	1,038	1,063
Regr. limits	2.2	560-	Ltd. data	Ok	ok	Ok	Ok	Ok	ok	ok	Ok	ok	Ok	ok

	PAT	T [°C]	Data set	ISB_poli	ISB_para	ISB_RLApoli	ISB_RLApara	EON	EON2	EON4	EON5	EON6	IIS	IIS2
s_{arlt}	2.2	520-	all data	0,380	0,365	0,438	0,296	0,366	0,338	0,669	0,668	0,475	0,341	0,308
Z	2.2	520-	all data	8,9	8,2	12,4	5,5	8,2	7,0	47,0	46,8	15,4	7,1	5,9
Outliers	2.2	520-	all data	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
slope	2.2	520-	all data	0,891	0,879	0,961	0,857	**0,708**	**0,741**	0,800	0,802	0,797	0,919	0,896
Regr. limits	2.2	520-	all data	**No**	**No**	Ok	**No**	**No**	**No**	**No**	**No**	**No**	**No**	**No**
s_{arlt}	2.2	560-	all data	0,206	0,185	0,206	0,221	0,180	0,163	0,272	0,270	0,172	0,162	0,185
Z	2.2	560-	all data	3,3	2,9	3,3	3,6	2,8	2,6	4,8	4,7	2,7	2,5	2,9
Outliers	2.2	560-	all data	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok
Slope	2.2	560-	all data	1,073	1,074	1,073	1,017	0,870	0,918	0,999	1,001	0,993	1,035	1,061
Regr. limits	2.2	560-	all data	Ok	ok	Ok	ok	Ok	ok	ok	ok	ok	ok	ok

PAT	T [°C]	Data set	ISB_poli	ISB_para	ISB_RLApoli	ISB_RLApara	EON	EON2	EON4	EON5	EON6	IIS	IIS2
1.1a	-	All data	Ok	(Ok)	Ok	No	Ok	Ok	No	No	Ok	(ok)	Ok
1.1a		Ltd data	Ok	(Ok)	Ok	Ok	Ok	(ok)	Ok	(ok)	Ok	ok	(ok)
1.1b	520		No	No	No	No	No	No	No	Ok	Ok	No	No
1.1b	560		No	No	No	No	No	No	Ok	Ok	Ok	No	No
1.2			Ok	No	Ok	No	ok	ok	Ok	Ok	Ok	Ok	Ok
1.3			Ok	(ok)	Ok	No	No	No	Ok	Ok	Ok	Ok	(ok)
2.1		All data	Ok	No	Ok	No	No	No	No	No	No	No	Ok
2.1		Ltd data	Ok	Ok	Ok	Ok	No	No	No	No	No	Ok	Ok
2.2	520-	OnlyD /all	Ok	Ok	Ok	Ok	No	No	No	No	No	Ok	Ok
2.2	520-	OnlyD /ltd	Ok	(ok)	Ok	Ok	Ok	(ok)	No	No	No	Ok	Ok
2.2	520-	Ltd data	Ok	Ok	Ok	Ok	No	(ok)	No	No	No	Ok	Ok
2.2	520-	all data	No	No	Ok	No	No	No	No	No	No	No	No
2.2	560-	OnlyD /all	Ok	Ok	Ok	Ok	No	No	No	No	Ok	Ok	Ok
2.2	560-	OnlyD /ltd	Ok	No	Ok	No	(ok)	Ok	No	Ok	(ok)	No	No
2.2	560-	Ltd data	(Ok)	(Ok)	Ok	Ok	Ok	(ok)	Ok	Ok	Ok	Ok	Ok
2.2	560-	all data	Ok	Ok	Ok	Ok	ok	Ok	ok	Ok	ok	Ok	Ok
3.1		Ltd data	Ok	Ok	-	-	-	-	-	-	-	-	-
3.2		Ltd data	ok	Ok	-	-	-	-	-	-	-	-	-
Total			No	No	No	No	No	No	No	No	No	No	No

CRL Assessment	Used CRL Method	Used data	Pipe D: further service for 50kh	Estimate of true life end [h]	Pat success
Only D, Only D, E Only D SIEM Only D SIEM2	Parametric Parametric Parametric Parametric	PE data only of Pipe D	Si Si Si Si	2.8M 32M 17M 17M	N N N N
All SIEM	Parametric	PE data of power utility steam pipes	Si	6.5M	N
All2, A All1, All SIEM2, All E	Parametric PD6605 Parametric Parametric Parametric	all PE-data	Si Si Si Si Si	330k 800k 1.4M 1.7M 6.9M	Y N N N N
All ECCC All ASTM	LDAR based on ECCC + Parametric LDAR based on ASTM + Parametric	all PE data after suitable "assimilation" process	Si Si	200k 790k	Y N
Omega Poli	Strain based MPC Omega Method (polynomial descr.)	all PE creep strain data	Si	2,5M	N
Omega Para	strain based MPC Omega Method (parametric descr.)		Si	na	N
Omega E	Strain based modified MPC Omega method		Si	90k	N
Omega E2		PE data with T < 650°C	Si	120k	N
Omega E4		2021 data + low stress PE data	si	175k	N
Omega E5		2021 data + low stress PE data with T<650°C	si	182k	N
Omega E6		2021 data + PE data with σ < 70 MPa	si	240k	N
Omega I	Strain based API RP 579 Omega method	only pipe D 520/560°C	Si	32 M	N
Omega I2			Si	105 M	N
Omega I2-ref	Full API RP 579		Si	152 M	na
Omega PoliLDAR	LDAR/ECCC +Omega Poli	all PE creep strain after suitable "assimilation"	Si	400k	N
Omega Para LDAR	LDAR/ECCC + Omega Para		Si	Na	N
New ASTM	ISO 6303	virgin material ASTM	Si	204k	N
New ECCC	DESA	virgin material ECCC	Si	240k	Y
New Omega E3	Strain based modified MPC Omega method	Virgin material 2021 project	Si	203k	?
IS	circolare ISPESL 15/92	creep strength acc. DIN 17175	Si	1,2M	N
Original E	Limite di accettabilità	virgin ASTM + PE data pipe D	Si	>50k	Y
Truth		Removal of the pipe from plant after further 100 kh. no evident damage			