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ECCC RECOMMENDATIONS - VOLUME 3 Part I [Issue 5]

DATA ACCEPTABILITY CRITERIA AND DATA GENERATION: GENERIC RECOMMENDATIONS FOR CREEP, CREEP RUPTURE, STRESS RUPTURE AND STRESS RELAXATION DATA

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DATA ACCEPTABILITY CRITERIA AND DATA GENERATION: GENERIC RECOMMENDATIONS FOR CREEP, CREEP RUPTURE, STRESS RUPTURE AND STRESS RELAXATION DATA

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A GUIDE TO ECCC RECOMMENDATIONS - VOLUME 3 Part I

ECCC Volume 3 Part 1 defines the material pedigree and testing practice information required to accompany existing and new creep, creep rupture, stress rupture and stress relaxation data for assessment by ECCC. The following guide indicates the location of the key information contained within Part 1.

ASSESSMENT DATA: MATERIAL PEDIGREE INFORMATION REQUIREMENTS

Table 1 Minimum material pedigree information requirements for EXISTING creep rupture and stress relaxation data

Table 2 Minimum material pedigree information requirements for NEW creep rupture and stress relaxation data programmes commenced after 1.1.96

ASSESSMENT DATA: TESTING PRACTICE INFORMATION REQUIREMENTS

Uninterrupted and Interrupted Creep Rupture Testing

Table 3a Minimum testing information requirements for EXISTING creep rupture data

Table 4 Minimum testing information requirements for NEW creep rupture data generated after 1.1.96 - Information (a) common to test series and (b) unique to individual test

Uniaxial and Model Bolt Stress Relaxation Testing

Table 6a Minimum testing information requirements for EXISTING stress relaxation data

Table 7 Minimum testing information requirements for NEW uniaxial stress relaxation data generated after 1.1.96 - Information (i) common to test series and (ii) unique to individual test

Table 7b Minimum testing information requirements for NEW model bolt stress relaxation data generated after 1.1.96 - Information (i) common to test series and (ii) unique to individual test

TESTING PRACTICES: REVIEW AND RECOMMENDATIONS

App. 1 Review of Creep, Creep Rupture and Stress Rupture Testing Standards and Practices

The results of this review are used to define the current lowest common testing practice specification (Table 3b) and recommended minimum requirements for the future (Table 5), ie.

Table 3b Lowest common testing practice specification based on requirements of current standards for EXISTING data

Table 5 Recommended minimum requirements for FUTURE (a) uninterrupted and (b) interrupted creep rupture testing

App. 2 Review of Stress Relaxation Testing Standards and Practices

The results of this review are used to define the current lowest common testing practice specification (Tables 6b,6c) and recommended minimum requirements for the future (Table 8), ie.

Table 6 Lowest common testing practice specification based on requirements of current standards for EXISTING data - (b) uniaxial stress relaxation tests, (c) model bolt stress relaxation tests

Table 8 Recommended minimum requirements for FUTURE (a) uniaxial and (b) model bolt stress relaxation testing

A formal list of recommendations concerning creep and rupture testing practices are given in Section 6. These form the basis of ECCC recommendations to ECISS.

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ABSTRACT

ECCC Recommendations - Volume 3 Part I defines the material pedigree and testing practice information required to accompany (i) existing and (ii) new creep, creep rupture, stress rupture and stress relaxation data for consideration by ECCC. The acceptability criteria for existing test results have been set to make full use of the available data. Those defined for new results are the consequence of a comprehensive review of current testing standards and laboratory procedures (Apps.1,2), and are aimed at improving the quality and homogeneity of data in the future. A number of recommendations are listed as part of the strategy to achieve this goal.

ECCC Recommendations Volume 3 Part I user feedback is encouraged and should be sent to:

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1. OVERVIEW

Prior to the assessment of creep, creep rupture, stress rupture[1] and stress relaxation properties, there is a need to confirm the integrity of the input data, both in terms of the pedigree of the material used and the testing practices adopted to generate the information. ECCC Volume 3 Part I considers the minimum material and testing pedigree information requirements for existing and future creep property data.

In formulating the acceptability criteria for assessment input data, one potential course of action would have been to recommend that all test results are accompanied by (i) a comprehensive list of material details and (ii) evidence to confirm that testing has been performed to conform with an acceptable modern specification. This would give complete confidence in the relevance and quality of the data, but could exclude a significant fraction of the currently available test information (some of which extends to very long durations).

The compromise has been to define minimum requirements to ensure the acceptability of existing data which have traditionally been regarded as reliable, but to recommend tighter acceptability criteria for the future. The basis for the recommendations relating to material pedigree and testing practice acceptability criteria are detailed in [1a], and Appendices 1 and 2 to this Volume. Appendix 1 covers creep and rupture testing, while Appendix 2 considers stress relaxation testing.

ECCC Volume 3 also recommends methods of determining the intermediate data used in assessment from raw laboratory test results (eg. $t_{f\varepsilon}$, $t_{p\varepsilon}$)[2]. The background to these recommendations is considered in detail in Appendix 1 for creep testing and Appendix 2 for stress relaxation testing.

2. MATERIAL PEDIGREE

The data acceptability criteria covering material pedigree are an integral part of the ECCC Terminology Document [1a].

2.1 Minimum Information Requirements for Existing Data

The minimum material pedigree information required for existing creep rupture and stress relaxation data is summarised in Table 1. These details are mandatory and essentially provide confirmation that the cast of material to which the data relate conforms to the requirements of the alloy specification under consideration in terms of chemical composition, product form and processing history.

When other information is available [1a], it should also be collated, in accordance with the format recommended in [2].

2.2 Minimum Information Requirements for New Data

The metadata requirements for the definition of material pedigree for new data[3] are more comprehensive (Table 2). The list provides a more complete description of the material and an opportunity for the effects of certain manufacturing variables on creep rupture properties to be evaluated.

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[1] creep, creep rupture and stress rupture data are referred to as creep rupture data for brevity in the following text

[2] the symbols, terms and terminology used throughout are as defined in the ECCC Terminology Document [1a]

[3] data generated for materials tested after 1.1.96

Testpiece location/orientation are considered in two different ways, both of which are regarded as acceptable. One approach is to allocate different material identifier codes to testpieces of the same material from different locations and with different orientations. In such circumstances, information concerning testpiece location/orientation is reported as part of Table 2. The alternative practice is to use one material identifier code and to identify different location/orientation information at the test description stage (ie. as part of Table 4). For new data, the requirement for information concerning location/orientation is mandatory, but may be reported as part of either Table 2 or Table 4. It is the responsibility of the databank supervisor to ensure that testpiece location/orientation information is entered in the appropriate section of his database.

As in the previous section, other information [1a] should be recorded, if available, in the format recommended in [2].

3. CREEP AND RUPTURE TESTING

Unlike material pedigree for which target requirements are set by the instigator of the assessment, the data acceptability criteria relating to testing practice are determined by the national/international standards and codes of practice adopted by the test houses (Apps.1, 2).

The minimum testing practice requirements for existing creep rupture data (Table 3) and the minimum requirements for the future (Table 4) are based on a comprehensive review of the content of nine national/international standards (Tables 1/1-16 of App.1) and the practices of ten prominent creep laboratories from six European countries (Tables 2/1-16 of App.1).

3.1 Minimum Information Requirements for Existing Data

It is assumed that the source laboratories for the existing data have followed the testing practices defined in one of the national/international standards reviewed in App.1 (ie. [3-11]), and every effort must be made to confirm that this is indeed the case. The minimum requirements defined in Table 3 are therefore set to ensure that the data generated according to any one of these standards are regarded as acceptable. The review of testing practices adopted by a number of laboratories indicates that these minimum requirements are generally exceeded by a comfortable margin (Tables 2/1-16 of App.1).

Table 3 is split into two parts. Table 3a defines the minimum testing practice information which must be supplied with existing creep rupture data before it can be considered for use in any ECCC assessment. When additional information is available it should be collated according to the format defined in [2].

Table 3b summarises the minimum testing practice specification to which existing data will have been generated if it has been gathered according to the requirements of [3-11] (Tables 1/1-16, App.1). It must be demonstrated that testing performed according to an unlisted standard/code of practice at least meets the minimum requirements tabulated in Table 3b.

3.2 Review of Existing Testing Standards

The review in App.1 collates the common features and identifies the inconsistencies between existing creep rupture testing standards. As a generality, these reflect the state-of-the-art at the time the standards were written and differences in national practices. The publication dates of the standards reviewed range from 1969 to 1991. During this time there have been significant improvements in temperature and strain measurement technology and a greater understanding of the sources and influence of errors in these parameters. In addition, while a number of the creep testing standards only consider the continuous measurement of creep strain using extensometry in uninterrupted tests (Section 2.3, [1a]), others are specifically written to also cover the measurement of total plastic strain by means of a measuring microscope during planned test interruptions in interrupted tests [3,5 -8]. The minimum requirements for new data recognise these considerations.

3.3 Minimum Information Requirements for New Data

The minimum testing practice information requirements for new creep and rupture data are given in Table 4. The table lists the new information requirements which should be regarded as mandatory for new material data generated for use by ECCC after 1.1.96 (ie. for test programmes started after this date). Table 4 is split into two parts. Table 4a contains the information requirements common to the test series, whereas Table 4b contains the information requirements unique to each test.

In practice, the scientist/engineer performing a creep rupture data assessment requires (i) certain basic testing information to hand (Table 4), (ii) an assurance that sensing device calibration and the tests have been conducted in accordance with an acceptable standard, and (iii) an assurance that the quality and consistency of the test data have been critically evaluated by the testing laboratory prior to release[4].

The comprehensive review of existing testing standards and laboratory practices in App.1 led to the formulation of a list of minimum requirements for (a) new uninterrupted (continuous measurement) and (b) interrupted creep rupture tests (Tables 5a and 5b respectively). When the recommendations were first formulated, a single testing standard/code of practice specifying the proposed requirements was unavailable. However, with the recommended amendments listed in Sect.6.1, ISO/DIS 204 [11] would provide an acceptable minimum standard for uninterrupted creep testing. Moreover, an equivalent standard was urgently required for interrupted creep testing. In the meantime, a new European Standard for uninterrupted and interrupted creep testing has been published which incorporates many of the recommendations listed in Sect.6.1 [12].

The consequence on the level of experimental uncertainties of adopting the proposed specification for creep rupture testing is considered for some typical examples in App.1. For example, the improvements in accuracy which may be achieved in the measurement of low creep strains (ie. $\varepsilon_p \leq 0.2\%$) in both uninterrupted and interrupted tests are quantified (Tables 4-10, App.1). Moreover, it is clear that in future, every effort should be made to maintain the tightest possible tolerances on applied load, temperature and strain measurement, irrespective of test method. In this respect, times to rupture and specific creep strains are particularly sensitive to relatively small variations in test temperature.

While every effort has been made to accurately estimate the uncertainties associated with various testing practices (App.1), there is a real need to establish the actual levels associated with high and medium sensitivity, uninterrupted and interrupted creep tests when used to determine the long duration properties of engineering steels at their normal operating temperatures (and the range of testing parameters and test results to which these uncertainties apply).

4. STRESS RELAXATION TESTING

The minimum testing practice requirements for existing stress relaxation data (Table 6) and the minimum requirements for the future (Table 7) are based on a review of the contents of five national standards (Tables 1/1-6 & 2/1-6 of App.2) and the practices of nine prominent creep testing laboratories from four European countries (Tables 3/1-11 of App.2).

4.1 Minimum Information Requirements for Existing Data

It is assumed that the source laboratories for existing stress relaxation data have followed the testing practices defined in one of the national standards reviewed in App.2 (ie. [13-17]), and every effort should be made to confirm that this is indeed the case. As for the minimum creep-

[4] The validation of test data integrity in terms of quality and consistency with associated results (prior to reporting) should be an integral part of any future testing standard - see App.1.

rupture testing practice requirements (Sect.3.1), the conditions defined in Table 6 are set to ensure that existing data generated according to [13-17] are regarded as acceptable. The review of testing practices adopted by the laboratories surveyed, indicates that these minimum requirements are generally exceeded by a comfortable margin (Tables 3/1-11 of App.2).

Table 6 is split into three parts. Table 6a defines the minimum testing practice information which must be supplied with existing stress relaxation data before it can be considered for use in any ECCC assessment. When additional information is available, it should be collated according to the format defined in [2].

Table 6b summarises the minimum testing practice specification to which existing uniaxial stress relaxation data will have been generated if it has been gathered according to the requirements of [13-16] (Tables 1/1-6 of App.2). It must be demonstrated that testing performed according to an unlisted standard/code of practice at least meets the minimum requirements tabulated in Table 6b.

Table 6c summarises the minimum testing practice specification to which model bolt stress relaxation data will have been collected, and is based on [17]. The SEP 1260 standard covers the testing of single material model bolt assemblies (those with component parts of different materials are regarded as special cases).

4.2 Review of Existing Testing Standards

The existing uniaxial and model bolt stress relaxation testing standards are reviewed in App.2. The common features in the four uniaxial testing standards [13-16] are collated and the inconsistencies identified (Tables 1/1-6 of App.2). In the case of model bolt testing there is only one draft standard [17] (Tables 2/1-6 of App.2).

The publication dates of the existing standards concerned with uniaxial stress relaxation testing date between 1969 and 1984 and reflect the state-of-the-art at the time they were prepared. The improvements in recent years in temperature and strain measurement technology and the greater understanding of the sources and influences of error in these parameters have already been acknowledged in Sect.3.2. The impact of these advances on the quality of stress relaxation data is potentially greater than on creep rupture data, and there is an urgent requirement to incorporate these into a state-of-the-art standard[5].

4.3 Minimum Information Requirements for New Data

The minimum testing practice information requirements for new stress relaxation data are given in Table 7a (uniaxial) and Table 7b (model bolt). The tables list the new information requirements which should be regarded as mandatory for new material data generated for use by ECCC after 1.1.96 (ie. for test programmes started after this date). Table 7a and 7b are split into two parts. Tables 7a(i) and 7b(i) contain the information requirements common to the test series, whereas Tables 7a(ii) and 7b(ii) contain the information requirements for each test.

As for creep rupture data analysis, the scientist/engineer performing an assessment of stress relaxation data requires (a) a knowledge of certain basic test information (Table 7), (b) an assurance that sensing device calibration and the tests have been performed in accordance with an acceptable standard, and (c) an assurance that the quality and consistency of the test data have been critically evaluated by the testing laboratory prior to release.[4]

The comprehensive review of existing testing standards and laboratory practices in App.2 has led to the formulation of a list of minimum requirements for new uniaxial and model bolt stress relaxation tests (Tables 8a and 8b respectively). There is an urgent requirement for modern

[5] New codes of practice for uniaxial and model bolt stress relaxation testing have been prepared and validated in BCR Project No.3127 [18].

standards covering both uniaxial and model bolt stress relaxation standards, and the recommendations listed in Sects.6.2 and 6.3 provide a basis for these.[6]

5. PRE-ASSESSMENT DATA PROCESSING

5.1 Creep Strain Results

The output from a creep test comprises a series of displacement-time co-ordinates, displacement readings being converted to strain values using the reference length, L_r.

Reference Length

In certain circumstances, the reference length is coincident with the extensometer gauge length and strain is determined with minimum error, eg. when the extensometer is fitted directly to the testpiece gauge section by pin or knife edge contact. Significant errors are possible if the reference length is not coincident with the extensometer/fiducial mark gauge length and no correction is made in the calculation of strain, eg. when the measurement points are located on shoulders or gauge length ridges with blend radii [20].

A simple approximate method of converting extensometer gauge length to reference length is given in [8,11]. The standards recommend that the reference length of a testpiece with ridges or shoulders is determined using the expression:

$$L_r = L_c + 2\sum_{i=1}^{N} l_i (d_o / d_i)^{2n} \qquad \text{for} \qquad L_o - L_c = 2\sum_{i=1}^{N} l_i \tag{1}$$

where L_c is the parallel length, L_o is the gauge length, d_o is the diameter of the parallel length and d_i is the mean diameter of the ith length increment, l_i, between the end of the parallel length and the end of the gauge length. In [8,11], the Norton stress exponent, n, in $\dot{\varepsilon}_{min} = C\sigma^n$ is taken to be equal to 5.

A WG1 evaluation of the sensitivity of the L_r calculation to n has highlighted the importance of using the exponent value specific to the material and temperature/stress conditions under consideration (App.1). In the absence of specific information for n, the following approach is recommended. Initially, values of n derived for other casts of the same alloy class may be used, or if these are unavailable, assume n equal to 5. Acceptable estimates of n are obtained from $n_{f\varepsilon} = \partial(\log t_{f\varepsilon})/\partial(\log \sigma_o)$ or $n_{p\varepsilon} = \partial(\log t_{p\varepsilon})/\partial(\log \sigma_o)$ values derived from the appropriate creep strength versus time diagram, where the creep strength is for a creep strain in the secondary regime[7]. As this information becomes available during the course of the test programme, the preliminary strain values should be recalculated using the appropriate value of n.

Creep Deformation Data

The analysis of creep strain data for the determination of constitutive equations to form the basis of models used in design/remaining life assessment will be considered in a future issue of Volume 5 [21]. This section of Volume 3 is concerned with the evaluation of experimental creep strain-time records to provide time to specific plastic strain or time to specific creep strain data for assessment (ie. $t_{p\varepsilon}$ or $t_{f\varepsilon}$). This is usually a process of interpolation between directly measured strain readings.

For uninterrupted (continuous measurement) creep tests, the accuracy of $t_{p\varepsilon}$ or $t_{f\varepsilon}$ is generally determined by the accuracy of the measured strains since the time intervals between recordings are normally small (ie. typically no more than a few hours, prior to data reduction, compared with a test duration of thousands of hours).

[6] prEN 10319 has been produced in response to this requirement [19]

[7] The use of $n_{p\varepsilon}$ is only recommended when initial plastic strains are <0.1%

In interrupted tests, the interruption interval also becomes important (App.1). Practices vary from linear interpolation between [log ε_p,log t] co-ordinates to curve fitting. It is demonstrated analytically in App.1 (Tables 4-7) that for interrupted tests performed in accordance with [8], accurate $t_{p\varepsilon}$ may be determined using the DIN 50 118 linear interpolation approach, providing the recommended interruption frequency is adopted.

5.2 Stress Relaxation Results

Uniaxial Testing

The output from a uniaxial stress relaxation test comprises a series of stress-time co-ordinates. The main problem in interpretation occurs if there are steps in the stress relaxation curve. These may be the result of (i) a furnace or laboratory temperature transient, (ii) ineffective extensometer performance at low relaxation rates or (iii) a test interruption. It is necessary to know the factor(s) responsible for individual steps since this (these) could influence the strategy adopted to smooth the curve in the vicinity of the discontinuity.

Steps due to (i) and (ii) should be relatively uncommon in laboratories implementing tight control over testing practice. The consequence of a test interruption on the stress relaxation curve can be minimised when it is feasible to off-load under controlled conditions. However, advice on the procedures to follow during an off-load/on-load interruption is not given in any of the existing standards, and it is strongly recommended that any new standard provides comprehensive guidance on this matter[5].

As for the determination of creep strain, the maintained total strain in a uniaxial stress relaxation test is determined on the basis of reference length. An n value equal to unity is recommended for the calculation of L_r using Eqn.1 for stress relaxation testing purposes.

Model Bolt Testing

A single [σ_R,t] co-ordinate is obtained from one model bolt test; a full relaxation curve being derived from the results of a number of tests. The remaining stress is determined from a knowledge of the elastic strain measured cold during bolt un-loading and the elastic modulus determined at the test temperature. Traditionally, the elevated temperature modulus used has been a 'static' value determined at a relatively low strain rate in a standard tensile test (ie. $E_{T(S)}$). Elastic modulus is strain rate sensitive at elevated temperatures due to recovery effects [22], and it is now accepted that a high strain rate (dynamic) value, $E_{T(D)}$, should be used in the determination of σ_R (App.2).

For a given Type (a) model design, L_r should be validated by comparing strain measurements determined from the mechanical extensometer and strain gauges located on the shaft.

6. RECOMMENDATIONS

The main recommendation concerning creep rupture *[and stress relaxation]* testing practice is that every effort should be made to maintain the tightest possible practical tolerances on temperature, applied *[or measured]* load and measured *[or applied]* strain (Apps.1,2). In this respect, times to specific events are particularly sensitive to temperature tolerance. The following recommendations target this overall goal.

6.1 Creep and Rupture Testing

6.1.1 Following the publication of Issue 4 of Part I, the recommendations contained in 6.1.2 to 6.1.12 have largely been incorporated into the new European creep testing standard, EN 10291 [12]. Those which have not been adopted are identified in Table 5a. New uninterrupted (continuous measurement) creep rupture data generated for use by ECCC should at least meet the requirements of EN 10291. Ideally, they should fully meet the requirements identified in 6.1.2 to 6.1.12.

6.1.2 For testpieces with $5 \leq d_o \leq 10$mm, a shape tolerance of ±0.02mm and a measurement accuracy of ±0.005mm is recommended for d_o. The reference length should be $\geq 3d_o$ ($\geq\sim 5d_o$ preferred), with a tolerance, ΔL_o, of 0.01 L_o.

Guidance for the determination of L_r for creep testpieces is given in Sect.5.1.

6.1.3 Maximum total-temperature deviations of ±3/4/5/6/7/8°C must be set for temperatures up to 600/800/1000/1100/1200/1350°C (where total-temperature deviation is true testpiece temperature minus specified test temperature).

As a guideline, measured-temperature deviations shall not exceed ±2°C up to 1000°C and ±3°C for 1000<T<1350°C. Measured-temperature deviation is the difference between the testpiece temperature and the temperature specified for the measurement equipment. The temperature specified for the measurement equipment is the specified test temperature corrected for all systematic errors which can be determined (refer App.1).

6.1.4 Base metal thermocouples should only be used at temperatures below 400°C or for times less than 1,000h, and should not be re-used. Above 400°C, rare metal thermocouples should be re-calibrated[8] after 4 years continuous service at temperatures up to 600°C, after 2 years for temperatures in the range 600 to 800°C, and after 1 year for temperatures in the range 800 to 1350°C <u>or</u> at the end of test when these periods are exceeded during the test[9].

Experience may dictate that the recommended re-calibration periods have to be reduced when thermocouples are used repeatedly for short duration tests.

Re-calibration periods for other types of thermocouple must be defined on the temperature drift criteria defined in Footnote 9.

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[8] Two thermocouple recalibration strategies are available. The objective of both is to ensure that the emf indicated by the thermocouple at the calibration temperature (corrected, where necessary, for all systematic errors) equates as closely as possible to the emf defined by the appropriate IEC 584-1 reference table for that temperature. Both strategies employ the use of reference thermocouples which are directly traceable to a National Standard. A pre-requisite is that the calibration tolerance of the new thermocouple is in accordance with IEC 584-2, Class 1 or an equivalent standard.
<u>Strategy 1</u> is based on in-situ-recalibration of the thermocouple, ie. thermocouple recalibration either in the actual testing furnace or in a calibration furnace with the same depth of immersion and temperature gradient along the thermocouple wires. The error determined during in-situ-recalibration is used to correct the specified temperature of the thermocouple. Reference thermocouple drift due to variable immersion depth during active and passive service is surveyed and minimised. If the error exceeds the limit associated with the uncertainty relating to immersion depth, the thermocouple is scrapped.
<u>Strategy 2</u> involves recalibration of the thermocouple in a calibration furnace in which the depth of immersion is similar to that in the testing furnace. If, on recalibration, the IEC 584-2 Class 1 tolerance is exceeded, the thermocouple is cut back/re-welded at the hot junction and/or annealed and re-calibration repeated.

[9] The recommended re-calibration times for Type S and Type R thermocouples are based on well established experience of the performance of these types of sensor and the observed times for which maximum thermocouple drift errors are maintained within the limits ±1/1.5/2/3/4/5°C for temperatures up to 600/800/1000/1100/1200/1350°C (App.1).

6.1.5 The combined heating and soaking time should be less than 24h (but ≤4h heating and ≤3h soaking following interruptions in interrupted tests).

6.1.6 Loading times should be limited to ≤10min, the load being applied as quickly as possible without shock.

6.1.7 The maximum bending stress due to misalignment on loading should be as small as possible. A limit of ±20% of the axial stress is a goal for the future.

6.1.8 Times should be known to an accuracy of better than ±1%.

6.1.9 The maximum deviation in laboratory air temperature should be limited to ±3°C when extensometers are used for uninterrupted (continuous measurement) creep testing. The temperature should be maintained to within ±2°C in the strain measurement laboratories used for interrupted test specimen inspection.

6.1.10 Average uninterrupted creep strain measurements should be made such that the total displacement error does not exceed ±max[0.01ΔL, 3μm]. Initial plastic strain and creep strain must be determined on the basis of reference length (Sect.5.1)[10].

6.1.11 It is recommended that cold and hot elastic modulus checks are performed on load-line assembled uninterrupted creep testpieces, prior to the start of test (to a fraction of σ_o), to confirm the integrity and accuracy of displacement extensometry. The measured values of E_S and $E_{S(T)}$ should be within ±10% of the expected value for the material.

6.1.12 The validation of test data integrity in terms of quality and consistency with associated results, prior to reporting, should become an integral part of any future testing standard.

6.1.13 Following the publication of Issue 4 of Part I, a procedure for interrupted creep rupture testing was incorporated into the new European creep testing standard, EN 10291 [12]. A number of the requirements relevant to interrupted testing in 6.1.2 to 6.1.12 and in 6.1.14 are included. Those which have not are identified in Table 5b. New interrupted creep rupture data generated for use by ECCC should at least meet the requirements of EN 10291. Ideally, they should fully meet the requirements identified in 6.1.2 to 6.1.12 and 6.1.14.

6.1.14 For interrupted creep rupture testing, there is the need for an accompanying hot tensile test performed at approximately the same loading rate to provide ε_i. The total error on the displacement measurement used to determine total plastic strain should not exceed ±max[0.01ΔL, 10μm]. Permanent strain[11] must be determined on the basis of reference length (Sect.5.1).

6.1.15 The uncertainties associated with strain determinations in high and medium sensitivity, uninterrupted and interrupted creep tests on engineering steels at normal operating temperatures should be established in a testing programme devised to quantify measurement repeatability and reproducibility.

6.1.16 Laboratory accreditation is recommended as a means of ensuring that testing standards are applied and that the results of testing are adequately documented.

6.1.17 The introduction of a scheme to encourage regular comparison testing is recommended to encourage high quality and homogeneity of test results.

The recommended minimum requirements for future uninterrupted and interrupted creep rupture testing are summarised in Tables 5a and 5b respectively.

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[10] The reference length may be different for the two measurements. However, until the results of further studies are available, it must be assumed to be the same, ie. that determined on the basis of creep deformation (Sect.5.1)

[11] Plastic strain (ε_p) is the sum of the permanent strain (ε_{per}) and the anelastic strain (ε_k), Table 1/16, App.1. Usually, ε_k is negligible and $\varepsilon_p \approx \varepsilon_{per}$.

6.2 Uniaxial Stress Relaxation Testing

6.2.1 It is recommended that the approved version of the Standard, prEN 10319 [19] should incorporate the guidance contained in 6.2.2 to 6.2.13.

6.2.2 Testpieces with $d_o \geq 5mm$ are permitted, although $d_o \geq 8mm$ are preferred. A shape tolerance of ±0.02mm and a measurement accuracy of ±0.005mm are recommended for d_o. The reference length should be greater than $10d_o$ (≥100mm preferred), with a tolerance of ±1%.

Guidance for the determination of L_r for stress relaxation testpieces is given in Sect.5.2.

6.2.3 Maximum total-temperature deviations of ±3/4/5°C must be set for temperatures up to 600/800/1000°C (where total-temperature deviation is true testpiece temperature minus specified test temperature, see 6.1.3).

6.2.4 The guidance given on thermocouples in 6.1.4 is also recommended for stress relaxation testing.

6.2.5 The combined heating and soaking time should be less than 24h with >1h at temperature before the start of test.

6.2.6 Loading times should be limited to ≤10min, the load being applied as quickly as possible without shock. The loading rate should be consistent with that applied in any associated hot tensile and creep tests, as appropriate.

6.2.7 The maximum bending stress due to misalignment on loading should be as small as possible. A limit of ±20% of the axial stress is a goal for the future.

6.2.8 Times should be known to an accuracy of better than ±1%.

6.2.9 The maximum deviation in laboratory air temperature should be limited to ±3°C when extensometers are used for stress relaxation testing.

6.2.10 Total strain should be controlled by maintaining the displacement across the reference length within the limits $\pm max[0.01\varepsilon_t.L_r, 0.000025L_r]$. The total strain achieved should be within $\pm max[0.01\varepsilon_t, 0.002]\%$ of the target strain. The control strain must be pre-determined on the basis of reference length. Guidance for the determination of L_r for uniaxial stress relaxation testpieces is given in Sect.5.2.

6.2.11 A new uniaxial stress relaxation standard should contain comprehensive guidance on the procedures to adopt during off-load/on-load test interruptions.

6.2.12 The recommendations contained in 6.1.11 and 6.1.13-15 are equally applicable to uniaxial stress relaxation testing.

6.2.13 It is recommended that cold and hot elastic modulus checks are performed on the load-line assembled stress relaxation testpiece, prior to the start of test (to a fraction of σ_o), to confirm the integrity and accuracy of displacement extensometry. The measured values of E_S and $E_{T(S)}$ should be within ±10% of the expected value for the material.

The recommended minimum requirements for future uniaxial stress relaxation testing are summarised in Table 8a.

6.3 Model Bolt Stress Relaxation Testing

6.3.1 It is recommended that the approved version of the Standard, prEN 10319 [19] should incorporate the guidance contained in 6.3.2 to 6.3.11.

6.3.2 Bolts with $d_o \geq 8mm$ are permitted, although $d_o \geq 12mm$ is preferred. A shape tolerance of ±0.02mm and a measurement accuracy of ±0.005mm are recommended for d_o.

The length to diameter ratio should be $L_r/d_o \geq 10$ for model bolts of Type (a) and $L_c/d_o \geq 5$ for Type (b) [17], with a tolerance of ±1% on $L_r(L_c)$.

6.3.3 Maximum total-temperature deviations of ±3/4/5°C must be set for temperatures up to 600/800/1000°C (where total-temperature deviation is true testpiece temperature minus specified test temperature, see 6.1.3).

6.3.4 The guidance given on thermocouples in 6.1.4 is also recommended for stress relaxation testing.

6.3.5 Heating and cooling rates for model bolts should be controlled within the range 50 to 100°C/h to minimise thermal stresses.

6.3.6 The maximum bending stress due to misalignment on loading should be as small as possible.

6.3.7 Times should be known to an accuracy of better than ±1%.

6.3.8 The variation in laboratory air temperature should be maintained to within ±2°C when an extensometer is used to determine extension (ie. Type (a)).

6.3.9 Total initial strain should be applied within the limits $\pm 0.01\varepsilon_t$. When an extensometer is used, the initial total strain must be pre-determined on the basis of reference length within the limits $\pm \max[0.01\varepsilon_t.L_r, 0.000025L_r]$. Guidance for the determination of L_r in these circumstances is given in Sect.5.2.

6.3.10 The new standard should recommend the use of dynamic elastic modulus to determine the relaxed stress (ie. $E_{T(D)}$).

6.3.11 The recommendations contained in 6.1.11 and 6.1.13-15 are equally applicable to model bolt stress relaxation testing.

The recommended minimum requirements for future model bolt stress relaxation testing are summarised in Table 8b.

7. SUMMARY

ECCC-WG1 Volume 3 Part I defines the material pedigree and testing practice information required to accompany (i) existing and (ii) new creep, creep rupture, stress rupture and stress relaxation data for consideration by ECCC. The acceptability criteria for existing data have been set to make full use of the available results. Those defined for new data are the consequence of comprehensive reviews of current testing standards and laboratory procedures (Apps.1, 2) and are aimed at improving the quality and homogeneity of data in the future. A number of recommendations are listed as part of the strategy to achieve this goal.

It is strongly recommended that the new standards defining procedures for (i) uninterrupted creep rupture testing, (ii) interrupted creep rupture testing, (iii) uniaxial stress relaxation testing and (iv) model bolt stress relaxation testing should fully adopt the recommendations listed in ECCC Volume 3 Part I.

8. REFERENCES

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17 SEP 1260, 1996, 'Relaxationsversuch bei erhöhter Temperatur mit Schraubenverbindungs-modellen'', Stahl-Eisen-Prüfblätter des Vereins Deutscher Eisenhüttenleute.

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19 prEN 10319, 2000, 'Metallic materials - Tensile stress relaxation testing'.

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21 ECCC Recommendations Volume 5, 2001, 'Guidance for the assessment of creep rupture, creep strain and stress relaxation data', ed. Holdsworth, S.R. & Merckling, G., publ. ERA Technology Ltd, Leatherhead, (a) Part I 'Generic recommendations and guidance for full-size datasets', (b) Part IIa 'Recommendations for the assessment of sub-size creep-rupture data', (c) Part IIb 'Recommendations for the assessment of weld creep-rupture datasets', (d) Part III 'Recommendations for the assessment of post exposure (ex-service) creep data'.

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Table 1 MINIMUM MATERIAL PEDIGREE INFORMATION REQUIREMENTS for Creep Rupture and Stress Relaxation Data EXISTING before 31.12.95

CATEGORY	MINIMUM INFORMATION REQUIRED[(a)]
Material Codes	- cast/heat number and/or material code used by testing laboratory[(b)] - country code[(c)]
Material Pedigree	- alloy name[(d)] - chemical composition (product or cast/heat)[(e)] - product form (with dimensions if available) - heat treatment *time*[(f)]/temperature/cooling medium

Table 2 MINIMUM MATERIAL PEDIGREE INFORMATION REQUIREMENTS for NEW Creep Rupture and Stress Relaxation Data Generated after 1.1.96

CATEGORY	MINIMUM INFORMATION REQUIRED[(a)]
Material Codes	**- cast/heat number** **- material code used by testing laboratory** - **country code[(c)]** - laboratory code[(g)]
Material Pedigree	**- specification and/or grade name** - **chemical composition (product or cast/heat)[(e,h)]** - *supplier/material manufacturer* (*country code*)[(c,f)] - *primary melt process*[(f)] - *deoxidation practice*[(f)] - *secondary melt process* (*if appropriate*)[(f)] - *ingot or continuous cast*[(f)] - *cast/heat weight*[(f)] - **product form** - product dimensions (and heat treated size if different)[(g)] - processing route[(g)] - product manufacturer[(g)] - **heat treatment *time*[(f)]/temperature/cooling medium** - testpiece location/orientation[(g,i)] - RT tensile properties[(g,h)] - HT tensile properties[(g,h,j)] - impact energy[(g,h,j)] - hardness[(g,h)] - microstructure[(g,k)]

NOTES:
(a) the reporting of additional information is not precluded, see [1a]
(b) unique cast/heat number is preferred, but may not be known
(c) country of test laboratory (same code as used for country of supplier/material manufacturer)
(d) alloy type, specification/grade or Trade/proprietary name
(e) mandatory elements depend on alloy type and are defined in Table 1.5 of Issue 3 of [1a]
(f) it is not practical for this information to be mandatory, but highly recommended that the it is reported when known
(g) additional requirements for tests started after 1.1.96
(h) the origin of the properties shall be traceable via the testing laboratory
(i) testpiece location/orientation information is mandatory either as material pedigree or testing information (see Table 4b)
(j) if specified in the material standard
(k) the laboratory shall be in a position to supply a micrograph on request

Table 3a MINIMUM TESTING INFORMATION REQUIREMENTS for Creep Rupture Data EXISTING before 31.12.95

CATEGORY	MINIMUM INFORMATION REQUIRED[(a)]	COMMENTS
Test	- type of test	- uninterrupted/interrupted[2] creep, creep rupture, stress rupture
Standard	- testing standard(s) obeyed	- eg. [3-11][(b)]
Testpiece	- details if not uniaxial smooth round bar - notch geometry & dimensions	- if appropriate - if appropriate
Temperature	- specified value	
Stress	- applied stress (σ_o)	
Test Results	- test duration (t) - continuing, broken, unbroken - total plastic strain $\varepsilon_p(t)$ and/or creep strain $\varepsilon_f(t)$	 - as appropriate - as appropriate

NOTES: (a) the reporting of additional information is not precluded, see [1a]

(b) it should be demonstrated that testing performed according to an unlisted standard at least meets the minimum requirements listed in Table 3b

Table 3b Lowest Common Testing Practice Specification Associated with the Requirements of [3-11] (see Tables 1/1-16 of App.1), ie. for Data EXISTING before 31.12.95

Testpiece	- diameter (d_o) - reference length (L_r) - shape tolerance for d_o - measurement tolerance for d_o	- ≥3mm - ≥$3d_o$ - ±0.04mm - ±0.01mm
Machine	- types	- all, if load controlled
Temperature	- thermocouple - number of thermocouples - calibration - measurement equipment - permitted deviation - frequency of measurement - laboratory ambient limits	- base metal or rare metal - sufficient - error of thermocouple determined - accuracy/resolution sufficient - ±3/4/6/8°C up to 600/800/1000/1100°C [measured] - sufficient - sufficiently constant
Load	- permitted uncertainty - time of load application	- ±$0.01\sigma_o$ - as rapid as possible without shock
Displacement	- total error – uninterrupted - total error – interrupted	- ±max[$0.0001L_r$, 10µm] - ±max[$0.0002L_r$, 20µm]

Table 4 MINIMUM TESTING INFORMATION REQUIREMENTS for NEW Creep Rupture Data Generated after 1.1.96

(a) Information Common to Test Series [(a)]

CATEGORY	MINIMUM INFORMATION REQUIRED[(b)]	COMMENTS
Test	- **type of test**	- uninterrupted/interrupted[2] creep, creep rupture, stress rupture
Standards	- **testing standard/code(s) obeyed**, (including those for temperature & displacement calibration, if not specified in testing standard/ code[(c)])	- requirements of EN 10291 with recommended amendments, as a minimum for uninterrupted testing (see Table 5) - equivalent minimum requirements for interrupted testing (Table 5b)
Testpiece	- reference length[(c)] - **notch geometry** - special features[(c)]	- method of determination, refer to standard/code - if appropriate - if appropriate
Machine	- environment[(c)]	- if not air
Test Results	- assurance of integrity	**-** confirmation that results are subject to internal audit of integrity (if not required by standard/code)

(b) Information Unique to Individual Test [(a)]

CATEGORY	MINIMUM INFORMATION REQUIRED[(b)]	COMMENTS
Testpiece	- location in source & orientation[(c,d)] - diameter[(c)] - reference length[(c)] - **details if not uniaxial round bar** - **notch geometry**	 - if appropriate - if appropriate
Machine	- environment[(c)]	- if not air
Temperature	- **specified value** - *heating/soaking time(s)*[(c,e)] - *laboratory ambient limits*[(c,e)]	 - if outside minimum requirements (Tables 5a,5b) - if outside minimum requirements (Tables 5a,5b)
Stress	- **applied stress (σ_o)**	
Test Results	- **test duration (t)** **- continuing, broken, unbroken** - initial plastic strain ε_i[(c)] - **total plastic strain $\varepsilon_p(t)$ or creep strain $\varepsilon_f(t)$** - rupture ductilities[(c)] - test integrity	 - date or clock duration[(c)] - from hot tensile or creep test **- $\varepsilon_p(t) = \varepsilon_i + \varepsilon_f(t)$** - Ar & Zr, or cannot be measured - reference to details of non standard incidents[(f)]

NOTES: (a) when Table 4a information is not common to every test in series, it must be reported in Table 4b
(b) the reporting of additional information is not precluded, see [1]
(c) additional information requirements for test programmes started after 1.1 96
(d) testpiece location/orientation information is mandatory <u>either</u> as material pedigree <u>or</u> testing information (see Table 2)
(e) it is not practical for this information to be mandatory, but highly recommended that it is reported when known
(f) eg. non standard interruptions, significant scaling, flaws on fracture surface or within gauge length

Table 5a Recommended Minimum Requirements for Uninterrupted Creep-Rupture Testing performed after 1.1.96

Testpiece	- diameter (d_o) - shape tolerance for d_o - measurement accuracy for d_o - reference length (L_r) - length tolerance (ΔL_o) - transition radius (R)	- ≥5mm[(a,b)] - ±0.02mm ($5<d_o\leq 10$mm)[(a)] - ±0.005mm ($5<d_o\leq 10$mm)[(a)] - $\geq 3d_o$ ($\geq\sim 5d_o$ preferred[(a)]) $L_r\leq 1.1L_c$[(c)] - ±0.01 L_o - $d_o/2\geq R\geq d_o/4$[(a,d)]
Machine	- types	- all, if load controlled
Temperature	- thermocouple - number of thermocouples - calibration - re-calibration - measurement equipment - heating/soaking time - permitted deviation - frequency of measurement - laboratory ambient limits	- new base metal to <400°C or <1,000h, else rare metal to IEC 60584-2, Class 1 - single tp m/c: - 2-3/testpiece, - multi tp m/c: - 1-2/testpiece or - ≥1/heating zone[(e)] (with regular control measurements) - by method traceable to International Unit - base metal; only new - rare metal; in situ[(f)], after 4yr (<600°C), 2yr (600-800°C), 1yr (800-1350°C) <u>or</u> at the end of test when scheme times exceeded[(g)] - uncertainty: ±0.5°C, - resolution: ±0.1°C[(a)] - re-calibration annually - ≤24h with >1h at T - ±3/4/5/6/7/8°C up to 600/800/1000/1100/1200/1350°C [total][(a)] - sufficient recording - ±3°C (creep laboratory)
Loading	- permitted uncertainty - pre-loading - time of load application - allowable bending - torsion	- $\pm 0.01\sigma_o$ - ≤10% of applied load[(a)] - ≤10min, without shock - minimised, future goal of ±20%[(a)] - minimised
Displacement	- total error - measurement	- ±max[$0.01\Delta L$, 3µm] - average from two sides[(a)]
Test Results	- time – uncertainty	- ±0.01t[(a)]

NOTES:
(a) proposed amendments to EN 10291

(b) d_o<5mm may be acceptable when source material thickness is limiting and testing is to be performed in inert environment; $d_o\geq$6mm preferred at higher temperatures when oxidation is a problem or when weldments or large grain size materials are being tested

(c) the action of ridges and shoulders and the stress exponent (n) should be considered when calculating L_r

(d) $R\leq d_o$ may be needed for extremely notch brittle materials

(e) in these circumstances, regular control measurements are required to determine the temperature differences between the thermocouple(s) of each heating zone and a significant number of testpieces within a given zone; both the systematic and non-systematic components of the temperature differences must be considered (see Section 6.1.3 and App.1 for more details); the non-systematic component shall not exceed ±2°C up to 800°C and ±3°C above 800°C

(f) see Footnote 7

(g) experience may dictate that re-calibration times may have to be reduced when thermocouple are repeatedly used for short duration tests

Table 5b Recommended Minimum Requirements for Interrupted Creep-Rupture Testing performed after 1.1.96

Testpiece	- diameter (d_o) - shape tolerance for d_o - measurement accuracy for d_o - reference length (L_r) - length tolerance (ΔL_o) - transition radius (R)	- $\geq$5mm[a,b] - ±0.02mm ($5 \leq d_o \leq 10$mm)[a] - ±0.005mm ($5 \leq d_o \leq 10$mm) - $\geq 3d_o$, ($\geq\sim 5d_o$ preferred) $L_r \leq 1.1L_c$[a,c] - ±0.01 L_o[b] - $d_o/2 \geq R \geq d_o/4$[a,d]
Machine	- types	- all, if load controlled
Temperature	- thermocouple - number of thermocouples - calibration - re-calibration - measurement equipment - heating/soaking time(s) - permitted deviation - frequency of measurement - laboratory ambient limits	- new base metal to <400°C or <1,000h, else rare metal to IEC 584-2, Class 1 - 1-2/testpiece or - ≥1/heating zone[e], with regular control measurements - by method traceable to International Unit - base metal; only new - rare metal; in situ[f], after 4yr (<600°C), 2yr (600-800°C), 1yr (800-1000°C) or at the end of test when scheme times exceeded[g] - uncertainty: ±0.5°C, - resolution: ±0.1°C[a] - re-calibration annually - ≤4h heating, ≤3h soaking - ±3/4/5°C up to 600/800/1000°C [total] - sufficient recording - ±2°C (inspection laboratory)
Loading	- permitted uncertainty - time of load application - allowable bending - torsion	- $\pm 0.01\sigma_o$ - ≤10min, without shock - minimised, future goal of ±20%[a] - minimised
Displacement	- total error - measurement	- $\pm$max[$0.01\Delta L$, 10μm] - average from two sides[a]
Test Results	- time – uncertainty	- ±0.01t

NOTES:
(a) proposed amendments to EN 10291
(b) d_o<5mm may be acceptable when source material thickness is limiting and testing is to be performed in inert environment; $d_o \geq$6mm preferred at higher temperatures when oxidation is a problem or when weldments or large grain size materials are being tested
(c) the action of ridges and shoulders and the stress exponent (n) should be considered when calculating L_r
(d) $R \leq d_o$ may be needed for extremely notch brittle materials
(e) in these circumstances, regular control measurements are required to determine the temperature differences between the thermocouple(s) of each heating zone and a significant number of testpieces within a given zone; both the systematic and non-systematic components of the temperature differences must be considered (see Section 6.1.3 and App.1 for more details); the non-systematic component shall not exceed ±2°C up to 800°C and ±3°C above 800°C
(f) see Footnote 7
(g) experience may dictate that re-calibration times may have to be reduced when thermocouple are repeatedly used for short duration tests

Table 6a MINIMUM TESTING INFORMATION REQUIREMENTS for Stress Relaxation Data EXISTING before 31.12.95

CATEGORY	MINIMUM INFORMATION REQUIRED[(a)]	COMMENTS
Test	- type of test	- uniaxial (ε_t control method), model bolt
Standard	- testing standard(s) obeyed	- eg. [16-17][(b)]
Testpiece	- details if not smooth round bar or model bolt options 1a or 1b [17]	- as appropriate
Temperature	- specified value	
Strain	- maintained total strain (ε_t)	
Test Results	- test duration (t) - continuing, discontinued - initial stress (σ_o) - stress at time t - σ_R(t)	 - as appropriate - as appropriate

NOTES: (a) the reporting of additional information is not precluded, see [1]

(b) it should be demonstrated that testing performed according to an unlisted standard at least meets the minimum requirements listed in Tables 6b,c

Table 6b Lowest Common Uniaxial Testing Practice Specification Associated with the Requirements of [13-16] (see Tables 1/1-6 of App.2), ie. for Data EXISTING before 31.12.95

Testpiece	- diameter (d_o) - reference length (L_r) - shape tolerance for d_o - measurement tolerance for d_o	- ≥4mm - ≥min[5d_o, 20mm] - ±0.04mm - ±0.01mm
Machine	- types (control mode)	- dead weight, lever weight, electro-mechanical, hydraulic (manual, servo-)
Temperature	- thermocouple - number of thermocouples - calibration - measurement equipment - permitted deviation - frequency of measurement - laboratory ambient limits	- base metal or rare metal - ≥2/testpiece - error of thermocouple determined - accuracy/resolution sufficient - ±3/4/6°C up to 600/800/1000°C [measured] - sufficient - sufficiently constant
Displacement	- control band - time of load application	- $\pm 0.015\varepsilon_t.L_r$ µm - <30min
Load	- permitted uncertainty	- $\pm 0.01\sigma$

Table 6c Lowest Common Model Bolt Testing Practice Specification Associated with the Requirements of [17] (see Tables 1/1-6 of App.2), ie. for Data EXISTING before 31.12.95

Testpiece	- diameter (d_o)	- ≥8mm
Temperature	- thermocouple - number of thermocouples - calibration - measurement equipment - permitted deviation - frequency of measurement	- base metal or rare metal - sufficient - error of thermocouple determined - accuracy/resolution sufficient - ±3/4/6°C up to 600/800/1000°C [measured] - sufficient
Displacement	- total error	- $\pm 0.01\Delta L$

Table 7a MINIMUM TESTING INFORMATION REQUIREMENTS for NEW Uniaxial Stress Relaxation Data Generated after 1.1.96

(i) Information Common to Test Series[a]

CATEGORY	MINIMUM INFORMATION REQUIRED[b]	COMMENTS
Test	- **type of test**	- method of ε_t control
Standards	- **testing standard/code(s) obeyed**, (including those for temperature & displacement calibration, if not specified in testing standard/ code[c])	- recommended minimum requirements (Table 8a)
Testpiece	- reference length[c] - special features[c]	- method of determination, refer to standard/code - if appropriate
Machine	- environment[c]	- if not air
Test Results	- assurance of integrity	- confirmation that results are subject to internal audit of integrity (if not required by standard/code)

(ii) Information Unique to Individual Test[a]

CATEGORY	MINIMUM INFORMATION REQUIRED[b]	COMMENTS
Testpiece	- location in source & orientation[c,d] - diameter[c] - reference length[c] - **details if not uniaxial round bar**	 - if appropriate
Machine	- environment[c]	- if not air
Temperature	- **specified value** - *heating/soaking time(s)*[c,e] - *laboratory ambient limits*[c,e]	 - if outside minimum requirements (Table 8a) - if outside minimum requirements (Tables 8a)
Strain	- **maintained total strain (e_t)** - loaded to ε_t or σ_o - displacement (loading) rate to ε_t[c]	
Test Results	- **test duration (t)** - **continuing, discontinued** - initial stress (σ_o) - plastic strain on loading - stress at time t - $\sigma_R(t)$ - test integrity	 - date or clock duration[c] - reference to details of non standard incidents[f]

NOTES:
(a) when Table 7a(i) information is not common to every test in series, it must be reported in Table 7a(ii)
(b) the reporting of additional information is not precluded, see [1a]
(c) additional information requirements for test programmes started after 1.1 96
(d) testpiece location/orientation information is mandatory <u>either</u> as material pedigree <u>or</u> testing information (see Table 2)
(e) it is not practical for this information to be mandatory, but highly recommended that it is reported when known
(f) eg. non standard interruptions

Table 7b MINIMUM TESTING INFORMATION REQUIREMENTS for NEW Model Bolt Stress Relaxation Data Generated after 1.1.96

(i) Information Common to Test Series[a]

CATEGORY	MINIMUM INFORMATION REQUIRED[b]	COMMENTS
Test	- **type of test**	- matching/non-matching bolt/flange materials
Standards	- **testing standard/code(s) obeyed**, (including those for temperature & displacement calibration, if not specified in testing standard/ code[c])	- recommended minimum requirements (Table 8b)
Testpiece	- reference length (for method with mechanical extensometry)[c] - special features[c]	- method of determination, refer to standard/code - if appropriate
Machine	- environment[c]	- if not air
Test Results	- assurance of integrity	- confirmation that results are subject to internal audit of integrity (if not required by standard/code)

(ii) Information Unique to Individual Test[a]

CATEGORY	MINIMUM INFORMATION REQUIRED[b]	COMMENTS
Testpiece	- location in source & orientation[c,d] - diameter[c] - $S_{o[flange]}/S_{o[bolt]}$ [c] - reference length or cylinder length[c] - **details if not Type (a) or (b) in [17]**	- if appropriate (Type (a) or (b) to be stated)
Machine	- environment[c]	- if not air
Temperature	- **specified value** - *heating/cooling rate(s)*[c,e] - *laboratory ambient limits*[c,e]	- if outside minimum requirements (Table 8b) - if outside minimum requirements (Tables 8b)
Strain	- **initial total strain (ε_o)**	
Test Results	- **test duration (t)** - initial calculated stress - stress at end of test - $\sigma_R(t)$ - test integrity	- $\sigma_o^* = \varepsilon_t.E_{T(S)}$ - reference to details of non standard incidents[f]

NOTES: (a) when Table 7b(i) information is not common to every test in series, it must be reported in Table 7b(ii)

(b) the reporting of additional information is not precluded, see [1a]

(c) additional information requirements for test programmes started after 1.1 96

(d) testpiece location/orientation information is mandatory either as material pedigree or testing information (see Table 2)

(e) it is not practical for this information to be mandatory, but highly recommended that it is reported when known

(f)) eg. non standard interruption

Table 8a Recommended Minimum Requirements for Uniaxial Stress Relaxation Testing performed after 1.1.96

Testpiece	- diameter (d_o) - shape tolerance for d_o - measurement accuracy for d_o - reference length (L_r) - length tolerance (ΔL_o) - transition radius (R)	- ≥5mm (≥8mm preferred) - ±0.02mm - ±0.005mm - ≥10d_o (≥100mm preferred[(a)]) $L_r \leq 1.1 L_c$[(a)] - ±0.01L_o - $d_o/2 \geq R \geq d_o/4$
Machine	- types (control mode)	- dead weight, lever weight, electro-mechanical, hydraulic (manual, servo-)
Temperature	- thermocouple - number of thermocouples - calibration - re-calibration - measurement equipment - heating/soaking time - permitted deviation - frequency of measurement - laboratory ambient limits	- new base metal to ≤400°C or <1,000h, else rare metal to IEC 584-2, Class 1 - 3/testpiece - by method traceable to International Unit - base metal; only new - rare metal; in situ[(b)], after 4yr (<600°C), 2yr (600-800°C), 1yr (800-1000°C) or at the end of test when scheme times exceeded[(c)] - uncertainty: ±0.5°C, - resolution: ±0.1°C - re-calibration annually - ≤24h with >1h at T - ±3/4/5°C up to 600/800/1000°C [total] - sufficient recording - ±3°C (creep laboratory)
Displacement	- control band - total error - attainment of target - pre-loading - time of application - allowable bending - torsion - measurement	- ±max[$0.01\varepsilon_t.L_r$, $0.000025L_r$] - ±max[$0.01\varepsilon_t$, 0.002]% - ≤$0.01\sigma_o$ - ≤10min, without shock - minimised, future goal of ±20% - minimised - average from two sides
Load	- permitted uncertainty - measurement frequency	- ±0.01σ - sufficient
Test Results	- time - uncertainty	- ±0.01t

NOTES: (a) the action of ridges and shoulders and the stress exponent (n) should be considered when calculating L_r

(b) see Footnote 7

(c) experience may dictate that re-calibration times may have to be reduced when thermocouple are repeatedly used for short duration tests

Table 8b Recommended Minimum Requirements for Model Bolt Stress Relaxation Testing performed after 1.1.96

Testpiece	- diameter (d_o) - shape tolerance for d_o - measurement accuracy for d_o - $S_{o[flange]}/S_{o[bolt]}$ - length to diameter ratio - cylinder length (L_c) - length tolerance (ΔL_o, ΔL_c) - transition radius (R)	- ≥8mm - ±0.02mm - ±0.005mm - ≥5 (f) - L_r/d_o ≥10 for Type (a) (a) - L_c/d_o ≥5 for Type (b) (b,f) - ≥50mm(b) - ±0.01L_o (or ±0.01L_c) - $d_o/2 \geq R \geq d_o/4$
Temperature	- thermocouple - number of thermocouples - calibration - re-calibration - measurement equipment - heating/cooling rate(s) - permitted deviation - frequency of measurement - laboratory ambient limits	- new base metal to ≤400°C or <1,000h, else rare metal to IEC 584-2, Class 1 - ≥1/heating zone(e), with regular control measurements - by method traceable to International Unit - base metal; only new - rare metal; in situ(c), after 4yr (<600°C), 2yr (600-800°C), 1yr (800-1000°C) <u>or</u> at the end of test when scheme times exceeded(d) - uncertainty: ±0.5°C, - resolution: ±0.1°C - re-calibration annually - 50-100°C/h - ±3/4/5°C up to 600/800/1000°C [total] - sufficient recording - ±2°C (inspection laboratory)
Displacement/ Strain(a,b)	- total measurement error - allowable bending - torsion - measurement	- Type (a) ±max[$0.01\varepsilon_t.L_r$, $0.000025L_r$] - Type (b) ±$0.01\varepsilon_t$ - minimised - minimised - dependent on method (ie. Type (a) or (b))
Test Results	- time - uncertainty	- ±0.01t

NOTES:
(a) for models with mechanical extensometry, the action of nut and flange shoulders should be determined by a comparison test (L_r at RT)
(b) for models with strain gauges
(c) see Footnote 7
(d) experience may dictate that re-calibration times may have to be reduced when thermocouple are repeatedly used for short duration tests
(e) in these circumstances, regular control measurements are required to determine the temperature differences between the thermocouple(s) of each heating zone and a significant number of testpieces within a given zone; both the systematic and non-systematic components of the temperature differences must be considered (see Section 6.1.3 and App.1 for more details); the non-systematic component shall not exceed ±2°C up to 800°C and ±3°C above 800°C
(f) ≥4 is acceptable when material is limited

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APPENDIX 1

REVIEW OF CREEP, CREEP RUPTURE AND STRESS RUPTURE TESTING STANDARDS AND PRACTICES

J Granacher [IfW TU Darmstadt]

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APPENDIX 1 to VOLUME 3

REPORT ON CREEP, CREEP RUPTURE AND STRESS RUPTURE TESTING STANDARDS AND PRACTICES

Prepared for ECCC-WG1

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Content

1. Introduction

In the frame of task 3, Working Group 1 (WG1) of the European Collaborative Creep Committee (ECCC) was charged to develop rules for creep data generation. This report contributes to that task with the following objectives:

- To review the creep, creep rupture and stress rupture testing procedures specified in national and international standards and the practices adopted in leading European laboratories.
- To define rules to enable the acceptability of creep, creep rupture and stress rupture data and to check if they have to be classified in terms of the testing conditions adopted.
- To formulate rules for the translation of raw laboratory test results into acceptable input data for assessment.

As a basic step to attain these objectives, a survey has been performed of the principal national and international standards relating to creep rupture and creep strain testing. A first aim was to see if there were significant differences between the standards, to see if the data generated would have to be classified according to testing practice before they were entered into a common assessment procedure. A second aim was to check if recommendations should be given to improve existing standards or to prepare new standards as a better basis for the generation of data in the future. Finally it was questioned whether recommendations were needed for the assessment of raw test data e.g. for deriving time to specific strain data from the original creep curve data.

The survey led to an overview of 9 different testing standards, in use worldwide or at a stage just prior to formal introduction. The overview is presented in Annex 1 in the form of Tables 1/1 to 1/16, containing in rows 1 to 8 the different standards and in columns the different important points thereoff. In the Tables, indications without brackets are mandatory, whereas indications in brackets () are recommended. If there is no indication in a column, the correspondent point is not specified in the standard.

In row 9 of Tables 1/1 to 1/16, explanations and definitions are given with some comments. These are neutral observations, i.e. with no statement relating to classification. Statements concerning classification of the different standards are included in chapter 2. In row 10, minimum testing requirements for existing creep and creep rupture data are indicated. Similarly, in row 11 recommendations for minimum testing requirements for the future are summarized.

In addition to the overview on testing standards, the creep and creep rupture testing practices of leading laboratories in several European countries have been reviewed (Annex 2, Tables 2/1 to 2/16). The main purpose of Annex 2 is also to provide assistance with the definition of minimum testing practice requirements (a) for existing creep and creep rupture data for assessment and (b) for data to be gathered in the future. Tables 2/1 to 2/16 are similar in structure to Tables 1/1 to 1/16. In rows 1 to 10, the testing practices of 10 laboratories are described in columns. Neutral observations are given in row 11, while some short comments relating to future testing practice are given in row 12. More detailed comments on testing practice are collected in chapter 3.

In the report, all types of testing are considered, i.e. pure creep testing up to a given plastic or creep strain, creep rupture testing with strain measurement and pure stress rupture testing. Here and in the main text of Volume 3, the three types of testing are referred to as "creep rupture" testing for brevity, unless there are differences in the detail under review which require reference to the specific type of test. Testing machines are considered as single machines with one test piece, multi-machines with one string of two or more test pieces and multi-specimen machines with several strings. In Volume 3 these differences are abbreviated to single test piece machines and multi-test piece machines. In addition, different modes of testing are considered in the following, ie. the uninterrupted test with or without continuous strain measurement and the interrupted test with or without strain measurement on test pieces which are repeatedly removed from the test machine.

The main aim of the work conducted was to check the acceptability of data generation in regard to rupture time and to times to specific plastic strain values of 0.2 , 0.5 and 1 %. However, other points such as the generation of creep data at low strain levels in the pimary creep range were also considered. Besides a study of the testing standards and practices used to generate existing creep and creep rupture data, recommendations were elaborated for new standards and practices with the aim of achieving optimal accuracy and compatibility in future data produced to assess the long term property values of heat resistant steels and alloys.

Drawing up this document was only possible within an active group of specialists from different countries and thanks are given to all members of ECCC-WG1 for their valuable contributions to this document.

2. Creep rupture testing standards

2.1 Standards from different countries

A general observation is that new (as ISO/DIS 204, 1991) or recently revised (as ASTM E 139-83, 1990) standards are more detailed and quote more "associated standards", e.g. standards for load and extensometer calibration. They also tend to recommend tighter tolerances, especially for temperature and strain measurement. However, elder standards such as BS 3500, 1969 or DIN 50 118, 1982 accomodate a relatively wide field of testing practices such as uninterrupted and interrupted testing, single and multi specimen machines (Table 1/1). Clearly, the standards of different countries reflect the testing practices and machines available in the country. The objective of an international standard should therefore be to combine the most important practices. However, this is not the case for DIS 204, which is only directed to the uninterrupted test.

2.2 Test environment and load application

Reference to the test environment (Table 1/2) is not given in all standards, although there can be little doubt that laboratory air is normally assumed. In addition, the method of load application is not generally ruled. Dead weight loading without or with lever transmission is the usual case. As a speciality, DIN 50 118 includes spring loading. In some cases, special standards as ISO 7500 are available describing load application as well as load calibration.

2.3 Tolerances of test temperature

A most important test parameter is the test temperature (Table 1/3 to 1/6). In some standards the maximum temperature is limited to 1 100 or even 1 000 °C. Such a limitation is regarded as unnecessary for uninterrupted testing whereas it makes sense for interrupted testing, although not for the reason of temperature tolerances, see chapter 3.2.

It will be demonstrated in chapter 4 that the temperature tolerance has the leading influence on the main test results. Depending on the nature of temperature measurement, which is practically only carried out with the aid of thermocouples, the tolerance depends on temperature. Most standards prescribe a tolerance of ± 3 °C up to a test temperature of 600 °C, ± 4 °C above 600 to 800 °C and ± 6 °C above 800 to 1 000 °C. Tolerances above 1 000 °C are often to be arranged, with values of ± 8 °C or more being typical. Temperature tolerances are referred to in two different ways. One group of standards prescribe a total temperature tolerance, which is defined as the difference between the true test piece temperature and the specified test piece temperature i.e. the specified test temperature. Another group of standards prescribe an indicated tolerance, which is defined as the difference between the temperature indicated by the measurement equipment and the temperature specified for the measurement equipment. In this case, the temperature specified for the measurement equipment is the specified test temperature corrected for all systematic errors which can be determined. The subject of systematic errors is discussed in more detail below.

In terms of optimum test result accuracy the use of total temperature tolerance is essential. On the other hand, an argument in favour of the specification of an indicated temperature tolerance is that this is the tolerance to which the laboratory technician usually relates by direct reference to his measurement device. Thus the additional specification of this tolerance would give helpful guidance for carrying out the tests, and a proposal to this effect is made later on in this chapter. Beside the indicated temperature tolerance, which mainly depends on the quality of the temperature control circuit(s) there are several other sources of temperature error severely influencing the total temperature tolerance. These sources are described in the newer standards and recommendations are given to minimize these individual errors. However, it is difficult to come to quantitative indications about the magnitude of these individual tolerances.

To give a better understanding of the situation, a typical total temperature tolerance of ±3 °C is analysed in terms of the main influences contributing to that tolerance. The analysis is limited to the example of test temperatures up to 600 °C and to the use of in-situ-calibrated *) rare (noble) metal thermocouples of type R or S. Here and in the following, in-situ thermocouple calibration means either in the testing machine or in a calibration furnace having

*) The example is based on the authors experience with thermocouple calibration, which is in agreement with 1), 2) and the recommendations in DIS 204. An opposite re-calibration philosophy allows a shorter depth of immersion in the calibrating furnace, after the thermocouple is fully annealed. Details will be discussed later on.

the same course of temperature along the thermocouple wires as the testing machine. This is often more concisely but less precisely expressed as "having the same depth of immersion". Discerning between single and multi-machines (SM, MM) with one string and multi-specimen machines (MSM) with more than one string, the following individual tolerances are assumed:

Type of temperature tolerance		tolerance (°C) for SM/MM	tolerance (°C) for MSM
1)	Thermocouple tolerance (new or after calibration)	±1	±1
2)	Drift of the thermocouple during service at 600 °C with in-situ [non-in-situ] calibration	±1[±2]	±1[±2]
3)	Difference between the temperature of the thermocouple and the test piece		
	- in time	±0.5	±0.5
	- in space	±1	±2
4)	Mean difference between indicated and specified temperature, which has to be corrected by all systematic errors	±1	±1
5)	Tolerance of the measurement device (including electrical contacts and cold junction)	±0.5	±0.5
Combined tolerance as the root of the sum of squares of the individual tolerances		±2.1[2.7]	±2.7[3.2]

Some details of that analysis need a short comment. The tolerance for new thermocouples is in accordance with IEC 584-2, class 1 [3]. If a used thermocouple is in-situ recalibrated against a fixed point calibrated thermocouple, which has a tolerance of ±0.5 °C at 600 °C, a tolerance of ±1 °C can be reached at best for the thermocouple error. This error is the deviation of the thermoelectromotive force (thermal emf) of the individual thermocouple from the value indicated in the corresponding reference table [4] for the same temperature. Indications of the drift, i.e. the change of the thermocouple error with time, of a rare metal thermocouple are reported in [1) 2)] (Fig. 1 and 2). There is a general tendency to negative drift values. This is more distinctively indicated in Fig. 2, but comparisons between the two Figures are difficult due to the fact, that constant immersion depth was only observed for Fig. 1. Further, the thermocouple types are different. As a generality the (negative) drift decreases with increasing temperature. For the example demonstrated above, for simplification, a symmetric drift value of ±1.0 °C is taken from Fig. 1 corresponding to about ±11 μV, which is assumed to be valid at 600 °C within a calibration period of 3 years for type S thermocouples. Resuming, it is supposed in this analysis that a thermocouple error detected due to a (re)calibration is used to correct the temperature specified for that thermocouple and thus for the correspondent temperature measurement equipment. A simple calculation scheme for that is described in [1]. Moreover, in the distant future, a systematic compensation of the thermocouple drift seems to be possible to a certain degree, but this will presuppose the results of systematic in-situ calibrations of the type of Fig. 1 with a subdivision into different temperatures according to Fig. 2. As an alternative, for a non-in-situ calibration an error of ±2 °C is assumed giving the combined tolerances in [brackets]. Just in this case, a ± tolerance is justified, because a calibration error due to a variation in immersion depth can lead to a positive drift and subsequently to a temperature decrease. In contrast to the Japanese results reported in [2], no greater drift is assumed for multi-specimen machines because the thermocouples thereoff are in Europe assumed to be only removed from the machine for calibration purposes.

The temperature difference between thermocouple(s) and test piece in time of ±0.5 °C is a realistic value for long term testing, if one considers that the thermal contact between thermocouple and test piece can vary by example due to scaling of the test piece or due to a relaxation of the fixing of thermocouple against the test piece. The temperature differences between thermocouple(s) and test piece(s) in space of ± 1 and ± 2 °C repectively are realistic values if one takes into account, that test machines with more than one string can have a greater temperature variation due to their normally much greater dimensions [1]. However, if relatively large multi-specimen machines have a number of heating zones with modern automatic temperature control, if regular control measurements are performed as detailed later on and if the machines present a long depth of immersion to the clamping rods, there is no reason for a highly inferior temperature distribution across and between the test pieces relative to that in the smaller furnaces of many single machines with a possible strong heat flux through the clamping rods [5].

The assumption of a mean difference between indicated and specified temperature of ±1 °C seems to be realistic [5]. The same is valid for a tolerance of the measurement device of ±0.5 °C. Combination of the independent individual errors or tolerances by a root sum of squares calculation is consistent with the ISO guide to the expression of uncertainty in measurement [6)].

From the above analysis, it is concluded that a total temperature tolerance band makes more sense than an indicated temperature tolerance band because splitting off the "measurement device" and "indicated - specified temperature" contributions is arbitrary and does not correspond to the actual circumstances of temperature uncertainty as a whole. Moreover concentration on the restricted indicated tolerance band creates a danger to overlook the other temperature errors. However, as a guidance, one can additionally prescribe an indicated temperature tolerance band. As a realistical proposal this tolerance band shall not exceed ± 2 °C up to 1 000 °C and ± 3 °C for $1\,000 < T < 1\,350$ °C.

In the analysis, in-situ calibration of rare metal thermocouples is assumed. The consequence of a variable depth of immersion for type S rare metal thermocouples is shown in Fig. 3. In the event of the immersion depth during calibration being different to that employed during testing, a further error of at least 1 °C must be considered according to the experience of the author [1)] , as done above, and base metal thermocouples are even much more dangerous in this respect, as will be discussed in chapter 2.5 . However, in contrast is the earlier mentioned opposite re-calibration philosophy of allowing a shorter depth of immersion in the calibrating furnace, after the thermocouple is fully annealed [*)] . This philosophy seems to be mainly developed from experiences with temperatures up to the range of about 600 °C and under conditions leading to some plastic deformation of the thermocouples [2) 7)] . Infact the thermocouple error due to chemical deterioration is relatively small up to about 600 °C as compared to higher temperatures from about 700 °C. In the latter temperature range deteriorations occur which cannot be reversed by annealing. However, for the moment both re-calibration philosophies are regarded as acceptable by WG1 until further evidence is collated to clarify this situation.

A relatively simple way of resolving the situation would be to re-calibrate typical thermocouples deteriorated after long term service (i) in their test machine in-situ and with, for example, two varied depths of immersion and (ii) non-in-situ before and after annealing in the calibration furnace, and to compare the measured values of thermal emf. As typical thermocouples, one could take a relatively short thermocouple from a single machine and a relatively

*) Personal communication of P. Mc Carthy, ERA

long thermocouple from a multi-(specimen)machine, in each case for a lower (e.g. 600 °C) and a higher (e.g. 800 to 1 000 °C) temperature

If one now considers the tolerances proposed in creep rupture testing standards (Table 1/3), a total tolerance of ±3 °C up to 600 °C is the normal case. The analysis given above demonstrates that about ± 2 °C can be reached under the best conditions. However, this expectation may be rather too optimistic for typical creep laboratories. This can be concluded from the results of various comparison creep (rupture) tests [8] [9], where the laboratories which participated in are assumed to have done their best. More information is expected to come up from a new project *).

In summary, a ± 3 °C total tolerance for temperatures up to 600 °C will remain a realistic number for creep laboratories, even if a tighter tolerance would be more desirable from the viewpoint of test accuracy and, according to the presented analysis, seems to be possible for high precision testing, i.e. with in-situ calibration of rare metal thermocouples and within test machines of type SM and MM with a single specimen string and several individually controled heating zones. These considerations are equally valid for higher temperatures, where higher tolerances are permitted, mainly as a consequence of greater thermocouple drift. Realistic total temperature tolerances for the future are ±4 °C from 600 to 800 °C, ±5 °C from 800 to 1 000 °C, ±6 °C from 1 000 to 1 100 °C, ±7 °C from 1 100 to 1 200 °C and ±8 °C from 1 200 to 1 350 °C.

As far as temperature measurement equipment is concerned (Table 1/4), an accuracy of ≤ 0.5 °C(±) and a resolution of ≤ 0.1 °C can be obtained and should be requested in a modern standard as well as a tolerance ± 0.1 °C for the cold junction. However, the latter tolerance should be included in the tolerance of the measuring device.

For large multi-specimen machines where it is not possible to attach at least one thermocouple to each test piece an indirect temperature measurement takes place. This measurement refers to at least one permanently fixed thermocouple per each heating zone of the test machine. As proposed in DIN 50 118 (Table 1/5) a repeated control measurement has to be performed to determine the systematic

*) ERA have submitted a funding application to BCR for a concerted action to examine these problems

temperature error between the mean test piece temperature of the heating zone and the temperature of the fixed thermocouple of this zone, see also [1). As a thermocouple error, this systematic temperature error has also to be used to correct the temperature specified for that thermocouple and thus for the measurement equipment of that heating zone. On this basis, for the future, regular control measurements are proposed for large multi-specimen machines to determine the temperature difference(s) between the thermocouples(s) of each heating zone and a significant member of test pieces within this zone. The systematic component of the differences delivers a temperature error to be considered in correcting the specified temperature(s) of the thermocouple(s) of the heating zone and, and as a new prescription, the non-systematic component of the differences shall not exceed ± 2 °C for temperatures up to 800 °C and ± 3 °C for temperatures above 800 °C. The control measurements shall be repeated every 3 years or after each modification or repair of the test machine. Experience may allow for longer periods of up to 5 years.

As a general result, one sees a relatively large number of individual influences on the test temperature. Also it is shown, that some of these influences cannot be expressed by individual tolerances whereas others can. In order to achieve the smallest possible total temperature tolerances a number of recommendations for improving testing practices are given in most standards, especially in the newer ones. As described above and in the next chapters these recommendations were taken over and some new ones were developed by WG1. A summary is given in Tables 1/3 to 1/6 and in the main text of Volume 3. However, observing these recommendations would need careful planning and control of difficult high precision measurements, going far beyond the practice of simply reading off a temperature measurement device.

During the discussion of further improvement in temperature tolerances some more proposals were made in WG1. As an example one could ask the creep laboratory for a more detailed test report or for the repeat measurement documentation of the temperature control system. Another point was to report the mean difference between indicated and specified temperatures, this being only possible in a simple and direct way if one thermocouple is attached to each test piece. Before such recommendations can be stated as mandatory, a compromise has to be found between the desirable target of accuracy and the effort necessary for the improvements.

2.4 Thermocouples

With regard to the type of thermocouple, it is difficult to understand why base metal thermocouples are admitted in the newest standard (DIS 204) or in the high precision oriented standard ASTM E139, even though their reuse is prohibited. This is emphasized by the fact, that most laboratories (see Annex 2, Table 2/4) in reality prefer rare metal thermocouples, even though the corresponding standard admits base metal thermocouples. For future standards, the use of base metal thermocouples should be prohibited for long term testing, i.e. for test times above 1 000 h at temperatures above 400 °C. More details to base metal thermocouples will follow in chapter 2.5.

An important requirement for high precision temperature measurement is the avoidance of any plastic or creep deformation of the thermocouples. Hence cold working due to fixing of the thermocouples and creep during service has to be minimized. If plastic deformation occurs a re-annealing of the thermocouple is recommended [2)] and this should always be performed before high precision recalibration.

Further, some rules should be observed [1) 2)] in the design of the complete measuring circuit which normally contains beside the thermocouple a couple of compensating leads, a cold junction, electrical junctions, switching terminals and some type of voltmeter, nowadays in most cases a digital high precision microvoltmeter. Essential elements of these rules are to minimize the differences of temperature and of thermal emf at all electrical junctions belonging together. An important means of reaching this goal is to arrange all circuits in a fully symmetrical way with regards to plus- and minus-poles.

Another important point of temperature measurement is the number of thermocouples. The minimum number of thermocouples per test piece (Table 1/5) is in most cases only recommended. This makes sense, because this number largely depends on the furnace and the number of test pieces in it. A minimum requirement for the future is proposed in Table 1/5. Control measurements to determine the temperature distribution across a greater number of test pieces in a multi-specimen machine are stated in the previous chapter. In special cases it can also be important for testing in smaller machines to measure the temperature distribution in the test furnace and across the test piece(s).

New thermocouples should be provided according to IEC 584-2 (1989) class 1 with an accuracy for type R or S of ±1 °C for $0 \leq T \leq 1\,100$ °C and of $\pm[1+0.003(T-1\,100)]$ for $1\,100 < T \leq 1\,600$ °C [3] or they should be calibrated against a fixed point calibrated thermocouple the values of which are traceable to the International Unit, see below.

In an overall view, there are no significant differences in temperature tolerances between standards. As a general recommendation, there should be a trend to smaller tolerances in the future.

2.5 Temperature calibration and frequency of measurement

An important point is temperature calibration, which involves rules for thermocouples as well as for the measurement device in the majority of standards. In most modern standards, in-situ calibration of the thermocouples is recommended because the error of a deteriorated thermocouple depends on its depth of immersion, as demonstrated in Fig. 3. As stated above in-situ calibration means either in the actual testing furnace or in a calibration furnace with the same depth of immersion and the same course of temperature along the thermocouple. The controversial re-calibration philosophy is described in chapter 2.3. These re-calibration philosophies are accompanied by rules to prevent the further use of a thermocouple when a certain drift or error is exceeded, see e.g. [1] [2].

In the UNI 5111-69 and JTS Z227/2 standards, there is reference to specific calibrating standards. As for other quantities, traceability to the International Unit should be imposed in future standards as is done in DIS 204. The same is true for the measurement device. For indirect temperature measurement, a systematic difference between test piece(s) and thermocouple must be acknowledged if identified (see DIN 50 118 and chapter 2.3).

The time interval between thermocouple calibrations varies (Table 1/6). For type S (rare metal) thermocouples, the time interval proposed is temperature dependent (DIN 50 118). For base metal thermocouples recalibration is problematic and "no reuse" should be prescribed (ASTM E139), any other course of action leading to significant differences as compared to rare metal thermocouples. The reason is that base metal thermocouples which are normally of type K (NiCr-Ni) show a short range ordering effect between 400 and 700 °C.

From this, the thermal emf depends on the cooling rate and/or the sequence of temperatures used for testing and calibration and a relatively strong immersion depth effect is present. A stable thermal emf without hysteresis is only apparent for cooling rates slower than 100 °C/h, which can normally not be achieved in creep test machines [10) 11)]. For quicker cooling rates, errors of more than ± 2 °C are possible. Further, the deterioration of type K-thermocouples is much stronger than for rare metal thermocouples.

Beside the type K thermocouple a new type N (NiCrSi-NiSi) was developed [10)] which is more stable and shows no hysteresis effects. However, type N thermocouples should not be recommended for creep rupture testing as long as their long terms stability is not yet experimentally proven.

It is stressed that the recalibration of thermocouples cannot be replaced by annealing. The latter can only remove the effects of plastic strain whereas by recalibrating the deterioration effects due to a chemical contamination of the thermocouples can be corrected. From this viewpoint all should be done to protect the thermocouples against contamination, i.e. to keep away from the test environment all materials with a high vapour pressure, e.g. metals such as Zn, Sn, Cu or also organic substancies as lubricants.

Another point is the frequency of temperature measurement which is mostly stated as "sufficient recording". A significant difference in some standards is the recommendation or prescription of "continuous recording". As a compromise in the future, "continuous recording of at least one thermocouple in a single machine or at least one thermocouple per each heating zone in a greater machine" should be imposed.

2.6 Load application

Regarding load (force) application, constant load and therefore constant initial stress is the normal case (Table 1/7). Only DIS 204 alternatively contains the case of constant applied stress. This seems to be less important, because constant initial stress (σ_0) creep data can easily be stepwise converted into the true stress (σ) and true strain (ϵ) data needed for finite element calculations. After [12)], this can be achieved by stepwise using a constant load creep equation or creep curve $\epsilon_p = f(\sigma_0)$ for stress $\sigma_0 = \sigma \cdot e^{-\epsilon}$ with $\epsilon = \ln(1 + \epsilon_p)$.

Stress and thus load are after test temperature the second most influential parameter on the test results. In most standards, the load tolerance is limited to ± 1 %, which seems to be a reasonable value. The time of loading is in most cases relatively imprecisely defined as "as rapid as possible" and "without shock". Numbers are only given in DIN 50 118, although the maximum loading times permitted are high. The different designs of test machines in use do not allow a clearer limitation up to now. A proposal for the future is to limit the loading time to a maximum of 10 minutes.

In several standards a preloading limited to 10 % of the load is recommended or imposed (Table 1/8). This is with regard to strain measurement using extensometers to avoid any nonlinear displacements during final loading of the load train (ie. clamping rods, test piece(s) and extensometer). A more detailed discussion of this point will follow in chapter 3.3.

An important point is the limitation of the (elastic) bending stress during the test. The prescription to "minimize bending" is not enough for the future. The rule to hold the bending stress below 10 % of the axial stress is probably impractical. For the future, WG1 proposes a limitation of bending stress to 20 % of the axial stress. It is assumed that this does not significantly influence creep rate, time to rupture and rupture ductility. A more detailed comment will be given in chapter 3.3.

Finally, the recommendation to minimize torsion is justified and seems to be sufficient in this form, because in the usual test machines this is secured by the structure of the loading equipment.

2.7 Supplementary test conditions

Some supplementary test conditions are contained in the standards, which are of importance for the test results (Table 1/9 and 1/10). In general, the laboratory air temperature is ruled to be "sufficiently constant" mainly in those standards concerned with uninterrupted testing. Here, this prescription is important for the exact working of the extensometers. It seems reasonable to include numbers in a modern standard, for example ±3 °C as in ASTM E139. For interrupted testing, on the other hand, constant laboratory temperature is only needed at the time of strain measurement of the cold test piece under the microscope. DIN 50 118 recommends ±3 °C for these circumstances, although ±2 °C would be better for the future.

The test duration need not be ruled in a standard. The normal tolerance of ± 1 % (Table 1/10) seems to be sufficient, if the main influences on the test duration results are regarded, see chapter 4. For the soaking time, a large variety of recommendations are made in the different standards. These are without doubt connected with the different testing practices of soaking over night or not (see also Table 2/10). Sometimes in an unclear way, the heating time is included, sometimes it is seperately specified, as in UNI 5111. If one takes into consideration the great number of different metallic materials being creep tested and their different responses to "short time annealing" at test temperature, it is difficult to judge whether the variety of heating and soaking times presented is significant. For long term testing, which is of main interest for heat resistant steels, one could assume that relatively short soaking times have negligible influence on the test results. Despite the improvements to heating and temperature control equipment in recent years for the near future a relatively long heating and soaking time limit of ≤ 24 h is needed for uninterrupted testing to allow for the different test machines in use. However, for interrupted testing it is recommended to reduce heating time to a maximum of 4 h and soaking time to a maximum of 3 h.

2.8 Test pieces +)

In this chapter (Table 1/11 and 2/12), only test pieces with circular cross sections are considered, since they are the normal case. In most standards, a lower limit is indicated for the test diameter corresponding to 3 to 4 mm. In a rather surprising way, ASTM E139 states an upper limit of 12.5 mm and in the Japanese standards fixed values of diameter are ruled. In order to avoid (a) an excessive influence of scaling in long term tests or (b) the possibility of excluding existing creep laboratories, a minimum diameter of 5 mm is regarded as reasonable. However, $d_0 < 5$ mm may be acceptable when source material thickness is limiting and testing is to be performed in inert environment. A greater

+) Thanks are due to Dipl.-Ing. P. Hortig who contributed to this chapter with calculations of the tolerance of reference length diameter $d_0 \geq 6$ mm should be preferred at higher temperatures when oxidation is a problem or when weldments or large grain size materials are being tested.

Relatively large differences in test piece geometry are due to the variety of ways in which extensometry may be attached for uninterrupted testing. In some standards it is assumed that relatively small collars serve as the means of attachment for the extensometer (example Fig. 4). This arrangement can artificially reduce the apparent level of creep strain (if an appropriate correction is not made). There is also the risk of premature rupture for brittle materials because of a notch effect and a danger of rupture outside the collars. Alternatively, extensometer knife edges are pressed against the test piece within the parallel length. Then, the notch effect can be stronger or the extensometer attachment can become unsafe. Test pieces for these two cases are assigned with "c.d." in Table 1/11. In other standards, a collar is incorporated as a part of the transition radius from the parallel (or "cylindrical") length L_c to the gripped ends (Fig. 5). In this case assigned with "g.d." in Table 1/11, the effect on apparent creep strain is stronger but the other two disadvantages are avoided. Proposals indicated in several standards to limit the dimensions of collars and transition radius to the gripped ends are not contained in Annex 1. In a general way, the constraint of any collar on indicated creep strain can be considered by introducing a reference length L_r (DIN 50 118, DIS 204). The reference length can be calculated according to these standards as proposed by [13] with a simple creep law $\varepsilon_p = A \cdot \sigma^n$ preferably with $n = 5$. As one can see from Fig. 4 for test pieces of the c.d.-type, the reference length L_r is smaller than the gauge length L_0 even for relatively small collars and that should be taken into consideration in the future. For specimens of the g.d.-type, a reasonable limit to the geometry of the collars can be reached by limiting the difference between the lengths L_r and L_c to 10 % as prescribed in DIS 204. In the same way, it is possible to account for shoulders bearing measurement marks for strain measurement in interrupted testing which are situated between the parallel length and the gripped ends of the test pieces (Fig. 5).

As a generality there is not a significant difference between the standards regarding test pieces. However, it seems reasonable for any further developments concerning collars or ridges to be based on the above mentioned recommendations of DIS 204, i.e. to calculate L_r and to keep $L_r \leq 1.1\ L_c$.

A further point concerns the transition radius R to the gripped ends of the test pieces. Significant differences between standards are not evident. The proposal $d_0/2 \geq R \geq d_0/4$ (initial test diameter d_0) seems to be the most reasonable for the future. However, for the special case of extremely notch brittle material $R \leq d_0$ should be admitted.

An important point is the shape tolerance of the test piece in the parallel length, i.e. the deviations from the ideal cylindrical and circular shape (Table 1/12). Significant differences are not observed between the standards.

In general, the test piece machining tolerance seems not to be so important if the shape tolerance is observed. However, this is not the case for the accuracy of diameter measurement which influences the accuracy of stress. An accuracy of ± 10 µm (BS 3500, DIN 50 118) is realistic and causes a stress error of 0.3 % for $d_0 = 6$ mm, an accuracy of ± 0.05 % (DIS 204, stress error ± 0.1 %) is desirable for the future.

The reference length L_r is in most standards ruled or recommended to amount to 5 d_0 (initial test diameter d_0). This is reasonable, as long as the product dimensions allow test pieces with a sufficient diameter d_0 to be withdrawn. However, from the current test practice, $L_r \geq 3\ d_0$ should still be permitted. An other reason for allowing $L_r/d_0 < 5$ is that even for a desired value of 5 a value < 5 can be obtained because the actual diameter d_0 has to be fitted to the fixed loads of multi-specimen machines to reach the preselected stress σ_0. For high precision strain measurement on the other hand a higher value of $L_r / d_0 = 10$ is often used.

The tolerance of reference length is in most standards limited to ± 1 %. It should be at least as small as the relative accuracy of strain measurement ($\epsilon = \Delta L/L_r$, strain ϵ, displacement ΔL, $d\epsilon_p/\epsilon_p = |d\Delta L/\Delta L| + |dL_r/L_r|$). In this sense, the recommendations of BS 3500 seem to be rather too strong, but a reduction to ± 0.5 % would be of interest for the future. A tolerance of ± 1 % is acceptable for the present.

To check wether the usual accuracy of control measurements at a typical test piece is sufficient to determine the reference length L_r to $\pm 0,5$ %, an error analysis was performed for the example of the test piece in Fig. 4. The reference length is calcuted according to DIN 50 118 and DIS 204 with the equation

$$L_r = L_c + 2 \sum_i [l_i \cdot (d_0/d_i)^{2n}] \quad .$$

The value of L_c can be calculated by the equation

$$L_c = L_0 - D_S + d_0 + 2R\,(1-\cos\alpha - \sin\alpha)$$

on the basis of the quantities L_0, D_S, d_0, R and α which can directly be measured at the test piece with the accuracy indicated in Table 1. For the summation of the expression $l_i(d_0/d_i)^{2n}$ the transition parts of radius R and of angle α are each divided into 100 length elements l_i and for these and diameters d_0 and D_S, radius R and angle α the diameter values d_i are calculated according to geometrical equations which are not reported here due to their complexity. For the stress exponent n of the supposed creep equation $\epsilon_p = A\sigma^n$ the Norton exponent can be taken because for constant load tests $\epsilon \propto \dot{\epsilon}_p$ can be assumed. Whereas in DIN 50 118 and DIS 204 n = 5 is recommended, different values of n were taken for the analysis described here.

At first the results for n = 4.3, 5 and 5.8 are presented in Table 1. One can see that the geometrical tolerances of L_0, d_0, D_s, α cause relatively small tolerances of L_r whereas even for the small variation of n = 4.3, 5 and 5.8 nearly the full amount of the permitted tolerance of L_r of ± 0.5 % is obtained. From this surprising result the conclusion has to be drawn that the reference length of test pieces of the type of Fig. 5 with collars or shoulders has to be calculated with the Norton exponent n estimated to an accuracy which can be taken as an example from Fig. 6 (e.g. ± 10 % for n = 2, ± 14 % for n = 5 or ± 16 % for n = 8). In general, this seems to be possible by deriving this exponent from the slope of the $\log\sigma_0 - \log t_r$ rupture curve for the corresponding temperature and stress values and using the Monkman Grant equation $\dot{\epsilon}_p \propto t_r^{-1}$, see also Volume 5 of WG1. In the case of new material a re-calculation of L_r and a re-evaluation of the strain results can be necessary when the correct value of n is unknown in advance. A possibility to enhance the admitted range of exponent n is to increase the reference length, i.e. the quotient L_r/d_0 by example from about 5 to about 10.

As a result of this study, for all types of test pieces with collars or shoulders, the method of calculating the reference length should be reported and especially the Norton exponent n should be indicated which is used and which depends on temperature and stress of the individual creep rupture test. Whereas the relatively simple procedure described here is sufficient for measuring the plastic strain in interrupted testing for uninterrupted testing with measurement of total strain $\epsilon_e + \epsilon_p$ a more sophisticated procedure is needed [14]) taking into account that for elastic strain ϵ_e and plastic strain ϵ_p different stress exponents ($n = 1$ and $n > 1$) exist and thus different (elastic and plastic) reference lengths.

2.9 Strain measurement

Strain measurement has an important influence on the quality of creep test results (Table 1/13 and 1/14). Because the effect of bending can not be ignored (see chapter 2.6), strain measurement should be generally carried out on opposite sides of the test piece. It is surprising that this is not a mandatory requirement in all standards and particularly disappointing that it receives no mention in the International Standards (DIS 204 and EN 123). For the moment therefore, significant differences between the standards can not be ignored in this point. For standards in the future, strain measurement on opposite sides should be mandatory, especially because in practice this is already realized in nearly all laboratories (Table 2/13).

For uninterrupted testing, extensometers are the usual tool of strain measurement. For the interrupted test, "other means" are admitted these normally being a length measurement miscrocope. The accuracy of strain measurement (Table 1/14) is covered in a variety of ways in the different standards (Table 2). Three basic rules are proposed. As rule no. 1, in some standards as UNI 5111 or EN 123 a fixed percentage of ± 1 % of total displacement is stated (in EN 123 only for strain values from 1 %); that is equivalent to a fixed proportion of strain. For small strain values, this would result in unrealistically low displacement tolerances, as can be seen from typical examples in Table 3. For a strain value of 0.05 % and a reference length of 40 mm, a displacement tolerance of ± 0.2 µm results, which probably can not be reached. In EN 123 this is partly considered by ±5 % displacement tolerance for strain values below 1 %. In other standards as NF A03-355, a fixed value of strain is ruled, i.e. ± 0.01 %. The disadvantage of this rule no. 2 is to obtain too large tolerances for small displacements. As an example, for 0.05 % strain and a reference length of L_r = 120 mm, a displacement tolerance of ± 12 µm is obtained, whereas a smaller value seems easily to be possible. As rule no. 3, a fixed value of displacement is stated as ± 10 µm in the Japanese standards and ± 1 µm in the US-standard ASTM E139, the latter being probably unrealistically small, at least for greater displacements or long term testing. From this rule, too small tolerances result for large displacements as again can be seen from Table 3. The other standards rule the strain tolerances in the form of combinations of the three basic rules. To avoid the disadvantage of too large tolerances for small displacements, in DIN 50 118 the compromise is stated to admit for the example of uninterrupted testing the greater value of a percentage tolerance as by example ± 0.01 % of strain on the one side and of a fixed displacement tolerance as by example ± 10 µm on the other side (no. 4 in Table 2). From this condition which can be written in term of strain as "max (0.01 %, $0.010 \cdot 100/L_r$)" or symbolically as in Table 1/14 as "max (0.01 %, 10 µm), a limit of reference length of $L_r = 0.01 \cdot 100/0.01 = 100$ mm can be calculated below which the fixed displacement tolerance is valid and above which the fixed strain tolerance is valid. Despite this giving an improvement for the low displacement range where the physical limits of measurement need a fixed displacement tolerance, for large strain values the tight strain tolerance remains unnecessary

A better solution is presented in ISO 9513 (no. 5 in Table 2), where a "mixed" tolerance of displacement ΔL is ruled. For class 1 extensometers, which are prescribed in DIS 204, the tolerance is max $(0.01\Delta L$, 3 µm) which is physically reasonable with respect to modern transducer technology. Above a displacement of $\Delta L = 3$ µm/0.01 = 0.3 mm, a proportional tolerance of displacement and thus of strain is valid. The above mentioned expression can be converted into strain terms as max $(0.01\,\epsilon$, 3 µm$\cdot 100/L_r)$ which could be symbolically written as max $(0.01\,\epsilon$, 3 µm). For the example of $L_r = 40$ mm, a limit strain of $\epsilon = 0.003 \cdot 100 / (40 \cdot 0.01) = 0.75$ % results, below which a fixed strain error of $0.01 \cdot 0.75 = 0.0075$ % is present. For $L_r = 120$ mm, this limit strain is 0.25 % with a smaller fixed strain tolerance of ± 0.0025 % below that limit (Table 3). The range of smaller strain tolerances due to longer reference lengths could also be widened according to the rule of DIN 50 118, for example down to $L_r = 30$ mm by reducing the displacement tolerance to 3 µm. However, the additional advantage of avoiding too small tolerances at the larger strain values is only realized by ISO 9513, the strain tolerance rules of which should therefore be prefered in the future. BS 3846 quoted by BS 3500 contains a rule not far from ISO 9513 by adding a proportional and a fixed strain error (no. 6 in Table 2).

A comparison of typical tolerances for 1 % strain at a typical reference length of 40 mm (column 41) gives permitted values of about ± 0.01 % to ± 0.025 % for the uninterrupted test. The smaller value will be typical for the future, the greater one for the past. On the other hand, by high precision creep testing of longer specimen, with e.g. a reference length L_r = 120 mm and with lower extensometer tolerances of by example ± 1 µm in displacement, as is indicated for some UK laboratories (see Table 2/14), much smaller inaccuracies are reached of about ± 0.001 % (Table 3). While such a high accuracy seems not to be important for the generation of time to 0.2 to 1 % strain data, it is important for high precision creep curves in the primary (transition) range of creep and thus for the application of creep data to components with relatively low values of permissable plastic strain.

For the interrupted test, the comparison in Table 1/14 gives typical inaccuracies of ± 0.025 to ± 0,05 % in strain (for a reference length of 40 mm). The second value is more typical for the past, the first should be attained in the future. Also in this case, the strain tolerance can be lowered by taking longer test pieces (Table 3). In principal however a significant difference between the uninterrupted and the interrupted tests is to be seen, which will be evaluated in chapter 4. For future standards, DIS 204 is seen as a good basis for uninterrupted testing, whereas strain tolerance in the interrupted test should be redefined according to ISO 9513 and lowered to a technically possible amount. The result is the recommendation "max (0.01 Δl, 10 µm)" (Tables 2 and 1/14).

Calibration requirements for the strain measurement devices are only stated in the newer standards. ISO 9513 as an associated standard for DIS 204 can be seen as typical for uninterrupted testing. The extensometers are calibrated in a special calibration rig normally working at room temperature. For interrupted testing no recommendations are given up to now in the standards. Here, a calibration of the microscope against a quartz glass scale should be prescribed and a regular check of the technicians by means of special test pieces. The latter is important, because the human influence on the interpretation of the position of the measuring marks is decisive and the uncertainty due to this factor forms the greater part of the strain tolerance. However, the different mode of calibration and the different types of inaccuracy resulting from there need some comment.

2.9

In the uninterrupted test, the strain inaccuracy determined in a special calibration rig as proposed by example in ISO 9513 gives only an indication how good the extensometer can work under the best possible circumstances. To make comparisons to the interrupted test, the additional question has to be answered, which further tolerances may arise from a 1 or 5 years service of the extensometer in a creep test machine. Clearly such influences are present, however it is very difficult to make an estimate. In the following, several individual tolerances are discussed.

If the test piece and the extensometer rods are of materials with different coefficients α of thermal expansion, a displacement of the test piece gives a displacement error. By example for ϵ_p = 0,2 % strain and a reference length of L_r = 42 mm, a displacement of Δl = 84 µm results and an error of $dl_T = \Delta l \cdot (\alpha_{spec.} - \alpha_{rod}) \cdot T$. For a test piece of a ferritic steel at 600 °C, $\alpha_{spec} = 12.5 \cdot 10^{-6}$ / (°C) can be taken and for an extensometer rod of 80 Ni 20 Cr-alloy α_{rod} = 15.5 is typical. The resulting error is $dl_T = 84\,(15.5 - 12.5) \cdot 10^{-6} \cdot 600 = \pm 0.15$ µm. For an austenitic alloy at 800 °C ($\alpha = 19 \cdot 10^{-6}$) and a ceramic ($Al_2O_3$) extensometer rod ($\alpha$ = 8), the error is $dl_T = \pm 0.74$ µm.

Further, contraction effects may occur, if the heated parts of the extensometer are of Ni-base alloys. For the example of ferritic material and Ni 80 Cr 20-extensometer rods, for an extensometer gauge length L_0 = 48 mm and 600 °C, a contraction of ϵ_c = 0.002 % can be estimated occuring during the first 1 000 h and leading to a displacement error due to contraction of $dl_c = L_0 \cdot \epsilon_c = \pm 1$ µm. For the ceramic rods, no contraction is to await (dl_c = 0).

As another influence, metallic extensometer rods can experience some bending due to thermal effects. If the bending amounts to f = 0.3 mm, in a simple geometric approximation a length variation $dl_1 = l \cdot (1 - \cos\alpha)$ with $\alpha = 2f/l$ can be estimated. For l = 500 mm and f = 0.3 mm, one obtains 0.36 µm for each rod, for a double sided extensometer a mean square root tolerance from the 4 rods will amount to $dl_1 = \pm 0.7$ µm, for ceramic rods, dl_1 = 0 can be assumed.

Another disturbance can result from the scaling of the test piece and the extensometer parts connected to the test piece. For an oxidation layer of

100 μm, which is easily obtained in longterm testing, an irregular movement of the extensometer parts of 1 % is assumed, i.e. $dl_s = \pm 1$ μm.

A further error can result from the fact, that the extensometer during calibration and in service is applied to different "test pieces" with an admitted tolerance of gauge length L_0 of ± 1 % according to ISO 9513, class I. For $L_0 = 48$ mm the tolerance is $\Delta L_0 = \pm 0.48$ mm. For a typical 10 mm-capacitive transducer, the displacement error dl_0 can vary by about ± 0.3 μm for a displacement of 0.48 mm, thus $dl_0 = \pm 0.3$ μm.

For the same transducer, for a variation of working temperature, which can be assumed to correspond at minimum to the room temperature variation, e.g. $\Delta T = \pm 3$ °C, a sensitivity of $S = 120 \cdot 10^{-6}$ / (°C) is indicated. The resulting error $dl_{RT} = S \cdot \Delta T$ amounts to $dl_{RT} = \pm 0.36$ μm. All other inaccuracies of the capacitive system which is here considered as a typical example, can be neglected.

As in test temperature (chapter 2.3), the individual tolerances or errors are independent to each other and the root of the sum of squares gives a combined error dl, which can be compared to a calibration error of $dl_{cal} = 1$ μm by example. Thus, for 600 °C, a ferritic test piece and Ni 80 Cr 20-extensometer rods $dl^2 = 0.15^2 + 1^2 + 0.7^2 + 1^2 + 0.3^2 + 0.36^2 + 1^2$ or $dl = \pm 1.9$ μm results and for 800 °C, an austenitic test piece and an extensometer with Al_2O_3-rods $dl^2 = 0.74^2 + 0^2 + 0^2 + 1^2 + 0.3^2 + 0.36^2 + 1^2$ or $dl = \pm 1.7$ μm.

So just for high precision extensometry with a calibration tolerance of ± 1 μm, one can assume the total tolerance to be about the double, i.e. ± 2 μm. For larger calibrating tolerances, this effect will be relatively smaller. However, for one sided extensometers the strain tolerances can easily become the triple, i.e. ± 6 μm or more without any possibility to control it.

In the interrupted test, the displacement measurement is carried out by a travelling or workshop microscope, the accuracy of which is ± 1 μm or better. The controling parameter is the visibility of the measuring marks. With the elder Vickers impressions in the test material, due to scaling the displacement tolerance was ± 20 μm after longterm testing as by example ruled in DIN 50 118. Introduction of rare metal or ceramic inserts in the specimens improves the accuracy to ± 10 μm. With a double image microscope, in which two complementary coloured images of the measuring marks can be unified to one white image thereoff [15] (Fig. 7), an accuracy of ± 5 µm can be reached now if ceramic inserts are used.

In this way, the strain accuracy of interrupted testing comes nearer to that of uninterrupted testing and that should be considered in further comparisons of the two different testing methods.

Another point relating to strain measurement is the frequency of strain readings, which in most standards is ruled as "sufficient measurement" or "continuous recording". The first indication is unclear and the second gives in the uninterrupted test, at least for long term testing, an overwhelming data flood to be instantaneously reduced. So a compromise should be the development of typical time sequences for strain measurement, as is done in some test laboratories (see chapter 4.2). For the moment, testing practice has to be observed to decide, whether significant differences in the creep strain data sequences are present or not. A special view for this point is needed for the interrupted test, where the frequency of strain readings due to the test interruptions has to be decisively lower than for the uninterrupted test.

2.10 Test results

A variety of creep and creep rupture test results are requested by the different standards (Tables 1/15 and 1/16). Requested results common to all standards are initial plastic strain ϵ_i (only for uninterrupted testing), creep strain ϵ_f, rupture time t_r and the ductility values A_r and Z_r. The total plastic strain ϵ_p is not requested in one standard (NF A03-3351), although it can be easily calculated as the sum of strains ϵ_i and ϵ_f. The only standards requiring nearly all possible strain values are ASTM E139 (without anelastic strain ϵ_k), DIS 204 (without total strain ϵ_t) and DIN 50 118 (all).

Whereas the above mentioned strain values are the primary results from a creep or creep rupture test (only t_r, A_r, Z_r in the case of a stress rupture test), other results such as time to specific creep or plastic strain ($t_{f\epsilon}$ or $t_{p\epsilon}$) or the corresponding strength values ($R_{f\epsilon}$ or $R_{p\epsilon}$) and the creep rupture strength R_r are secondary results which need some basic assessment to be determined. Regarding this point, the existing standards can be separated into those which do not consider assessment and those which do, and even then, usually only the results of a test series at one temperature and on one homogeneous test material. An example of such a basic assessment is shown in Fig. 8. A graphical method is used, which can be easily applied by experienced technicians. Computer aided methods are possible and sometimes used. However they bear some danger to produce erroneous values, if the test results present some scatter, while an experienced specialist will avoid such errors or will directly search for the cause of scatter.

Summarising, the following conclusion can be drawn. If secondary test results such as times to specific strain values are to be considered in a subsequent assessment as is intended in the frame of ECCC working, a basic evaluation procedure should be included in future standards or take the form of a separate standard. For the moment, the generation of such creep test results is left to the basic assessment practices of the different laboratories, while it is not carried out according to DIN 50 118 or to ASTM E 139.

In this context, another point normally not ruled in standards but usually practiced in most laboratories is the method of detecting "uncharacteristic behaviour" associated with single test results. The usual way is to compare the results of the individual tests with others from within the same test series or with appropriate data for the same material type. This is normally done at each campaign of assessment. If uncharacteristic behaviour is confirmed, the usual consequence is to repeat the test and to cancel the old results before reporting or to withdraw them after reporting when the error is detected at a later campaign of assessment. Further, a well working laboratory will try to find out its errors on the base of its internal test records. This method is far more efficient then any external analysis of metadata, which additionally forces the transmission of a giantic and expensive amount of data, which are nearly always without any use. Further, such check procedures and internal data retracing systems are part of any accreditation. As a consequence, in future for improved standards an internal assessment procedure should be recommended to check the results within the laboratory before the first reporting and also in repeated assessment campaigns.

2.11 Final remarks to testing standards

The overview given in Annex 1 and discussed here indicates a relatively small number of significant and possibly characteristic differences between creep testing standards. These need further investigation in combination with the actual testing practices adopted by the laboratories. This is done in chapter 3. In addition an investigation is needed to establish the extent to which the generated test results are influenced by the testing tolerances or inaccuracies. This is done in chapter 4.

From the comparison and discussion of existing testing standards, a view has been developed with the aim of generating creep rupture data with improved repeatability and reproducibility in European laboratories in the future. An important point in this regard is the availability of a common testing standard. This is the case for uninterrupted testing with DIS 204, which however needs some future improvements. For interrupted testing, only EN 123-75 is available, which does not meet all needs for the future. Therefore a new European or ISO standard for interrupted creep, creep rupture and stress rupture testing should be established or the future standard ISO 204 should be extended to interrupted testing.

3. Creep rupture testing practices

3.1 Laboratories, test procedures and test machines

The testing practices of the laboratories of 10 WG1 members from 6 European countries have been reviewed. The overview in Tables 2/1 to 2/16 represents the typical testing practices of the individual countries according to the specific standards indicated (Table 2/1). Uninterrupted as well as interrupted tests are performed and single machines, multi machines as well as multi-specimen machines are used. The usual test atmosphere is air (Table 2/2). Dead weight loading with or without lever is the normal case. As a speciality, one laboratory has spring loaded multi-specimen machines and some laboratories also have test machines with servocontrolled loading. The load application in most laboratories is covered by standards, the details of which are considered below. From the points reported here, it is concluded that there are no significant differences influencing the quality of creep or creep rupture data generation in the laboratories surveyed.

3.2 Test temperature

The maximum test temperature in the different laboratories (Table 2/3) is situated between 800 and 1 350 °C depending on the materials to be tested. With regard to the heat resistant-steels treated up to now within ECCC, the limits presented are sufficient. For interrupted testing the highest test temperature indicated is 1 000 °C. The reason for this limitation is the progressive scaling of the test pieces and the clamping parts making it impossible to detach the test pieces for the strain measurement during the interruptions.

The test temperature tolerances are consistently indicated as total temperature tolerance as defined in chapter 2.3. In no case are they greater but in some cases they are a little smaller than permitted by the standards. However, small tolerances of ± 2 °C by example should be viewed with some caution, especially in connection with the use of base metal thermocouples. Typically, temperature tolerances are ± 3 °C, for tests up to 600 °C, ± 4 °C for tests above 600 °C up to 800 °C, and ± 5 °C for tests above 800 °C up to 1 000 °C, and this is in accordance with the proposals for future standards in Table 1/3. Considering chapter 2.3, it will be very difficult to lower these tolerances, which are influenced by so many parameters.

The tolerance of the temperature measurement equipment (Table 2/4) is in most cases ± 0.5 °C with a resolution normally ranging from ± 0.1 to ± 0.5 °C. For the future, values for the resolution of ± 0.2 °C should be achievable. It is unclear up to now, if the values indicated are only for temperature measurement or also for continuous recording. For this, in one case a greater tolerance of ± 1 °C is indicated.

Thermocouples are nowadays mainly of the rare metal type. Type R (Pt13Rh-Pt) is preferred in the UK and Type S (Pt10Rh-Pt) in other countries, the differences between these types being negligible. It is hoped that the use of base metal thermocouples will be reduced in the future and at least above 400 °C and 1 000 h will no longer be used (see also chapters 2.3 to 2.5).

The minimum number of thermocouples varies (Table 2/5), as seen for the standards. For single machines, 3 or 2 thermocouples for the test piece depending on its length (or possibly the number of heating zones) is usual. For multi-machines, 3 thermocouples are usual for the string and for multi-specimen machines 1 thermocouple per each heating zone is the minimum indicated. What is indicated partly on Table 2/6, column 18 for the case of indirect temperature measurement, is the need to periodically repeat the determination of systematic temperature differences between working thermocouples and test pieces of the same heating zone as already discussed in chapter 2.3. This control measurement becomes increasingly important as the test piece capacity of the machine increases. Generally the indications to the minimum number of thermocouples seem to be acceptable and agree with the proposals in Table 1/5.

The adopted practices for temperature calibration (Table 2/6) specifically refer to standards only in some laboratories. The need for a special temperature calibration standard or at least for more detailed instructions in the testing standards seems to be an important point for the future. Surprisingly not all laboratories indicate an in-situ calibration practice, which is, according to the experiences fo the author and a majority of specialists, very important for the recalibration of rare metal thermocouples at least for temperatures above 600 °C [x)] . Recalibration of base metal thermocouples can not be

x) An existing opposite re-calibration philosophy is described in chapter 2.3

recommended, see chapter 2.5. The time interval between two calibrations (Table 2/5, proposals for the future, see Table 1/5) is in some laboratories the greater value of 1 year or the time of an individual test ("before and after test"). In German laboratories longer calibration times are usual for rare metal thermocouples. However, this practice is connected with in-situ calibrations which take into account the immersion depth effect of deteriorated thermocouples. A general recommendation, to replace thermocouples whenever this is practicable, was proposed by one laboratory but this seems unnecessary, if in-situ calibration is carefully performed.

In addition to thermocouple calibration, all laboratories calibrate their temperature measurement equipment. However, the time interval between equipment calibration is generally not given, and in practice should not exceed 1 year (Table 1/6).

The frequency of temperature measurement (Table 2/6) is a point on which there is a wide variance. Two main groups can be discerned. In the first group, temperature is scanned and recorded following short intervals of 2 to 10 min. In one laboratory a 1s-interval is the rule if the temperature change is greater than 0.25 °C. In the second group "sufficient recording" is indicated according to the individual testing standards. In the latter case it remains with the laboratory to choose the necessary frequency according to the stability of the temperature control circuits. However a general rule based on the philosophy of the first group should be reached in the future as an indication of sufficient readings. As a minimum requirement for the future, at least 1 thermocouple should be recorded per heating zone (Table 1/6).

A further point of test temperature is the use of the International Temperature Scale. Although the valid scale is ITS 90, some laboratories still refer to IPTS 68. The differences between these scales are given in Table 4. The maximum difference is 0.4 °C at 760 °C. As long as new reference tables [4] are not (officially) available one can take the conversions given in Table 1 to correct T_{68} to T_{90} [16) 17)].

As a generality if one ignores certain doubts about the use of base metal thermocouples and the absence of in-situ calibration of rare (noble) metal thermocouples (assumed by some to be partly compensated by a more frequent replacement of the thermocouples), no significant differences in regard to test temperature are apparent between the different laboratories.

For the future more research work and systematic measurements of the type described in [1) 2) 7)] is of interest to improve the knowledge of the long term drifting of rare metal thermocouples and to secure the rules of calibration of these thermocouples.

3.3 Loading and load tolerance

The use of load (or more specifically force control) in creep testing is typical in most laboratories (Table 2/7). Only one laboratory surveyed also tests with constant applied stress. As discussed in chapter 2.6, there is no great necessity to that. In nearly all laboratories a load tolerance of 1 % is prescribed, and this seems to be reasonable. For the loading time, some laboratories give, according to the standards, the unclear indication "as rapid as possible". Numbers vary from 0.24 to 5 min. A proposal is to set an upper limit of 10 min (Table 1/7). Another proposal to use a loading time consistent with that used for hot tensile tests was earlier declined. With respect to long term testing, this time is not very important. With respect to replacing initial plastic strain by the plastic strain determined from a hot tensile test, the declined proposal would have been ideal. However, if this is not possible the alternative approach is to perform the hot tensile test to generate initial plastic strain values at the loading rate of the creep rupture test. If the latter point is considered significant differences in the creep and creep rupture data generated will probably not exist, if "as rapid as possible" is not longer than 10 min.

Preloading (Table 2/8) to improve strain measurement quality is used in most laboratories. However, this is seen to be unnecessary in some UK laboratories, possibly because they perform a cold load at room temperature to check the integrity of the extensometers. This is sometimes taken to be an alternative procedure (Table 1/8). However, because preloading is the only sure way to minimize tolerances and to exclude nonlinear movements of the single extensometer parts, this should be recommended for the future extensometry.

Another point with the indication "minimized" is maximum bending stress. Only one laboratory indicates a number of maximum elastic bending strain (5 % of elastic axial strain), presumably for test begin. The other laboratories indicate only "bending minimized". Obviously there is a lack of systematic measurements. It is the authors experience that proportions of bending stress to axial stress of up to 40 % can be observed. Systematic measurements should be performed in the future to assure that a maximum proportion of 20 % bending stress of axial stress can be obtained as is proposed in chapter 2.6. As far as the current testing practice is concerned, balanced readings of two transducers attached at opposite sides of the test pieces in the uninterupted test or of measurement marks at the test pieces in the interrupted test are presumably carried out by all laboratories (see column 40 in Table 2/13). They give an important help but no full information about bending because the main effect thereoff is creep ratchetting in the axial direction. This will mainly occur in interrupted testing due to repeated bending in different directions, when the specimen is periodically removed from the test machine for strain measurements. At the present time the indication "bending minimized" should be sufficient but for the future, a limit should be given which was fixed in WG1 to 0.2 σ_0 (Table 1/8).

3.4 Other test conditions

Some supplementary test conditions, which are also of influence on the test results, were discussed in chapter 2.7. The laboratory air temperature (Table 2/9) is important for uninterrupted tests carried out with extensometers. That temperature is in this case in all laboratories within ± 2 or ± 3 °C. The requirements depend on the type of transducer used. Capacitance types are particularly sensitive to temperature and humidity changes. Extremely low limits of ± 1 or even ± 0.5 °C are reported which can presumably also in the future not be reached in all laboratories and ± 3 °C seems to be a reasonable tolerance (Table 1/9). For interrupted tests, the temperature of strain measurement of the test pieces under a microscope in a separate inspection laboratory is relevant. This temperature is kept within ± 2 °C in the examples surveyed and that tolerance should also be prescribed in future standards.

In regard to test duration, the indications show some differences. Long term testing up to 100 000 h or more seems very common in the UK as well as in Germany, whereas in France and Italy rather relatively shorter maximum test times are usual. Laboratories from other countries take an intermediate position in this regard. The different numbers are not significant for test quality, although they will give inhomogenuous data in regard to long term assessments. This will be a serious problem but is outside the considerations of this report

The test time accuracy (Table 2/10) is in the most laboratories ± 1 % or better, if one considers test times above 100 h. From this point no problems arise. The time from which the full stress σ_0 is acting is the time $t = 0$ in all laboratories, in accordance with the standards (Table 1/16).

The soaking times adopted (Table 2/10) are varied as seen in the different standards (Table 1/10). For the future a more uniform soaking time range would be desirable and the same is valid for the heating time. As reported in chapter 2.7, the heating + soaking time was limited in WG1 to 24 h for uninterrupted testing. For interrupted testing, shorter times are proposed (Table 1/10).

Another question concerns the influence of test interruptions, which is important for the comparison of the results of uninterrupted and interrupted testing. An overview of several systematic studies on this problem is given in [5]. It is also experimentally demonstrated, that unloading and reloading, decrease and reincrease of test temperature and annealing times resulting from unloading and reloading under test temperature do not influence the results. An influence however can be expected from repeated bending as discussed in chapter 3.3. From [5] a weak acceleration in creep rate and a corresponding weak reduction in typical test times (time to specific strain and to rupture) due to systematic interruptions was not determined in all cases but can not fully excluded. As an estimate, an average time reduction of about 5 % for interrupted testing as compared to uninterrupted testing may be assumed. More systematic work should be done in the future in this direction [*)].

*) ERA have submitted a funding application to BCR for a concerted action to examine these problems

3.5 Dimensions and tolerances of test pieces

The test pieces used in the laboratories surveyed have cross sectional areas from 15 to 162 mm^2 and corresponding test diameters d_0 from 4.5 to 14.4 mm (Table 2/11). A typical value for the latter is 8 mm. Only in one case 2.5 mm is indicated, possibly as a speciality. As discussed in chapter 2.8, diameters from 5 mm seem generally to be acceptable with some exceptions, although greater diameter should be preferred when metal loss due to scaling is a problem. As an example for d_0 = 5, 6 or 8 mm, a radial loss of metal of 0.2 (0.05) mm gives an increase of stress of about 18(4), 15(3) or 11(2.5) %. If an intermediate stress increase is assumed to be typical, e.g. the half of the above indicated percentages, remarkable stress increases are to be seen even for 8 mm test piece diameter. Because scaling is an unavoidable effect at the upper temperature limit of each steel and nearly all alloys, more attention should be given to this point in the future. However for the moment, from the above numbers and the fact that most results are not obtained at the highest temperature for the individual materials, it seems justifiable to accept the data generated on test pieces with the different diameters considered above.

A difference in test piece geometry is present between the German laboratories which adopt a greater diameter near the ends of the parallel length of the test pieces but inside the gauge length L_0 ("g.d." in column 32), and other laboratories which prefer a constant diameter within the gauge length ("c.d." in column 32). The advantages and disadvantages of both solutions are discussed in chapter 2.8, and no significant differences are obvious with the exception that the reference length of g.d. test pieces depends on the stress exponent n, a fact which was presumably neglected up to now in most cases. However, a similar problem exists for c.d. test pieces with small collars. Even small collars may not be neglected, as can be assumed to occur in some laboratories. What happens in the latter case can be seen from the example in Fig. 4. There, for relatively small collars a reference length of L_r = 42.0 mm is calulated according to DIN 50 118 (n = 5), whereas the gauge length is L_0 = 43.8 mm. So an error of 4 % results, if $L_r = L_0$ would be assumed. Therefore, some attention should be given to a better calculation of reference length in the future.

As a further point, the transition radius from the parallel length to the gripped ends or to an intermediate test piece portion with greater diameter is in most cases between 0.25 d_0 to 0.4 d_0, in same cases d_0 is reached. The size of this radius is less important, as long as the reference length L_r becomes not greater than 110 % of the parallel length L_c (chapter 2.8).

The shape tolerance of the test piece diameter (Table 2/12) is in practice rather smaller than stated in the standards (Table 1/12). The machining tolerances indicated are often greater. However, the latter seem to be rather unimportant as compared to the tolerance of the diameter measurement, which is in many cases relatively high with ± 0.01 mm. If one assumes a tolerance of cross sectional area $dS_0/S_0 = 2\, dd_0/d_0$ with the diameter tolerance $dd_0 = \pm 0.01$ mm, and with a diameter $d_0 = 6(8)$ mm, one obtains a tolerance of cross sectional area of $dS_0/S_0 = \pm 0.33(0.24)$ % or of initial (nominal) stress $\sigma_0 = F_0 / S_0 = \mp 0.33(0.24)$ %. With a stress tolerance due to the load tolerance of $dF_0/F_0 = 1$ % (see column 22 in Table 2/7), the total stress tolerance can be calculated again using the error summation law (see chapter 2.3) as $d\sigma_0 / \sigma_0 = \sqrt{1^2 + 0.33^2(0.25^2)} = 1.05(1.03) \approx 1$ %. As one can see, the test piece diameter tolerance is negligible under the circumstances described. As will be shown in chapter 4, the stress tolerance is besides temperature tolerance an important basis to estimate the error of creep test results.

The surface quality of the test pieces is in the most laboratories "ground". The main reason is possibly, that a good shape tolerance can be easier reached in this way.

The reference length of the test pieces is according to the standards in most cases $L_r = 5\, d_0$. Sometimes this value varies within small limits. In special cases of high precision creep testing, $L_r = 10\, d_0$ is used. The accuracy of the reference length is ± 0.05 to 0.1 % in most laboratories, which is much smaller than the maximum amount of ± 0.5 % admitted in WG1 for the future. Much smaller values are indicated by some UK laboratories in accordance with BS 3500. These smaller tolerances are unnecessary if the reference length is only used to calculate the strain ϵ from the displacement Δl, i.e. $\epsilon = \Delta L/L_r$, see chapter 2.8. Possibly such small tolerances are connected with the use of the reference length to determine the displacement ΔL itself. The problems of calculating the reference length have been discussed earlier.

In summary, it is unlikely that the different test piece geometries and dimensions adopted by different laboratories are likely to be responsible for signifcant differences in the creep rupture properties determined. One typical test piece for all types of test approximates $d_0 = 8$ mm and $L_r = 40$ mm. A second typical test piece for high precision creep testing has a reference length $L_r = 100$ mm to 125 mm.

3.6 Strain measurement and strain tolerances

Strain measurement (Table 2/13) is performed on opposite sides of the test piece by all laboratories (but one), thereby giving an essential confidence to the strain results.

In some laboratories, creep tests and stress rupture tests are conducted separately, i.e. creep and stress rupture tests are not performed on the same test pieces. Adopting this practice, strain results are not available to give advanced information about the rupture time to be expected of test piece. This does not lower the quality of the individual test results but is a certain disadvantage for the planning and supervision of tests and may be a source of inhomogeneity for the assessment of the results. However, there is a general and recommended trend to increasingly combine the measurement of creep and rupture time on the same test piece. Besides, this will lead to more economic testing.

As for the means of the strain measurement, extensometers are usual in uninterrupted testing, whereas a length measurement microscope is the normal tool for interrupted testing, see also Table 1/13.

The tolerance of strain measurement (Table 2/14) is a very important point in creep tests. In uninterrupted testing it is usual to use a class 1 extensometer according to ISO 9513 (Table 1/14) and also prescribed in DIS 204. The strain tolerance of the calibration thereoff is max (0.01 Δl, 3μm) or max (0.01 ϵ, 3 μm·100/L_r). In some cases even smaller tolerances are indicated down to 0.002 % or 1 μm and in other laboratories greater values as for example max (0.01 %, 10 μm · 100 / L_r) according to DIN 50 118. However, as indicated in chapter 2.9, the working inaccuracy of the extensometer will be greater, e.g. for a ± 1 μm-calibration ± 2 μm with double sided extensometry and ± 6 μm or more with one sided extensometry. Even if it may be extremely difficult, the questions connected with the total accuracy of extensometers should be investigated in more detail. As a generality, it is realistic to go for the future to tolerances according to DIS 204.

In interrupted testing, greater strain tolerances up to max(0.02 %, 20 µm) according to DIN 50 118 are indicated. Also here, for the future a lower and better based limit should be attained, for which max (0.01 Δl, 10 µm) is proposed, see also chapter 2.9. The limit in interrupted testing is normally not the tolerance of the length measurement microscope, which is nowadays ± 1 µm. The controlling parameter is the visibility of the measuring marks, which can change the precision of measurement from ± 5 µm to ± 20 µm in long term tests of scaling materials. With special inserts made of rare metal or even better of ceramics (Fig. 5) an improvement to ± 10 µm is now possible. With a double image microscope and a specimen with ceramic inserts presenting central bores (Fig. 7), an accuracy of ± 5 µm can be reached, see chapter 2.9.

For an overview, typical strain inaccuracies for a reference length of about 40 mm are reported in column 44 of Table 2/14. Further examples are given in Table 3. The values range in general from 0.003 % to 0.05 %. The effect of these differences on the creep results generated by different laboratories can only be quantified on the basis of the error analysis performed in chapter 4. In this regard the strain tolerance due to the tolerance of the reference length L_r is to be included in the total strain tolerance. As is shown in chapter 2.8, this can be done by the equation $d\epsilon/\epsilon = |d\Delta L/\Delta L| + |dL_r/L_r|$. If the tolerances of strain measurement are in accordance to the proposals in Table 1/14, row 11 and chapter 2.9, the relative strain tolerance due to the displacement measurement will be at minimum $d\epsilon/\epsilon|_{\Delta L} = 1$ %. The relative strain tolerance due to the tolerance of 0.5 % of the tolerance of reference length according to Table 1/12 will be $d\epsilon/\epsilon|_{Lr} = 0{,}5$ %. Thus the total relative strain error can be estimated according to the error summation law to $d\epsilon/\epsilon = \sqrt{1+0.5^2} = 1{,}1$ % ≈ 1 %. Therefore the influence of a tolerance of reference length of ± 0.5 % on the strain tolerance can be neglected.

As far as strain readings are concerned, "sufficient measurement" is stated by most laboratories, in a similar way to temperature measurement. As discussed in chapter 2.9, this may be sufficient for the creep data generated up to now, but clearer guidelines should be given in the future. Examples of measurement frequencies for interrupted and for uninterrupted tests respectively are given in chapter 4.2.

In summary, the action of the different strain tolerances must be analysed. Any other differences concerning strain measurement (with the exception of the problems with reference length) seem not to be significant for existing data, whereas for the future improvements are possible (Tables 1/13 and 1/14).

3.7 Results of the test laboratories

The laboratories indicate that in general they report more test results than are required by the corresponding standards. So in all cases of uninterrupted testing the total plastic strain ϵ_p as well as the creep strain ϵ_f are reported. Only in one laboratory is initial plastic strain ϵ_i not reported. However, in this case the response was that the plastic strain could be determined from hot tensile tests, to replace the initial plastic strain ϵ_i . This is also the experience of the authors laboratory [12)].

As a speciality of the interrupted test, only the permanent strain ϵ_p'' can be measured (Table 1/16). This strain ϵ_p'' is approximately equal to the non-proportional strain ϵ_p' as long as the anelastic strain ϵ_k is negligible, this being assumed in nearly all cases and leading to a (total) plastic strain ϵ_p . For an exact combination of strain values ϵ_p'' and ϵ_p', ϵ_k has to be measured and this is only possible in the uninterrupted test by a special unloading procedure, which is usually performed in 4 of 10 laboratories surveyed. However, the presentation and evaluation of creep data becomes relatively complex if the anelastic strain is considered and this problem was not further discussed in WG1.

Under the approximation $\epsilon_k = 0$, the relation between ϵ_p and ϵ_f is $\epsilon_p = \epsilon_i + \epsilon_f$. Therefore, if ϵ_i is known it is sufficient to report ϵ_p or ϵ_f and WG1 agreed that either ϵ_p or ϵ_f but in any case ϵ_i has to be reported from the uninterrupted test. From the interrupted test delivering only the plastic strain ϵ_p the initial plastic strain ϵ_i has to be reported as the result of an accompanying hot tensile test which is performed with approximately the same loading rate and strain tolerance as the uninterrupted test. Also the reference length is to apply in this hot tensile test to determine the plastic strain as is done in the uninterrupted test.

Beside the primary test results so far discussed and including the rupture values t_r, A_r and Z_r (see also chapter 2.10), "secondary results" which need some basic assessment are reported. These secondary results, which are times $t_{f\varepsilon}$, $t_{p\varepsilon}$ or stresses $R_{f\varepsilon tT}$, $R_{p\varepsilon tT}$ (Table 2/16) to specific strain values (at given time t and temperature T), were regarded by an individual laboratory as being "not part of the test procedure". If however, as is practiced now in the frame of ECCC, data of this type, particularly $t_{p\varepsilon}$ are collected to give the basis of an assessment, the question arises whether a future standard should contain a basic procedure for determining such values at least of $t_{p\varepsilon}$- and $t_{f\varepsilon}$-type (e.g. DIN 50 118 or ASTM E139, chapter 4.2). Such an evaluation procedure (example Fig. 8), which concentrates on results for one test material at one test temperature, is normally graphical.

Another point requiring further discussion is the necessary degree of availability of values $t_{f\varepsilon}$, $R_{f\varepsilon tT}$ and $t_{p\varepsilon}$, $R_{p\varepsilon tT}$ in the future. This question is connected to the planned assessment and has to be answered from the viewpoint of the use of creep data for design and supervision of components. For the testing practice this question is already cleared up by the above discussed decision to report ε_i in every case and either ε_p or ε_f as customery for the laboratory. A third way already sometimes in use is to begin interrupted tests in the uninterrupted mode, see by example Fig. 5 and [12].

As far as the strain basis (ε_p or ε_f) for typical times is concerned, the times $t_{p\,0.2}$, $t_{p\,0.5}$ and $t_{p\,1}$ have been taken for the WG1 check of assessment methods and in these circumstances no inadmissible data mixture occurs. However for the future, a solution on principle to that problem has to be found.

3.8 Final remarks to testing practice

Another important point of testing practice is the accreditation of test laboratories. Two laboratories report that they have already obtained an accreditation. Most other laboratories indicate in different ways that they are preparing to become accredited. The value of accreditation is not seen in the same light by all WG1-members. Some critical remarks were made from one laboratory which considered accreditation as being more a formality than a means of assuring constant test quality over years and over all test machines. However, the majority sees advantages resulting from accreditation.

Another important point is the execution of comparison tests and this is partly more emphasized than accreditation. If one considers the large number of parameters and the variety of testing practices detailed in the previous chapters, one gains an impression how difficult creep tests are to perform to the same quality over long times and in most cases in a large number of test machines. Therefore, comparison tests are an ideal means of obtaining and assuring best quality and of giving confidence in creep data generation. These benefits can only be obtained by repeatedly performing comparison tests on the same test material at distinct time intervals. Such tests are also an ideal means of assuring comparability of different test modes, as uninterrupted and interrupted. Because interrupted tests in some respects are more difficult, a way to assure their quality could even be the execution of comparison tests and this could become a part of a standard for interrupted testing, for example to compare typical strain results of each 3 tests of uninterrupted and interrupted mode within the same laboratory. This should be possible because laboratories performing interrupted tests normally also perform uninterrupted tests.

If reviewing the differences between the testing practices obeyed in the different laboratories, some initial conclusions can be drawn. The most important point is that there do not seem to be significant differences between the tolerances of the main test parameters temperature and stress. However, the strain tolerance in uninterrupted testing is in general smaller than in interrupted testing. The action of these tolerances on the variability of the main test results will be analysed in chapter 4.

Other important points, from which significant difference could originate, can not so clearly be analysed. These include the use of base metal thermocouples, the non-in-situ calibration of rare metal thermocouples, the use of test pieces with relatively small diameters exposed to greater metal losses due to scaling and some other points as soaking time and one sided strain measurement. Here only improvements to standards, as proposed in chapter 2, and repeated comparison tests can improve the testing practice to obtain lower scattered creep, creep rupture and stress rupture results in the future.

4. Influence of typical test tolerances on main test results +)

4.1 Tolerances and results considered

As a result of chapters 2 and 3, typical tolerances for the most important creep rupture test parameters have been determined (i.e. temperature T and initial stress σ_0). These tolerances are:

± 3 °C for $T \leq 600$ °C, ± 4 °C for $600 < T \leq 800$ °C,
± 5 °C for $800 < T \leq 1\,000$ °C, and
1 % for σ_0.

Further, typical tolerances of the main creep test results, i.e. test time t and as an example plastic strain ε_p have been determined. These tolerances are:

- ± 1 % for a characteristic time
- -5 % of a characteristic time for interrupted testing as compared to uninterrupted testing, and
- in the uninterrupted test ± 3 µm (future) to ± 10 µm (past) displacement for about 40 mm reference length, i.e. about ± 0.01 % (future) to ± 0.025 % (past) in strain ε_p, for high precision creep testing ± 1 µm on ≥ 100 mm reference length, i.e. ± 0.001 % in strain ε_p, the latter values being taken for double sided extensometry and only for initial calibration,
- in the interrupted test ± 10 µm (future) to ± 20 µm (past) displacement for about 40 mm reference length, i.e. ± 0.025 % (future) to ± 0.05 % (past) in strain ε_p.

In the strain tolerances inaccuracies due to the inaccuracy of the reference length e.g. due to neglecting a small collar in uninterrupted testing or due to taking a mean stress exponent of 5 are not included. So the tolerances of the past technique can be to some degree higher.

The aim is now to analyse the action of the above presented tolerances on the accuracy of the main creep rupture test results for two purposes:

to assess the accuracy of the test results, and
to evaluate the significant differences existing between the uninterrupted and the interrupted creep test.

+) Thanks are due to Dipl.-Ing. M. Monsees, IfW Darmstadt, who contributed to this chapter with calculations and graphical presentations.

Being the main test results, the rupture time t_r and the times $t_{p\epsilon}$ to plastic strain ϵ_p = 0.2 and 1 % were chosen for evaluation. In this way the time values taken for the creep rupture assessment studies in WG1 are represented. In the analysis, all the tolerances mentioned above are considered, where applicable, in their action on the chosen time results $t_{p\,0.2}$, $t_{p\,1}$ and t_r. As for the case of temperature (chapter 2.3) but now for time, the individual tolerances of test parameters and test results are combined to give an overall time tolerance. The first step in the analysis is to convert the individual tolerances of temperature T, stress σ_0 and strain ϵ_p, as appropriate, to individual time tolerances. The basis for the conversions are the functions $t_r(T,\sigma_0)$ and $t_{p\epsilon}(T,\sigma_0,\epsilon_p)$. The first is determined from an analysis of stress rupture curves and the second from an analysis of creep curves leading to a creep equation $\epsilon_p(T,\sigma_0,t)$. The tolerance of time measurement of ± 1 % (chapter 2.7) and the interruption time difference of -5 % (chapter 3.5) are used directly in the analysis.

To have a good connection to the assessment work in WG1, the analysis, has been carried out on heat resistant alloys of similar pedigree to the materials being considered as part of the evaluation of assessment methodologies in the frame of WG1.

The following steels were chosen for the analysis because of the availability of creep equations for these materials

- 2.25 Cr-1Mo, no. 7zt ,
- 1 Cr-1 Mo-0.5 Ni-0.25 V, no. 217am ,
- 12 Cr-1 Mo-0.3 V, no. 220am , and
- 17 Cr-13 Ni-2 Mo-0.2 N, no. 123e .

These steels are individual test materials with creep properties, which are typical for the corresponding alloy classes. For steels no. 7zt, 217am and 220m, the creep equations and their coefficients are described in [12], for steel no. 123e the creep equation is not yet published [18]. Typical creep curves calculated by these equations are shown in Fig. 9. The creep rupture curve equations were not determined for the above mentioned individual test materials but for the corresponding steel classes. The equations are composed of a polynomial of a monotonic stress function and a time temperature parameter and their coefficients are represented in Table 5. More details are contained in [12) 18) 19)].

The creep and rupture curve equations are valid for the normal range of application of the steels. These ranges will not be exceeded by the analyses, which are described in chapter 4.3. Before these analyses are carried out, a further time tolerance has to be determined, originating from the translation of creep curve data points into a time to specific strain.

4.2 Translation of raw data into assessment input data

As discussed in chapters 2.10 and 3.7, only a few standards describe methods to translate raw laboratory creep test results into input data for assessment (e.g. the determination of $t_{p\varepsilon}$ from (ε_p ,t) creep curve data). As an example, the widely used method of DIN 50 118 is taken. According to that method, experimentally measured creep data points are plotted in a logarithmic strain-time-diagram and successive points for each test are linearly connected (Fig. 10). This method was used to construct Fig. 8 and can be easily performed without any numerical analysis. Clearly, the interpolation error or time tolerance resulting from linear curve construction technique depends on the time scale used for the creep measurements and the data collection strategy is very different for uninterrupted and interrupted creep testing. Typical acquisition schedules and time scales are represented in Table 6.

The time tolerance e_l resulting from linear interpolation is the maximum time deviation between the interpolation line and a typical creep curve in Fig. 10, thus

$$e_l = \max \left[(t_{p\varepsilon\, lin} - t_{p\varepsilon}) \,/\, t_{p\varepsilon} \right] \tag{1}$$

with $t_{p\varepsilon\, lin}$ being the value due to linear interpolation in the log strain-log time-curve and $t_{p\varepsilon}$ being the true value situated on the creep curve, both time values being valid for a strain ε_{p0}. For the determination of the tolerance e_l , an ideal creep curve represented by one of the above cited creep equations can be taken, which is for a strain value ε_{p0} linearly interpolated according to Fig. 10 between time points corresponding to a time scale from Table 6. By a trial and error method explained below a strain value ε_{p0} is determined, for which the interpolation time error will be the maximum and this will give the tolerance ε_l . It is noted that the error e_l is only caused by the interpolation which takes place between successive creep data points. The uncertainty of the data points is not included in that error. That uncertainty is caused by the stress, temperature and strain tolerances, the action of which on time to specific strain is investigated separately in the next chapter.

If more than two data points enclose immediately the value ϵ_{p0} (Fig. 11), an additional rule is needed for the interpolation. A commonly used procedure in this case is to take the geometric mean of all values $t_{p\epsilon 0}$ linearly interpolated between succeeding creep data points for strain ϵ_{p0}. The increase in time tolerance due to such a situation is again not a consequence of the interpolation. This can easily be demonstrated for the example of a double reversal, which is the normal case. Three interpolation errors emerge, which are assumed to be no greater than the without reversals situation. The averaging process equalizes the incluence of the tolerances due to strain, temperature and stress. However, as indicated above, the actions of these influences will be separately considered in the next chapter. For existing creep curves, the case of curve reversals is relatively seldom observed as can be seen from the examples in Fig. 12. In this figure, the creep curves with first data points at 100 to 300 h are uniquely determined from interrupted tests according to a technique very common in Germany but also in some other countries (Table 2/1). A mixed technique has been employed to produce the most other curves, with the early data points being determined by continuous measurement at short times and later data points at longer times being collected by interrupted measurements. Addionally, some curves appear which are uniquely determined from uninterrupted tests. The relatively few curve reversals range mainly within the accuracy of strain measurement and are limited to the region of relatively low strain values. For the austenitic steel the problem of determining time to plastic strain is visible. The times $t_{f\epsilon}$ to specific creep strain values ϵ_f would for this material be determined with smaller tolerances and down to smaller time values.

The calculation of the time tolerance e_1 was carried out for the 4 steels mentioned in chapter 4.1, each for one typical temperature, for the time scales or increments for uninterrupted and interrupted testing in Table 6 and for the typical values $\epsilon_p = 0.2$ and 1 %. In detail (Fig. 10), for two succeeding values t_j and t_{j+1} of the time scale, the stresses $\sigma_{0\,j}$ and $\sigma_{0\,j+1}$ were determined for the given strain ϵ_{p0}. Then, the stress σ_0 was varied in fine steps between $\sigma_{0\,j}$ and $\sigma_{0\,j+1}$ and for each stress value the interpolation of Fig. 10 was performed. For an individual stress value $\sigma_{0\epsilon}$ and the correspondent time $t_{p\epsilon}$, the maximum value e_1 according to eq. (1) was obtained. The results are presented in

Table 7 to 10. For the uninterrupted test with its tighter time scale, only one example was calculated at about 1 000 h. For the interrupted test, also only one example was calculated for $\epsilon_p = 0.2$ % but the full time scale up to 50 000 h was considered for $\epsilon_p = 1$ %. The other time tolerances e_σ and ϵ_T indicated in the Tables are discussed in the next chapter.

If one first considers the interpolation time tolerance e_1, one sees extremely small tolerances for uninterrupted testing which are far below the tolerance of time measurement $e_0 = 1$ % from chapter 4.1 . The tolerance e_1 for interrupted testing is predictably greater and exceeds the test duration tolerance by a factor of up to 5. If one excludes times below 150 h, which are of low interest for interrupted testing, a maximum interpolation time tolerance of about 2 % is observed with greater values of up to 5 % in single cases. However, for times above 10 000 h, where the main body of interrupted test data is situated, 1 % interpolation time tolerance are not exceeded. For the time range of 1 000 to 10 000 h, additional interruption times of 1 600 h, 3 500 h and 7 000 h can be assumed to lower the time tolerance e_1 to a similar amount. At least for about 10 000 h, the time tolerance for 0.2 % strain is rather a little smaller than for 1 % strain. From the logarithmic nature of this interpolation no large differences of interpolation time are to be expected for the different strain values.

In summary, one can take a mean interpolation time tolerance of $\underline{e_1 = \pm 2\ \%}$ for interrupted creep testing in comparison to a tolerance of $\underline{0 \leq e_1 < 0.02\ \%}$ for uninterrupted testing. These indications are only valid for the examples calculated. However, from the similarity of strain time curves one can assume that other conditions do not result in totally different numbers. Due to the normal curvature of creep curves, the interpolation time error is negative in the normal case. However, because the error is relatively small, it may be considered as a ± tolerance to simplify the following analyses.

4.3 Time tolerances due to test tolerances

For the test tolerances stated in chapter 4.1, the resulting tolerances of creep and rupture times are now calculated. For this calculation, the steels and equations refered to in the previous chapters are employed with the same temperatures. Also, again the values of time to 0.2 or 1 % plastic strain and the rupture time are considered as typical results.

At first, the tolerances of the times $t_{p\,0.2}$ and $t_{p\,1}$ are considered. The procedure is demonstrated in Fig. 13 for a typical value of $t_{p\,1}$ = 30 000 h. To estimate the influence of stress tolerance (± 1 %), the percentage change of time $t_{p\,1}$ (or $t_{p\,0.2}$) is calculated from the differences between the creep curves for $\sigma_0 = R_{p1\,30\,000}$ (or $R_{p0.2\,30\,000}$) and for $1.01 \cdot \sigma_0$ as well as for $0.99\ \sigma_0$. Both changes of $\Delta t_{p\,1}/t_{p\,1}$ were averaged to give the percentage tolerance of time to 1 % (or 0.2 %) $\pm e_\sigma$ for a stress tolerance of $\mp$1 %. In a corresponding way, the percentage tolerance of time to 1 % (0.2 %) $\pm e_T$ for a tolerance of true temperature of $\mp$3 °C was calculated. The use of only one temperature tolerance and of 30 000 h - values seems to be sufficient, because this analysis can anyway give only some representative figures.

The calculated time tolerances e_σ and e_T are presented in Tables 7 to 10. One sees that the time tolerance e_σ is in most cases much smaller than the time tolerance e_T. This underlines the decisive effect of temperature on creep test results and will be discussed in more detail in the next chapter. In test parameter regions with high initial plastic strain, the tolerance e_σ increases, this is typical for short term values of austenitic steels (Table 10), where an assessment on the basis of creep strain ε_f would probably give better results but would need an additional assessment of the stress-strain curves $\varepsilon_i(\sigma_0)$ to come to plastic strain values ε_p, which are of interest for application to components. If the short term values of the austenitic steel are omitted, typical values of 20 to 25 % are observed for e_T and typical values 4 to 8 % for e_σ. In an overview, which is limited to 30 000 h-values (Table 11), similar numbers are indicated. As a rough estimate one can concentrate these time tolerances to $\underline{e_\sigma = \pm 5\ \%}$ and $\underline{e_T = \pm 20\ \%}$.

Further, the influence of a strain tolerance $\pm\Delta\varepsilon_p$ is expressed in terms of the tolerance $\pm e_\varepsilon$. Again this is determined using a creep curve represented by the corresponding creep equation to calculate times to specific strain values for $\varepsilon_p - \Delta\varepsilon_p$, ε_p and $\varepsilon_p + \Delta\varepsilon_p$, as is demonstrated in Fig. 14 for time t_{p1}. The strain tolerances were selected according to the findings of chapter 4.1 as 0.001 %, 0.01 %, 0.025 % and 0.05 % in plastic strain ε_p.

For the uninterrupted test and for the strain tolerances of ± 0.01 to ± 0.025 %, a mean value of time tolerance e_ε of about $\underline{e_\varepsilon = 8 \text{ to } 20\ \%}$ is observed for $t_{p0.2}$ = 30 000 h and a mean value of $\underline{e_\varepsilon = 1 \text{ to } 3\ \%}$ for t_{p1} = 30 000 h. For these mean values, the geometric mean of the values of the 4 individual steels was taken. These time tolerances are estimates for the relatively common test on test pieces with a reference length L_r = 40 mm. The greater tolerance is partly characteristic for uninterrupted testing in the past, the smaller one is more characteristic for future testing (DIS 204). For high sensitivity creep testing however, a much smaller minimal time tolerance of e_ε = 1 % for time $t_{p0.2}$ and of e_ε = 0.1 % for time t_{p1} is calculated. However, according to the findings of chapter 2.9 about the double strain tolerance and thus time tolerances can be expected to be realistic and therefore $\underline{e_\varepsilon = 2\ \%}$ for $t_{p0.2}$ and $\underline{e_\varepsilon = 0.2\ \%}$ for t_{p1} are taken.

For the interrupted test and the strain tolerances of ± 0.025 to ± 0.05 %, the mean time tolerance is $\underline{e_\varepsilon = 19 \text{ to } 38\ \%}$ for $t_{p0.2}$ = 30 000 h and $\underline{e_\varepsilon = 3 \text{ to } 6\ \%}$ for t_{p1} = 30 000 h. Again, the geometric mean of the values of the 4 individual steels was taken and the greater tolerances are more characteristic for the interrupted testing in the past whereas the smaller tolerances can be reached in the future. Anyway, the influence of the larger strain tolerances in the uninterrupted test is clearly to be seen. The consequence will be discussed in the next chapter.

The interrelation between the time tolerances for times to 0.2 and 1 % plastic strain and for the corresponding tolerances of stress, temperature and plastic strain were determined with the creep equations and are represented also in Table 11. At the lower strain of 0.2 %, due to primary creep the time tolerance is greater than the strain tolerance. At the strain of 1 %, which is in the range of secondary creep, both tolerances are similar.

In a second step, the tolerances of rupture time due to the stress and temperature tolerances were estimated. It was assumed that these tolerances would be situated in the same range as the corresponding tolerances of time t_{p1}. However it was of interest to prove that by a direct calculation.

For this calculation, the rupture equations of Table 5 were taken. For the tolerances of rupture time t_r only time tolerances $e_{r\sigma}$ and e_{rT} due to stress and temperature tolerances have to be considered (Fig. 15). The calculation of these tolerances was again limited to the temperature tolerance of ± 3 °C and to 30 000 h - data. The results are presented in Table 12. As a rough estimate one can concentrate the rupture time tolerances to $\underline{e_{r\sigma} = 6\ \%}$ and $\underline{e_{rT} = 21\ \%}$, these values being valid for the uninterrupted as well as for the interrupted test and indeed showing no great differences to the earlier stated tolerances $e_\sigma = 5$ % and $e_T = 20$ % of time to specific strain.

4.4 Total time tolerances in creep rupture tests

From the individual tolerances of times to specific strain or to rupture respectively determined in the last chapters for typical examples, a total or combined time tolerance can be derived and on this basis, the influence of the individual tolerances on the creep rupture test results can be evaluated.

The individual tolerances to be considered as contributing to the time to specific plastic strain are

- time tolerance due to stress: $e_\sigma = \pm 5$ %
- time tolerance due to temperature: $e_T = \pm 20$ %
  (in a simplified way only temperatures up to 600 °C are taken into account)
- interpolation time tolerance
  - in the uninterrupted test $e_1 = 0$ %
  - in the interrupted test $e_1 = \pm 2$ %
- tolerance of time measurement $e_0 = \pm 1$ %
- tolerance of characteristic times due to systematic test interruptions
  - in the uninterrupted test $\varepsilon_i = 0$ %
  - in the interrupted test $\varepsilon_i = \pm 5$ %

    (for an easier calculation, a ± tolerance is taken rather increasing the tolerance of interrupted testing)
- time tolerance due to strain measurement
  - in the uninterrupted test

    for 0.2 % plastic strain $\pm e_\varepsilon = 2$ to 8 to 20 %

    for 1 % plastic strain $\pm e_\varepsilon = 0.2$ to 1 to 3 %

    the smallest values being characteristic for high precision creep testing and the values in the middle for testing according to DIS 204 on $5d_0$ test pieces with $L_r = 40$ mm.

- in the interrupted test
  for 0.2 % plastic strain $\pm e_{\varepsilon}$ = 19 to 38 %
  for 1 % plastic strain $\pm e_{\varepsilon}$ = 3 to 6 %
  the smaller values being characteristic for the future of interrupted testing

Because the individual tolerances are independent of each other, as in the case of temperature tolerances (chapter 2.3), combined time tolerance can be determined using the root of the sum of squares of the individual tolerances, ie.

$$e_{t\varepsilon} = \sqrt{e_{\sigma}^2 + e_T^2 + e_1^2 + \varepsilon_i^2 + e_0^2 + e_e^2} \qquad (2)$$

The result is shown in Table 13.

In the uninterrupted test, the temperature tolerance has the decisive influence, as long as the smaller strain tolerances are obeyed, and this presumably will be the more typical case in the future. Even when the strain tolerances of past practice are substituted into Eqn 2, the combined time tolerance $e_{t\varepsilon}$ is acceptable. However, one sees a clear influence of the strain level delivering distinct differences for ε_p = 0.2 %, whereas practically no influence can be seen for ε_p = 1 %. As far as high precision creep testing results are concerned, the analysis, which is limited to strain values from 0.2 %, can not demonstrate the advantages of that testing variant, which is mainly the much more exact determination of transition creep in the primary range. However, also for that case, the urgent demand to optimize test temperature is obviously dominant, if the aim is not only to compare the action of parameters within one laboratory but to collect creep data from different laboratories to perform a common assessment.

In the interrupted test, the temperature tolerance also has the decisive influence, as long as the smaller strain tolerances are obeyed. For the time $t_{p\,0.2}$, the tolerances are greater than those for $t_{p\,1}$. This influence is stronger for the test results from the past and one can perceive the limits of this mode of testing. But as earlier mentioned these limits can be widened by reducing the strain tolerances and taking longer test pieces. Further one can begin with uninterrupted testing and continue by example from 0.1 or 0.2 % strain in the interrupted mode. For the time t_{p1}, practically no differences can be seen between the past and the future strain tolerances.

As indicated in chapters 2.8 and 4.1, for both testing techniques the tolerances estimated for the past can be yet greater due to errors of the reference length caused by neglecting collars or by taking a uniform stress exponent of $n = 5$.

To estimate a total time tolerance of rupture time, the following individual time tolerances have to be considered (Table 13):

- rupture time tolerance due to stress $e_{r\sigma} = \pm 6$ %
- rupture time tolerance due to temperature $e_{rT} = \pm 21$ %
- tolerance of time measurement $e_0 = \pm 1$ %
- tolerance of time due to interruption $\varepsilon_i = \pm 5$ %

Again the root of square sum of the individual tolerances gives an estimate of a combined or total rupture time tolerance of $e_{tr} = \pm 22$ % which is practically independent of the test mode (uninterrupted or interrupted). As assumed, this tolerance is of similar magnitude as the tolerance of time to 1 % plastic strain and again the tolerance of test temperature has the dominant influence.

In this way, total time tolerances were estimated for typical examples. These would vary for other examples but give an impression of the magnitude and of the main influences, these being the test temperature and for lower strain values the mode of testing.

To demonstrate what could be reached in the future, for high precision uninterrupted testing in single machines the smaller temperature tolerance of ± 2 °C is assumed which needs an extremely careful temperature technique. In this case a tolerance $e_T = 13$ % can be taken and with the other numbers of Table 13 for uninterrupted testing, for time $t_{p0.2}$ a total tolerance of $e_{t\varepsilon} = \pm 14$ % is estimated. For interrupted testing with the best possible length measurement system ± 5 µm displacement tolerance can be assumed. In combination with a reference length of 80 mm a time tolerance of $e_\varepsilon = 5$ % for time $t_{p0.2}$ can be estimated and thus with the other numbers of Table 13 for uninterrupted testing in multi-specimen machines for time $t_{p0.2}$ a total tolerance of $e_{t\varepsilon} = \pm 22$ %. From these examples a trend can be seen and it can be concluded, that due to possible improvements of the testing technique the future limits of accuracy are open for both test modes.

5. Conclusions

Valuable results have been obtained from the collaboration of a number of European laboratories and the overviews of testing standards and practices given in chapters 2 and 3. These emphasize in partly different ways high testing accuracy, economy of testing and securing of property values by long term testing and by generating combined creep and rupture data.

On the basis of the overviews and from the discussions at ECCC-WG1 meetings a list of agreed recommendations have been elaborated for the future improvement of testing practice (Table 14). An important observation is that existing test methods can be further used with the recommended improvements. The future ISO-standard (DIS 204) can be recommended for uninterrupted testing whereas for interrupted testing a new European or ISO-standard should be established or DIS 204 should be extended. In regard to testing economy and to the generation of homogeneous data, a combined creep and rupture long term testing practice is recommended.

Other important questions such as the testing of notched and welded test pieces could not be treated in the frame of this report but should be considered in the future.

A key finding of the review in chapter 4 is that variations in test temperature have the strongest influence on the tolerances of important creep test results such as the times to 0.2 and 1 % plastic strain and the rupture time (Table 13). Differences in the test time tolerances associated with the uninterrupted and the interrupted testing methods are evident, although mainly at strains below 0.2 %. For both test methods, a trend of reducing testing tolerances is predicted for the future. This is partly anticipated for uninterrupted high precision creep testing, which presents its main advantages below 0.2 % plastic strain.

As far as the acceptability of the creep rupture data of type $t_{p0.2}$, t_{p1} and t_r is concerned, all data obtained in the past from tests conducted according to the standards ASTM E 139, BS 3500, DIN 50 118, EN 123, NF A03-355, JIS Z 2271/2272 and UNI 5111 are acceptable. This conclusion is valid for all laboratories which can demonstrate that their testing practice conforms to one of these standards.

For the future, tighter tolerances should to be observed, DIS 204 and the above mentioned list of recommendations serving as a model.

During several discussions it has become clear that not all desirable recommendations can be realized in the near future because existing testing resources do not allow it. However, for the far future a list of long term recommendations should not fall into oblivion to gradually bring together the testing techniques of the different European countries. This list contains the introduction of higher loading rates to attain the stress rate of hot tensile testing, the introduction of higher heating rates and shorter soaking times to minimize preannealing of the test pieces, the general establishment of in-situ thermocouple calibration facilities to assure better test temperatures, the long term testing of the new type N base metal thermocouples and the general introduction of combined creep and stress rupture testing at the same test pieces to obtain an optimum basis for creep rupture assessments.

6. Literature

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7. Figures and Tables

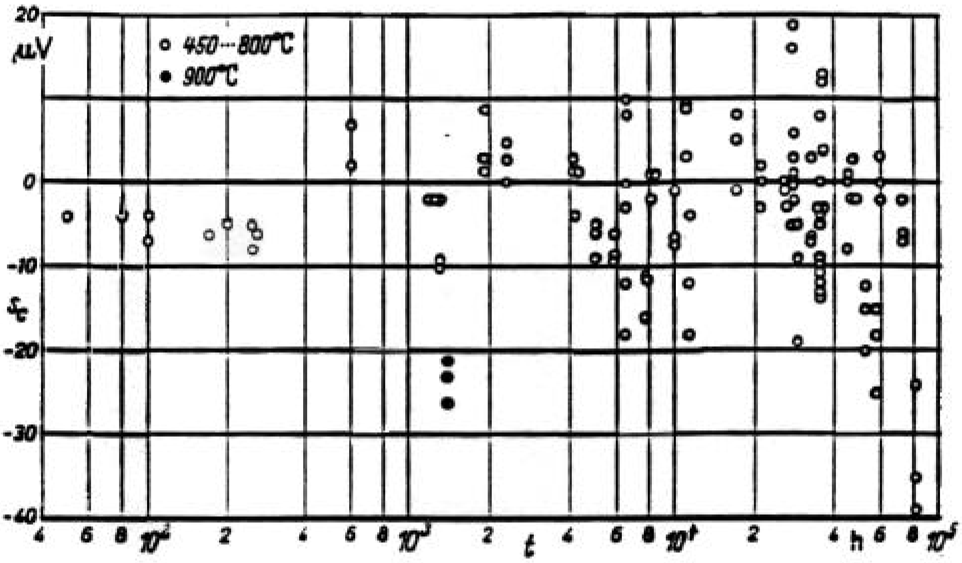

Fig. 1. Drift $s_c = \Delta_t - \Delta_0$ (error Δ_t at time t - error Δ_0 at time 0) of type S thermocouples determined by in situ calibrations as a function of working time t, after [1)]

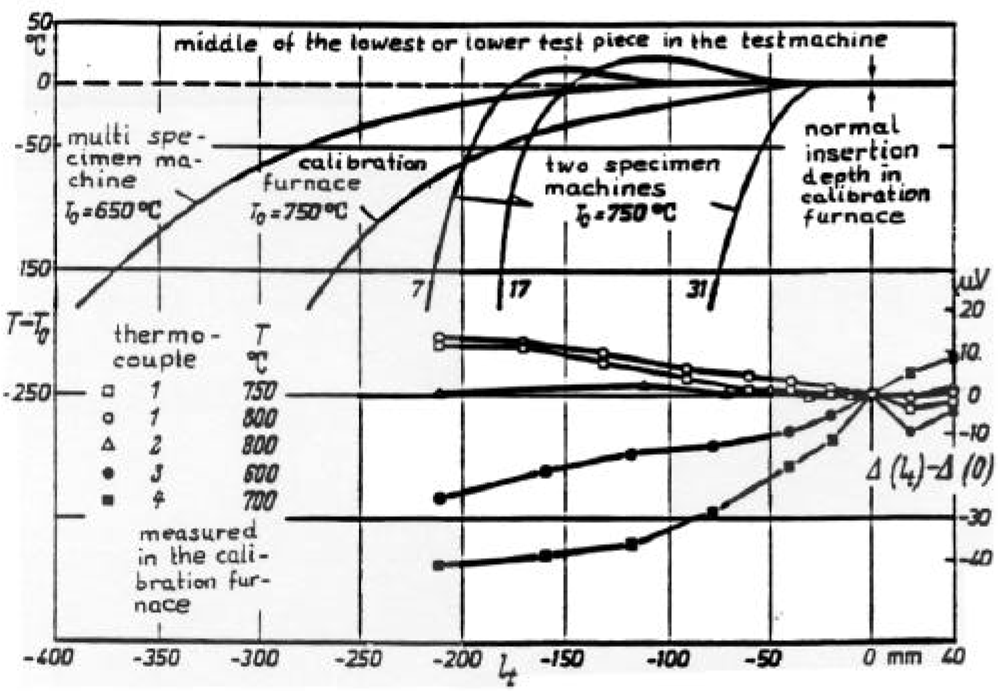

Fig. 3. Variation of temperature difference $T - T_0$ in different creep testing systems and in the calibration furnace as well as variation of thermocouple error $\Delta(l_t) - \Delta(0)$ as functions of the depth of immersion l_t, type S thermocouples, after [1)]

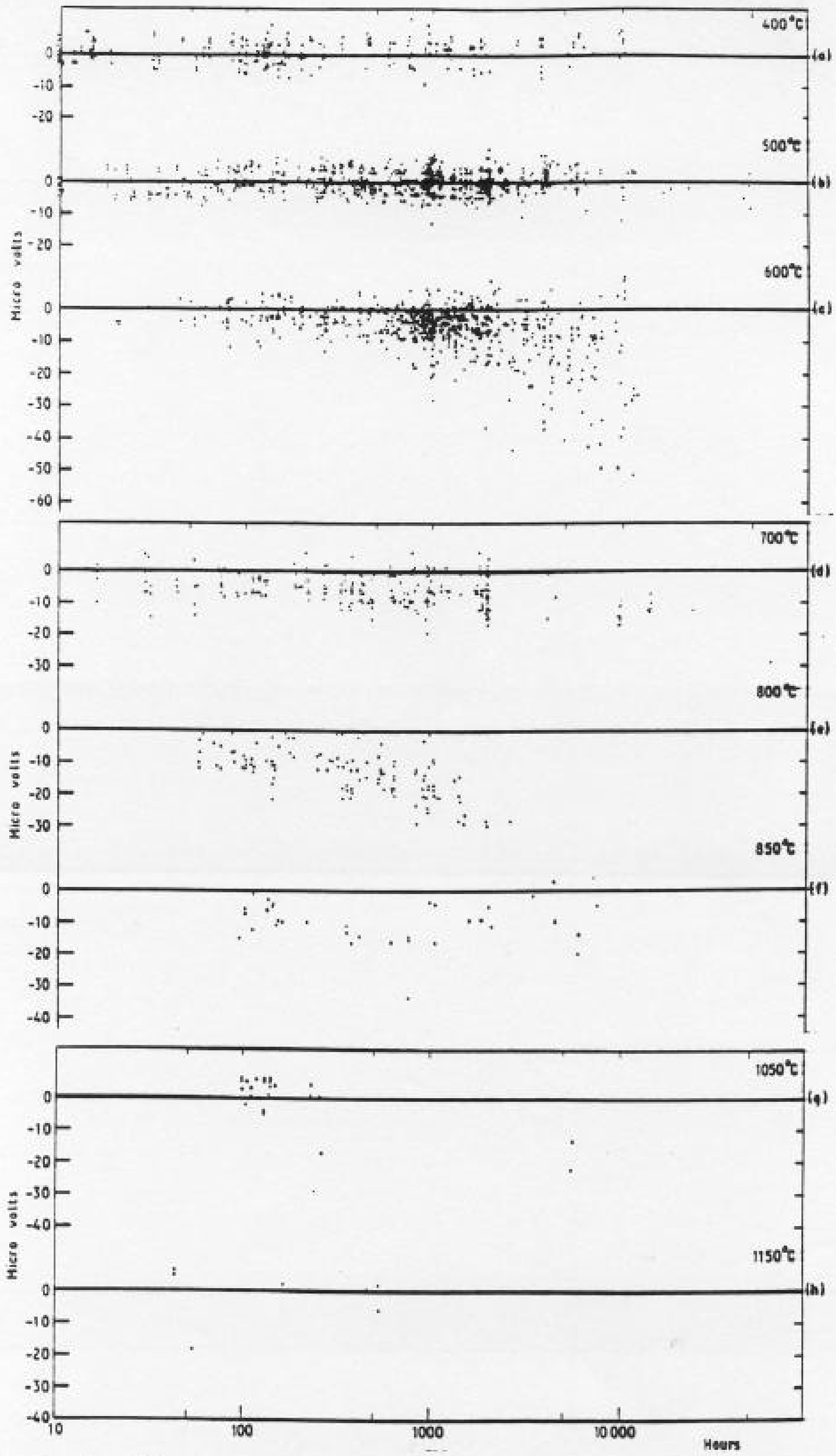

Fig. 2. Recalibration errors observed on type R thermocouples after use at various temperatures, after [2)]

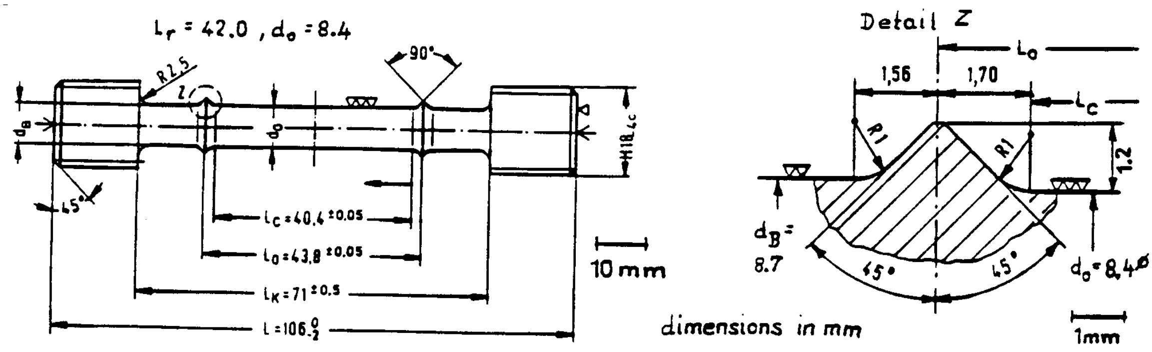

Fig. 4. Example of a test piece approximately of type "constant diameter" (c.d. in Table 1/11) with collars for fixing the extensometer and detail of the collar (L_r / L_c = 1.04)

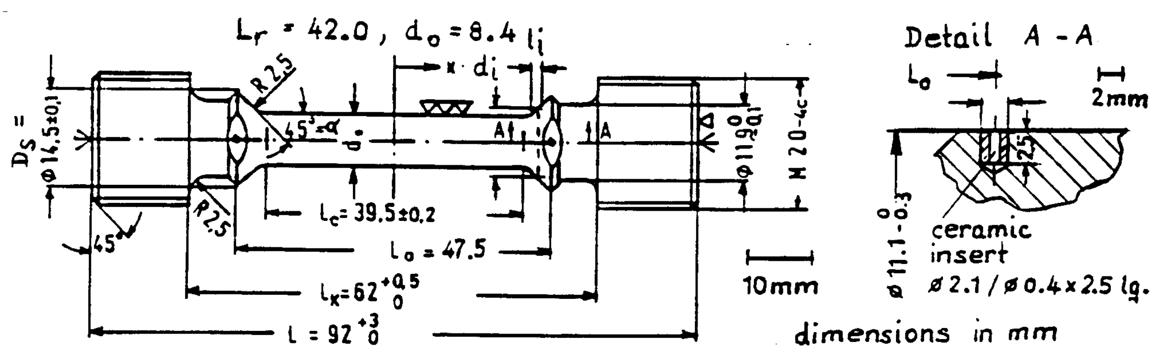

Fig. 5. Example of a test piece of type "greater diameter near the ends" (g.d. in Table 1/11) with collars for uninterrupted testing and with ceramic measuring marks for consecutive interrupted testing (L_r / L_c = 1.06)

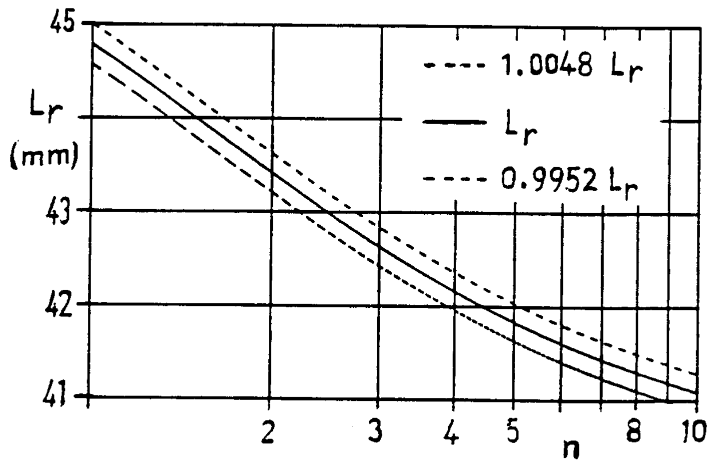

Fig. 6. Reference length of the test piece of Fig. 5, calculated as a function of the stress exponent n

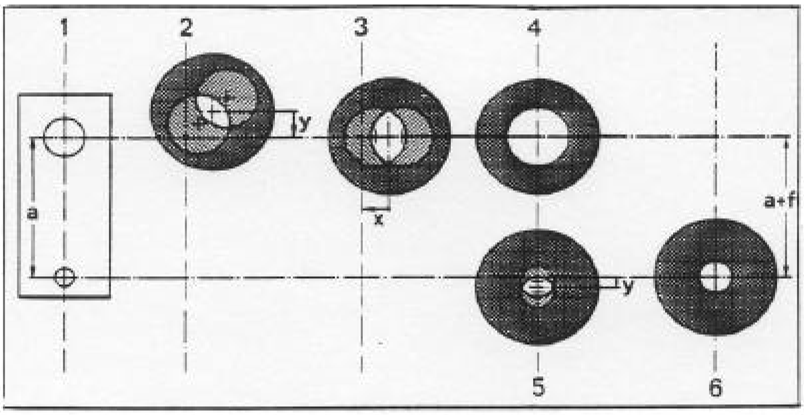

Fig. 7. Measurement with double-image attachment. After aligning the workpiece (1), set the upper bore - via the possible intermediate positions 2 and 3 - as shown in position 4. Read the value on the reversible counter or reset at zero and move the testpiece via possible position 5 to 6. The second reading is then taken: the difference between the two represents the measured value. With this method there is no need to take note of the different diameters of the bores (a = specified dimension, f = error), after [15].

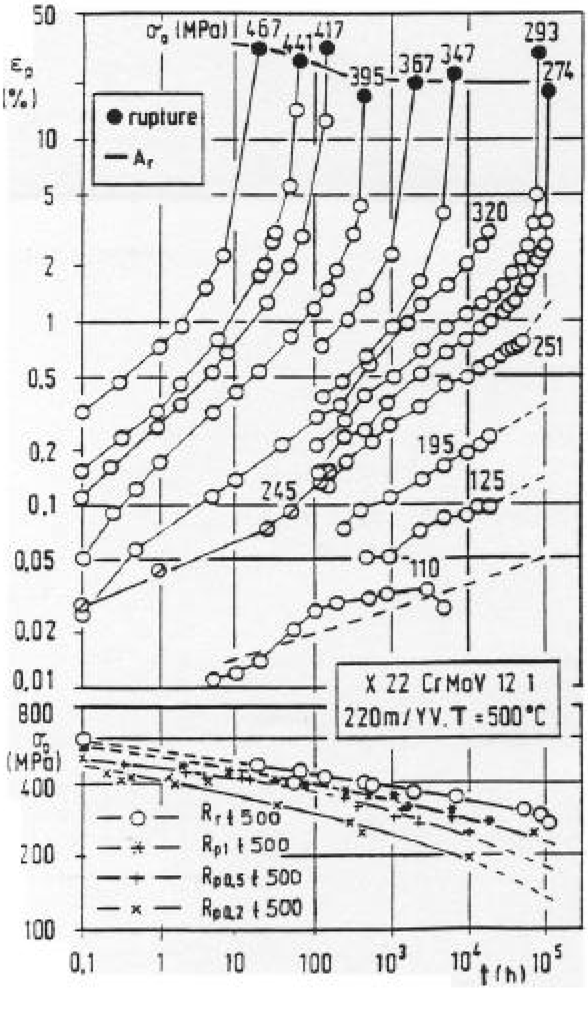

Fig. 8. Example of a graphical assessment (according to DIN 50 118) of creep rupture test results to generate times $t_{p\varepsilon}$ and stresses $R_{p\varepsilon tT}$ to specific plastic strain as well as values of rupture strength R_{mtT} and elongation after rupture A_r (dotted lines are extrapolated or (at σ_0 = 110 MPa) graphically smoothed

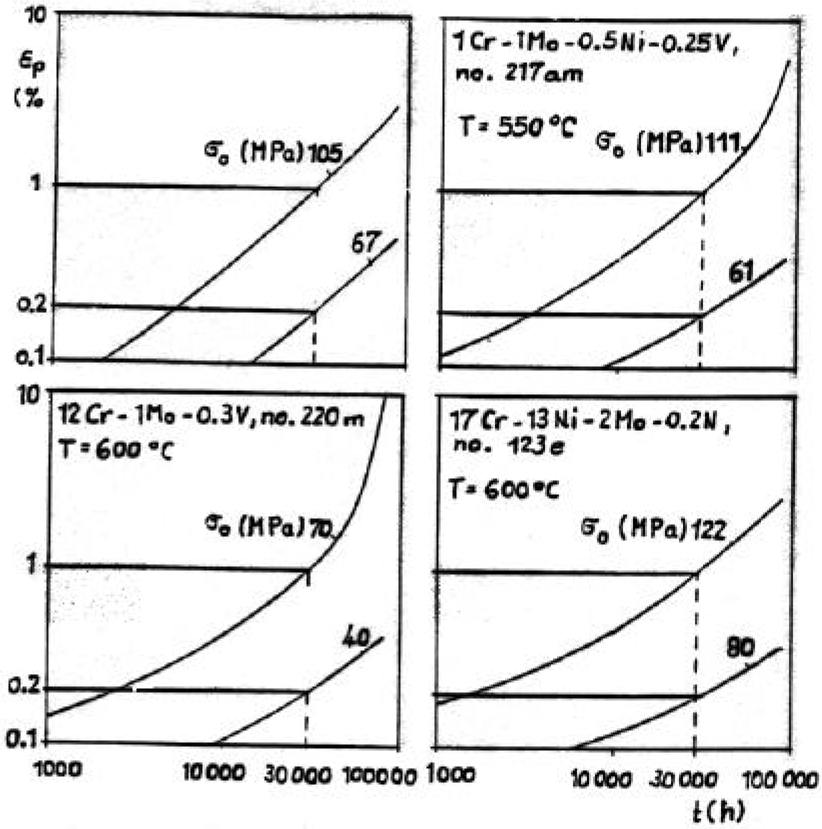

Fig. 9. Typical creep curves from the creep equations used for the analysis of tolerances of time to specific plastic strain

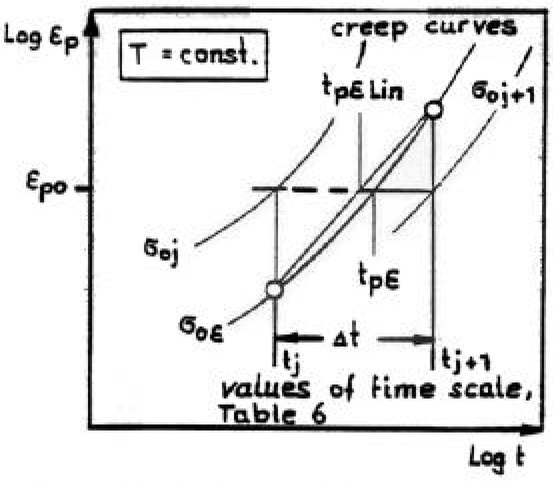

Fig. 10. Determination of a time $t_{p\varepsilon}$ to specific plastic strain for the example of strain ε_{p0} by linear interpolation according to DIN 50 118

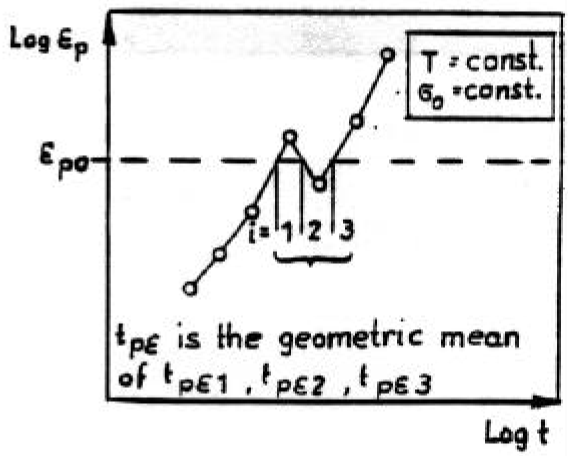

Fig. 11. Determination of a time $t_{p\varepsilon}$ to specific strain ε_{p0} in the case of creep curve reversals

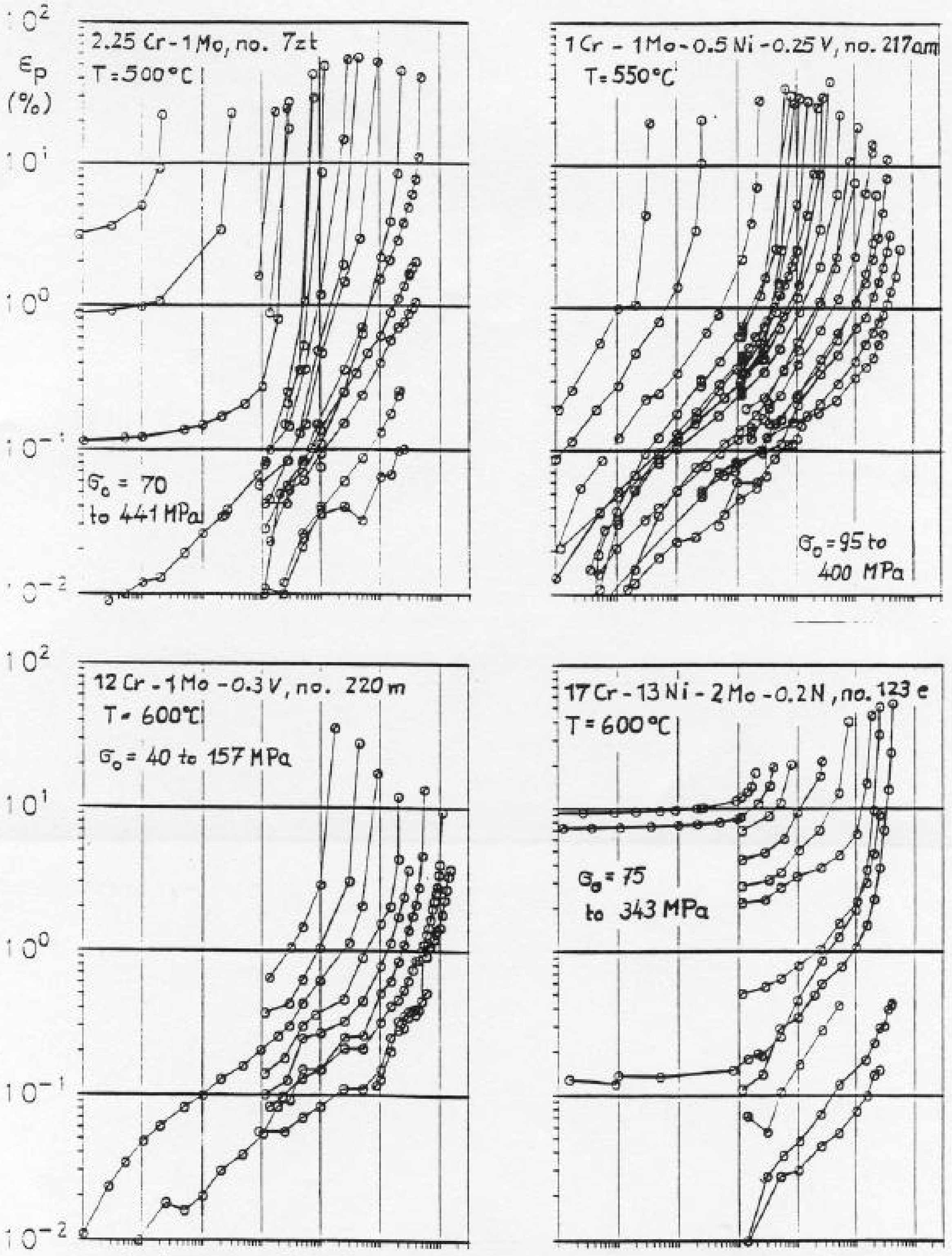

Fig. 12. Typical creep curves from the uninterrupted test beginning with times below 10 h and from the interrupted test beginning with times from about 100 h

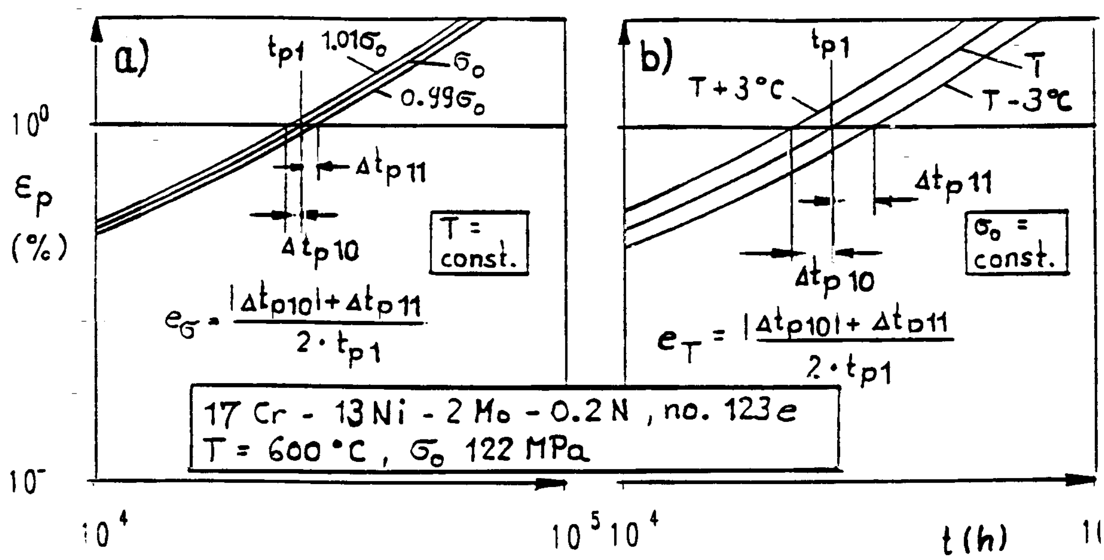

Fig. 13. Examples of the determination of the time tolerances e_σ (a) and e_T (b)

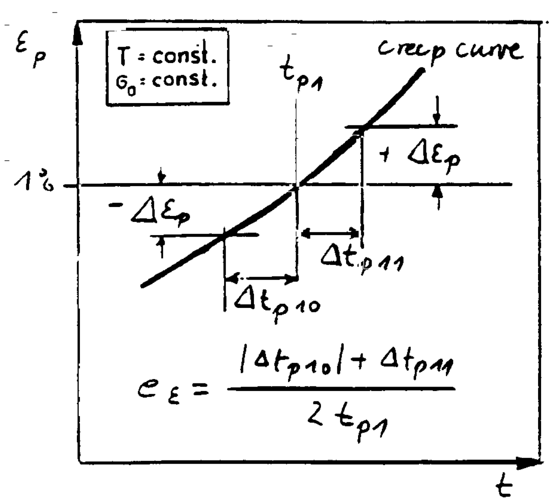

Fig. 14. Determination of the time tolerance e_ε for a given strain tolerance $\Delta\varepsilon_p$ for example of $\varepsilon_p = 1$ %

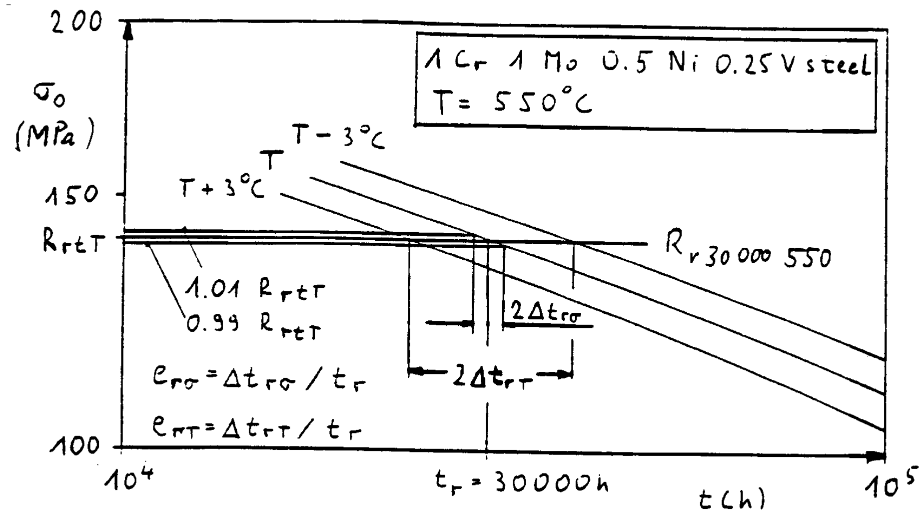

Fig. 15. Example of the determination of the rupture time tolerances $e_{r\sigma}$ and e_{rT}

Quantity	± tolerance	± tolerance of L_r (°C)
L_0 = 47.5 mm	0.01 mm	0.024
d_0 = 8.4 mm	0.005 mm	0.013
D_s = 14.5 mm	0.05 mm	0.115
α = 45°	1°	0.026
R = 2.5 mm	0.1 mm	0.063
L_r(n=4.3/5/5.8)	0.2 mm	0.478
Combined tolerance of L_r = 41.85 mm (root sum of squares)		0.497

Table 1. Influence of typical test piece tolerances and of a variation of stress exponent n on the tolerance of the reference length L_r, test piece according to Fig. 7

No.	Rule	Standard /Test type	Tolerance (±)	Comments
1	Fixed proportion of displacement Δl or of strain ε	UNI 5111 EN 123	0.01 Δl $\begin{cases} 0.01\ \Delta l & \varepsilon \geq 1\ \% \\ 0.05\ \Delta l & \varepsilon < 1\ \% \end{cases}$	Too small tolerances for small displacement
2	Fixed value of strain	NF A03-355/ui.t.	0.01 %	Too large tolerances for small displacement
3	Fixed value of displacement	JIS Z 2271/ui.t. ASTM E139/ui.t.	10 µm 1 µm	Too small tolerances for large displacement
4	Max (No.2, No.3)	DIN 50 118/ui.t.	$\max(0.01\ \%,\ 0.01\ \frac{100}{L_r})$, i.e. 0.01 % for $L_r \geq 100$ mm	Too small tolerances for large displacement
5	Max (No.1, No.3)	ISO 9513/ui.t. for DIS 204	max(0.01 Δl, 3 µm) i.e. 0.01 Δl from 0.3 mm	Well adapted to transducers
6	Added (No.1 & No.2)	BS 3848 for BS 3500	0.008 ε + 0.004 (% in ε) , Grade C	near 5
7	Max (No.1, No.3)	new ISO/i.t.	max(0.01 Δl, 10 µm) i.e. 0.01 Δl from 1 mm	"$\max(0.01\cdot\varepsilon,\ \frac{0.010\cdot 100}{L_r})$"

Table 2. Overview of strain tolerances indicated in different standards

No.	Rule	Standard /Test type	Equation	± Tolerance of strain ε in % for a strain in % of 0.05 L_r = 40 mm	0.2	1	5	0.05 L_r = 120 mm	0.5	1	5
1	Fixed proportion of displac. Δl or of strain ε	UNI 5111 EN 123	$0.01\cdot\varepsilon$ $\begin{cases} 0.01\cdot\varepsilon & \varepsilon\geq 1\ \% \\ 0.05\cdot\varepsilon & \varepsilon\geq 1\ \% \end{cases}$	0.0005 = 0.2 µm 0.0025	0.002 0.01	0.01 0.01	0.05 0.05	0.0005 0.0025	0.002 0.01	0.01 0.01	0.05 0.05
2	Fixed value of strain	NF A03-355 /ui.t.	0.01 %	0.01 = 4 µm	0.01	0.01	0.01	0.01 = 12 µm	0.01	0.01	0.01
3	Fixed value of displac. Δl	JIS Z2271 /ui.t. ASTM E 139 /ui.t.	$1/L_r$ $0.1/L_r$	0.025 0.0025	0.025 0.0025	0.025 0.025	0.025 0.0025 = 1 µm	0.008 0.0008	0.008 0.0008	0.008 0.0008	0.008 0.0008 = 1 µm
4	Max (No.2, No.3)	DIN 50 118 /ui.t.	$\max(0.01\ ,\ \frac{1}{L_r})$	0.025	0.025	0.025	0.025	0.01	0.01	0.01	0.01 = 12 µm
5	Max (No.1, No.3)	ISO 9513 /ui.t. for DIS 204	$\max(0.01\cdot\varepsilon\ ,\ \frac{0.3}{L_r})$	0.008	0.008	0.01	0.05	0.0025	0.0025	0.01	0.05
6	Added (No.1 & No.2)	BS 3848 for BS 3500	$0.008\cdot\varepsilon+0.004$	0.004	0.006	0.012	0.044	0.004	0.006	0.012	0.044
7	Max (No.1, No.3)	new ISO /i.t.	$\max(0.01\cdot\varepsilon\ ,\ \frac{1}{L_r})$	0.025	0.025	0.025	0.05	0.008	0.008	0.008	0.05

Table 3. Typical examples of strain tolerances for the standards of Table 2

T_{90}/°C	0	10	20	30	40	50	60	70	80	90
0	0.000	− 0.002	− 0.005	− 0.007	− 0.010	− 0.013	− 0.016	− 0.018	− 0.021	− 0.024
100	− 0.026	− 0.028	− 0.030	− 0.032	− 0.034	− 0.036	− 0.037	− 0.038	− 0.039	− 0.039
200	− 0.040	− 0.040	− 0.040	− 0.040	− 0.040	− 0.040	− 0.040	− 0.039	− 0.039	− 0.039
300	− 0.039	− 0.039	− 0.039	− 0.040	− 0.040	− 0.041	− 0.042	− 0.043	− 0.045	− 0.046
400	− 0.048	− 0.051	− 0.053	− 0.056	− 0.059	− 0.062	− 0.065	− 0.068	− 0.072	− 0.075
500	− 0.079	− 0.083	− 0.087	− 0.090	− 0.094	− 0.098	− 0.101	− 0.105	− 0.108	− 0.112
600	− 0.115	− 0.118	− 0.122	− 0.125	− 0.08	− 0.03	0.02	0.06	0.11	0.16
700	0.20	0.24	0.28	0.31	0.33	0.35	0.36	0.36	0.36	0.35
800	0.34	0.32	0.29	0.25	0.22	0.18	0.14	0.10	0.06	0.03
900	− 0.01	− 0.03	− 0.06	− 0.08	− 0.10	− 0.12	− 0.14	− 0.16	− 0.17	− 0.18
1000	− 0.19	− 0.20	− 0.21	− 0.22	− 0.23	− 0.24	− 0.25	− 0.25	− 0.26	− 0.26
T_{90}/°C	0	100	200	300	400	500	600	700	800	900
1000		− 0.26	− 0.30	− 0.35	− 0.39	− 0.44	− 0.49	− 0.54	− 0.60	− 0.66
2000	− 0.72	− 0.79	− 0.85	− 0.93	− 1.00	− 1.07	− 1.15	− 1.24	− 1.32	− 1.41
3000	− 1.50	− 1.59	− 1.69	− 1.78	− 1.89	− 1.99	− 2.10	− 2.21	− 2.32	− 2.43

Table 4. Differences between the Temperature T_{90} (°C) according to ITS 90 and the Temperature T_{68} (°C) according to IPTS 68, after [16) 17)]

Test type	Time scale
uninterrupted test	E1: t = 0, 0.5, 1., 1.5, 2, 3 (1) 8, 10 (5) 40, 50, 60 min, 1, 2, 3, 4, 6, 8, 10, 12, 14, 16 (3) 40 (5) 160 (12) h
interrupted test	V1: t = 0, 100, 250, 500, 1 000, 2 500, 5 000, 10 000 (5 000) 40 000 (10 000) h
values in brackets(): time steps Δt	

Table 6. Typical time scales for strain measurement in creep and creep rupture tests

Steel type:	2.25Cr - 1Mo
Equation:	$lgt = B_o + \tau \cdot (B_1 + B_2\,\sigma_o^{m} + B_3\,\sigma_o^{2m})$ with $\tau = (T(K) - T_a) / 1\,000$
Coefficients after [12]:	$B_o = 19.200$ $B_1 = -53.293$ $B_2 = 59.022$ $B_3 = -25.691$ $T_a = 200$ K $m = 0.1$
Steel type:	1Cr 1Mo 0.5Ni 0.25V
Equation:	$lgt = B_o + \tau \cdot (B_1 + B_2\,\sigma_o^{m} + B_3\,\sigma_o^{2m})$ with $\tau = 1\,000 / T(K)$
Coefficients after [18]:	$B_o = -25.000$ $B_1 = 27.0374$ $B_2 = -0.07212$ $B_3 = -0.056638$ $m = 0.375$
Steel type:	12Cr 1Mo 0.3V
Equation:	$lgt = B_o + \tau \cdot (B_1 + B_2\,\sigma_o^{m} + B_3\,\sigma_o^{2m})$ with $\tau = 1\,000 / T(K)$
Coefficients after [12]:	$B_o = -25.000$ $B_1 = 32.841$ $B_2 = -1.408$ $B_3 = -0.613$ $m = 0.2$
Steel type:	17Cr 13Ni 2Mo 0.2N
Equation:	$lgt = B_o + \tau \cdot (B_1 + B_2\,\sigma_o^{m} + B_3\,\sigma_o^{2m} + B_4\,\sigma_o^{3m})$ with $\tau = 1\,000 / T(K)$
Coefficients after [18]:	$B_o = -17.000$ $B_1 = 112.589$ $B_2 = -150.828$ $B_3 = 88.345$ $B_4 = -19.000$ $m = 0.1$

Table 5. Equations of rupture curves of the steels selected for the analysis of rupture time tolerances

test type	plastic strain ϵ_p (%)	time scale t (h)	time $t_{p\epsilon}$ (h)	time tolerances e_l (%)	e_σ (%)	e_T (%)
uninter-rupted	1	988 1 000	995	0	± 5	± 22
inter-rupted	0.2	10 000 15 000	12 301	-0.2	± 4	± 21
	1	100 250	147	-4	± 9	± 25
		500	332	-2	± 7	± 23
		1 000	666	-2	± 6	± 22
		2 500	1 369	-3	± 5	± 21
		5 000	3 319	-1	± 5	± 20
		10 000	6 557	-1	± 4	± 20
		15 000	11 925	-0.2	± 4	± 19
		20 000	17 400	-0.1	± 4	± 19
		25 000	22 416	-0.1	± 4	± 19
		30 000	27 811	0	± 4	± 19
		35 000	32 373	0	± 4	± 19
		40 000	36 913	0	± 4	± 18
		50 000	44 096	0	± 4	± 18

Table 7. Time tolerance e_l for linear interpolation of time $t_{p\epsilon}$ to specific strain and time tolerances e_σ and e_T for significant tolerances of stress ($\pm$1 %) and temperature ($\pm$3 °C), steel 2.25Cr-1Mo, no. 7zt, T = 550 °C

test type	plastic strain ϵ_p (%)	time scale t (h)	time $t_{p\epsilon}$ (h)	time tolerances e_l (%)	e_σ (%)	e_T (%)
uninter-rupted	1	988 1 000	994	-0.01	± 7	± 20
inter-rupted	0.2	10 000 15 000	12 426	-0.5	± 4	± 20
	1	100 250	134	-4.7	± 8	± 20
		500	325	-2.3	± 8	± 20
		1 000	646	-2.3	± 8	± 20
		2 500	1 328	-4.4	± 7	± 20
		5 000	3 255	-2.1	± 6	± 20
		10 000	6 307	-2.1	± 5	± 20
		15 000	11 901	-0.6	± 5	± 20
		20 000	17 028	-0.3	± 5	± 20
		25 000	21 952	-0.2	± 4	± 20
		30 000	27 364	-0.1	± 4	± 20
		35 000	31 745	-0.1	± 4	± 20
		40 000	36 884	-0.1	± 4	± 20
		50 000	44 597	-0.2	± 6	± 20

Table 8. Time tolerance e_l for linear interpolation of time $t_{p\epsilon}$ to specific strain and time tolerances e_σ and e_T for significant tolerances of stress ($\pm$1 %) and temperature ($\pm$3 °C), steel 1Cr-1Mo-0.5Ni-0.25V, no. 217am, T = 550 °C

test type	plastic strain ϵ_p (%)	time scale t (h)	time $t_{p\epsilon}$ (h)	time tolerances		
				e_l (%)	e_σ (%)	e_T (%)
uninter-rupted	1	988 1 000	996	-0.02	± 7	± 26
inter-rupted	0.2	10 000 15 000	12 571	-0.6	± 4	± 22
	1	100	152	-4	± 8	± 28
		250	355	-2	± 9	± 28
		500	692	-2	± 7	± 26
		1 000	1 380	-2	± 6	± 26
		2 500	3 324	-2	± 6	± 25
		5 000	6 445	-3	± 5	± 24
		10 000	11 669	-0.9	± 5	± 23
		15 000	17 066	-0.5	± 4	± 23
		20 000	22 504	-0.3	± 4	± 23
		25 000	26 644	-0.2	± 4	± 22
		30 000	31 621	-0.2	± 4	± 22
		35 000	37 636	-0.1	± 4	± 22
		40 000	44 829	-0.3	± 4	± 22
		50 000				

Table 9. Time tolerance e_l for linear interpolation of time $t_{p\epsilon}$ to specific strain and time tolerances e_σ and e_T for significant tolerances of stress (± 1 %) and temperature (± 3 °C), steel 12Cr-1Mo-0.3V, no. 220m, T = 600 °C

test type	plastic strain ϵ_p (%)	time scale t (h)	time $t_{p\epsilon}$ (h)	time tolerances		
				e_l (%)	e_σ (%)	e_T (%)
uninter-rupted	1	988 1 000	994	-0.001	± 22	± 23
inter-rupted	0.2	10 000 15 000	12 510	-0.6	± 8	± 25
	1	100	140	-3		
		250	347	-2	± 45	± 26
		500	742	-3	± 27	± 23
		1 000	1 604	-5	± 15	± 22
		2 500	3 495	-2	± 9	± 21
		5 000	7 025	-2	± 7	± 20
		10 000	12 016	-0.5	± 7	± 20
		15 000	17 120	-0.2	± 7	± 20
		20 000	22 237	-0.1	± 7	± 20
		25 000	27 578	-0.1	± 7	± 20
		30 000	32 536	-0.1	± 7	± 20
		35 000	35 398	-0.0	± 7	± 20
		40 000	45 780	-0.1	± 7	± 20
		50 000				

Table 10. Time tolerance e_l for linear interpolation of time $t_{p\epsilon}$ to specific strain and time tolerances e_σ and e_T for significant tolerances of stress (± 1 %) and temperature (± 3 °C), steel 17Cr-13Ni-2Mo-0.2N, no. 123e, T = 600 °C

Steel, case	A tolerance of → with an amount of → corresponds to a tolerance of ↓		σ_0 ±1 %	T ±3 °C	ε_p ±0.001 %	±0.01 %	±0.025 %	±0.05 %
2.25Cr-1Mo-steel no. 7zt T = 500 °C	$t_{p0.2}$ = 30 000 h	± σ_0 in %	1	5	0.2	1	4	7
		± T in °C	1	3	0.1	1	2	4
		+ t in %	e_σ=4	e_T=20	e_ε = 0.6	5	14	29
		± ε_p in %	3	17	0.5	5	12.5	25
	t_{p1} = 30 000 h	± σ_0 in %	1	5	0.0	0	1	1
		± T in °C	1	3	0.0	0	0	1
		+ t in %	e_σ=4	e_T=19	e_ε = 0.1	1	3	5
		± ε_p in %	4	18	0.1	1	2.5	5
1Cr-1Mo-0.5Ni-0.25V-steel no. 217 am T = 550 °C	$t_{p0.2}$ = 30 000 h	± σ_0 in %	1	6	0.3	3	6	13
		± T in °C	0	3	0.1	1	3	6
		+ t in %	e_σ=3	e_T=20	e_ε = 0.8	8	20	40
		± ε_p in %	2	12	0.5	5	12.5	25
	t_{p1} = 30 000 h	± σ_0 in %	1	5	0.0	0	1	1
		± T in °C	1	4	0.0	0	0	1
		+ t in %	e_σ=4	e_T=20	e_ε = 0.1	1	3	6
		± ε_p in %	4	18	0.1	1	2.5	5
12Cr-1Mo-0.3V-steel no. 220m T = 600 °C	$t_{p0.2}$ = 30 000 h	± σ_0 in %	1	6	0.2	2	5	10
		± T in °C	1	3	0.1	1	3	6
		+ t in %	e_σ=4	e_T=22	e_ε = 0.8	8	19	38
		± ε_p in %	2	14	0.5	5	12.5	25
	t_{p1} = 30 000 h	± σ_0 in %	1	6	0.0	0	1	1
		± T in °C	1	3	0.0	0	0	1
		+ t in %	e_σ=4	e_T=22	e_ε = 0.1	1	3	6
		± ε_p in %	4	20	0.1	1	2.5	5
17Cr-13Ni-2Mo-0.2N-steel no. 123e T = 600 °C	$t_{p0.2}$ = 30 000 h	± σ_0 in %	1	3	0.1	1	3	6
		± T in °C	1	3	0.1	1	3	6
		+ t in %	e_σ=8	e_T=23	e_ε = 1.0	10	24	48
		± ε_p in %	4	12	0.5	5	12.5	25
	t_{p1} = 30 000 h	± σ_0 in %	1	3	0.0	0	1	1
		± T in °C	1	3	0.0	0	0	1
		+ t in %	e_σ=7	e_T=19	e_ε = 0.1	1	3	6
		± ε_p in %	5	16	0.1	1	2.5	5
		creep test:			uninterrupted: high precision	future	past	
							interrupted: future	past

Table 11. Influences of test tolerances on the tolerances of time to 0.2 or 1 % plastic strain and interrelation of the latter tolerances with stress, time and strain tolerances

Steel type	T (°C)	$R_{r\,30\,000\,T}$ (MPa)	$e_{r\,\sigma}$ (%)	$e_{r\,T}$ (%)
2.25Cr 1Mo	500	144	∓ 6	∓ 18
1Cr 1Mo 0.5Ni 0.25V	550	141	∓ 5	∓ 25
12Cr 1Mo 0.3V	600	87.2	∓ 6	∓ 24
17Cr 13Ni 2Mo 0.2N	600	159	∓ 6	∓ 17

Table 12. Tolerances $e_{r\,\sigma}$ and $e_{r\,T}$ of rupture time t_r for tolerances of stress σ_0 of ±1 % and of temperature of ±3 °C for 4 steel types each at a typical temperature and for a rupture time of 30 000 h

Individual time tolerances (± %)		for	uninterrupted creep rupture test			interrupted creep rupture test	
e_σ	$(\sigma_0 \pm 1\%)$	for time to specific strain		5		5	
e_T	$(T \pm 3°C)$			20		20	
e_1				0		2	
e_0				1		1	
e_i				0		5	
e_ε for $t_{p0.2}$			2 to	8 to	20	19 to	38
e_ε for t_{p1}			0.2 to	1 to	3	3 to	6
case			high precision	new	past	new	past
	$\pm\,\Delta L$ (μm)		1	3	10	10	20
	L_r (mm)		100	40	40	40	40
Total time tolerance $e_{t\,\varepsilon}$ (%)		for $t_{p0.2}$	21	to 22 to	29	29 to	43
		for t_{p1}	21	to 21 to	21	22 to	22
$e_{r\,\sigma}$	$(\sigma_0 \pm 1\%)$	for rupture time		6		6	
$e_{r\,T}$	$(T \pm 3°C)$			21		21	
e_0				1		1	
e_i				0		5	
Total time tolerance $e_{t\,r}$ (%) for t_r				22		22	

Table 13. Estimate of total tolerances $e_{t\,\varepsilon}$ of times to 0.2 or 1 % plastic strain and $e_{t\,r}$ of rupture time

Standards	Prefer DIS 204 with some additional recommendations as a common standard for uninterrupted testing. For interrupted testing a new standard should be established or DIS 204 should be extended.
Test procedures, test machines type of load application	In uninterrupted and interrupted testing and with all test machines and types of load application, the goal should be the tightest possible tolerances of stress, temperature, and strain measurement.
Test temperature	A total temperature tolerance shall be observed with ±3/4/5/6/7/8 °C up to 600/800/1 000/1 100/1 200/1 350 °C (Annex 1, Table 1/3). An indicated temperature tolerance of ± 2 °C up to 1 000 °C and ± 3 °C above 1 000 °C shall be observed. Rare metal thermocouples should be used above 400 °C or 1 000 h. Periodic in-situ calibration or no reuse of these thermocouples is recommended (Table 1/5). An opposite re-calibration philosophy admits a shorter depth of immersion in the calibrating furnace, after the thermocouples has been fully annealed. Sufficient recording of at minimum 1 thermocouple per heating zone is recommended. For less than 1 thermocouple per test piece regular control measurements have to be performed. The systematic component of resulting temperature distribution is used to correct the temperature, the non-systematic component shall not exceed ± 2 (3) °C up to (above) 800 °C.
Load application	Constant load testing with relatively short loading time (<10 min) is recommended. Preloading is recommended, if it supports the function control of the extensometer. Elastic bending stress σ_b should be limited to a portion of axial stress σ_0, e.g. $\sigma_b \leq 0.2\sigma_0$ and torsion should be minimized.
Supplementary test conditions	Laboratory air temperature should be limited to ±3 °C for extensometers and to ±2 °C for strain measurement in interrupted tests. Test time tolerance should be ±1 %. Heating and soaking time should be more tightly specified (Table 1/10).
Test pieces	For the example of diameter $5 \leq d_0 \leq 10$ mm, a shape tolerance of ±0.02 mm and a measurement accuracy of ±0.005 mm is recommended. The reference length should be $L_r \geq 3d_0$, better $5d_0$ (or $10d_0$ for high precision creep testing) and $L_r \leq 1{,}1\ L_c$ with a tolerance of ±0.5 %. The action of collars and shoulders and the stress (Norton) exponent have to be considered when calculating L_r.
Strain measurement	Strain measurement in interrupted/uninterrupted testing shall be carried out on opposite sides of the test piece. A ± tolerance of max(0.01 Δl, 3 µm) for uninterrupted testing and of max(0.01 Δl, 10 µm) for interrupted testing is recommended as well as strain reading according to fixed time scales.
Test results	To assist optimal data use, complete strain values, i.e. ϵ_i and e_p or e_f shall be reported from the uninterrupted test in addition to rupture data t_r, A_r, Z_r. In the interrupted test, accompanying hot tensile tests (for ϵ_i) are necessary. A standard assessment procedure should be ruled for secondary results, at least for times $t_{p\epsilon}$, $t_{f\epsilon}$ to specific strain (Tables 1/15, 1/16).
Accreditation	Accreditation is recommended to assure working according to standards.
Comparison tests	Repeated comparison tests are recommended as the best means of assuring high quality and homogenity of test results.

Table 14. Recommendations of future improvements in creep and creep rupture testing practices

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S t a n d a r d s / t e s t p r o c e d u r e s / t e s t m a c h i n e s

Row	Column 0	1	2	3
0	Standard /Language if not English	Doc.Ref. 5524/WG1/	test procedure uninterrupted: ui.t. interrupted: i.t.	machine type
1	ISO/DIS 204 (1991)	/9	uninterrupted test	single machine multi machine
2	DIN 50 118 (1982) /German	/10	uninterrupted } test interrupted	single machine multi specimen machine
3	BS 3500 (1969)	/19	uninterrupted } test interrupted	single machine multi machine multi specimen machine
4	EN 123-75 (1975)	/8	uninterrupted } test interrupted	single machine multi machine multi specimen machine
5	ASTM E 139-83 (1990)	/26	uninterrupted test	
6	NF A03-355 (1985) /French	/30	uninterrupted test (interuption only due to rupture)	single machine multi (specimen) machine
7	UNI 5111-69 (1969) /Italian	/23	uninterrupted } test interrupted	single machine multi machine multi specimen machine
8	JIS Z 2271 (1978) JIS Z 2272	/41 /42	uninterrupted [creep] test uninterrupted } rupture test interrupted	single machine single machine multi specimen machine
9	comments 9 standards	see Doc.Ref. 5524/WG1 /as above	i.t.:interruptions for strain measurement. Only in the Japanese standards (JIS) are creep and rupture tests separated ui.t.: 9 stand. i.t.: 5 stand.	single mach. SM: 1 spec. multi mach. MM: 1 string multi specimen mach. MSM: > 1 string (specimen = test piece) SM: 8 stand., MM: 6 MSM: 7
10	minimum requirements for the past	uninterrupted and interrupted testing is acceptable		all machine types are acceptable if they fulfil the following requirements of testing accuracy
11	minimum requirements for the future			

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A t m o s p h e r e / T y p e o f l o a d a p p l i c a t i o n

Row	Column 0	4	5	6	7	8
0	Standard	atmosphere	load application dead weight	lever type	spring loaded	load calibration standard
1	ISO/DIS 204 (1991)		X	X		ISO 7500/1 DIS 7500/2
2	DIN 50 118 (1982) /German	air	X	X	X	DIN 51226
3	BS 3500 (1969)	air is assumed				EN 10002-2 BS 1610-P.3
4	EN 123-75 (1975)					
5	ASTM E 139-83 (1990)	air vacuum inert gas				ASTM E4, E74
6	NF A03-355 (1985) /French					
7	UNI 5111-69 (1969) /Italian		(X)	(X)		
8	JIS Z 2271 (1978) JIS Z 2272					
9	comments From column 5, indications without brackets are mandatory, indications in brackets () are recommended	for normal cases, air can be assumed	load application is not generaly ruled			
10	minimum requirements for the past	air	all types are acceptable if they fulfil the requirements of load accuracy			
11	minimum requirements for the future					

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T e s t   t e m p e r a t u r e   1

Row	Column 0	9	10		
0	Standard	temperature range	temperature tolerances (±°C) indicated-specified temp.		
1	ISO/DIS 204 (1991)	≤ 1000 °C	T ≤ 900 °C 3 900 < T ≤ 1000 °C	3	4
2	DIN 50 118 (1982)	≤ 1100 °C	T ≤ 600 °C *) 3 600 < T ≤ 800 °C 800 < T ≤ 1000 °C 1000 < T ≤ 1100 °C	4	6 8
3	BS 3500 (1969)	≤ 1000 °C	test duration above 100 h T ≤ 600 °C *) 3 600 < T ≤ 800 °C 800 < T ≤ 1000 °C	4	6
4	EN 123-75 (1975)	≤ 1000 °C	T ≤ 800 °C *) 4 800 < T ≤ 1000 °C	4	6
5	ASTM E 139-83 (1990)		T ≤ 1000 °C 2 T > 1000 °C	2	3
6	NF A03-355 (1985)		T ≤ 900 °C 3 T > 900 °C	3	4
7	UNI 5111-69 (1969)		T ≤ 600 °C 3 600 < T ≤ 800 °C 800 < T ≤ 1000 °C T > 1000 °C	4	6 1 %
8	JIS Z 2271/2 (1978)		x) 300 < T ≤ 600 °C *) 3 600 < T ≤ 800 °C 800 < T ≤ 1000 °C	4	6
9	comments accuracy of a (fixed point) calibrated r.m.t.c. is ± 1(0.5) °C at 600 °C, of a calibrated b.m.t.c. ± 1.5 °C at 600 °C		up to 600 °C 600 to 800 °C *) total temp. tolerances: true test piece temp. - specified temp. x) only for tests up to 10 000 h		
10	minimum requirements for the past		Total *) in most cases: ± 3 / 4 / 6 / 8 °C up to 600/800/1000/1100 °C		
11	minimum requirements for the future	≤ 1350°C ui.t. ≤ 1000°C i.t.	Total *): ± 3 / 4 / 5 / 6 / 7 / 8 *) up to 600/800/1000/1100/1200/1350°C Indicated: ± 2 up to 1000, ± 3 above 1000		

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Test temperature 2

Row	Column 0	11	12	13
0	Standard	measurement equipment (± °C) tolerance	resolution	type of thermocouple
1	ISO/DIS 204 (1991)	≤ 0.5	1	
2	DIN 50 118 (1982)	included in column 10		(r.m., Type S)
3	BS 3500 (1969)	≤ 0.5 ≤ 0.2c.j.	≤ 0.5	b.m. or r.m.
4	EN 123-75 (1975)	≤ 0.5		(r.m.)
5	ASTM E 139-83 (1990)	sufficient		
6	NF A03-355 (1985)	suffi- cient		
7	UNI 5111-69 (1969)		< 1	
8	JIS Z 2271/2 (1978)			
9	comments	c.j.: cold junction		r.m.:rare met. (e.g. type S,R) otherwise:b.m.: base metal (e.g. K) r.m. is only re- commended in 2 cases
10	minimum requirements for the past	sufficient		b.m. or r.m.
11	minimum requirements for the future	≤ 0.5 (0.1 c.j.)	≤ 0.1	new b.m.t.c. only for ≤ 400 °C or ≤ 1 000 h, else use r.m.t.c.

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Test temperature 3

Row	Column 0	14	15
0	Standard	minimum number of thermocouples	temperature calibration
1	ISO/DIS 204 (1991)	(2 per t.p., L ≤ 50 mm SM) (3 per t.p., L > 50 mm SM) (1 per t.p., 3/furnace MM) *)	verification of thermocouple and of measurement device, the latter traceable to the Internat. Unit (in-situ calibration)
2	DIN 50 118 (1982)	(3 per test piece SM) (1 per heating zone MSM) *)+)	determination of error of thermoc. and of measurement device, +) diff. betw. t.p. and thermoc. (in-situ calibration)
3	BS 3500 (1969)	(2 per t.p., L ≤ 50 mm SM) (3 per t.p., L > 50 mm SM) (1 per t.p., MM) *)	determination of error of thermoc. and of measurement device
4	EN 123-75 (1975)	(2 per t.p.,vert. furnace SM) (1 per t.p.,horiz.furnace SM) (suff.number per t.p. MM) *)	(verification of thermocouple (in-situ calibration) and of difference between test piece and thermocouple)
5	ASTM E 139-83 (1990)	2 per t.p., L ≥ 25 mm 3 per t.p., L ≥ 50 mm	(determination of error of thermoc. and of measurement device) (ASTM E 220) (in-situ calibration)
6	NF A03-355 (1985)	(2 per t.p.) (1 per t.p.) *)	determination of thermocouple error
7	UNI 5111-69 (1969)	(3 per t.p.) suff. number per machine *)	acc. to UNI 4768
8	JIS Z 2271/2 (1978)	(2 per t.p., L ≤ 50 mm) (3 per t.p., L > 50 mm) (suff. number of t.c.) *)	acc. to JIS C1602
9	comments	*) to confirm the temperature within the allowable limits Number of thermocouples is in most cases only recommended	+) indirect temperature measurement with repeated determination of systematic error temp. calibration is not always ruled
10	minimum requirements for the past	sufficient number of t.c.	determination of error of t.c.
11	minimum requirements for the future	2 - 3 per t.p. SM 1 - 2 per t.p. MM 1 per heating zone MSM, and correction of systematic errors +) from non-systematic component ≤ ± 2 °C for T ≤ 800 °C and ≤ ± 3 °C for T > 800 °C	new t.c.: acc. to IEC 584-2 (1989), class 1 or calibrated against a fixed point calibrated t.c. traceable to the International Unit b.m.t.c.: only new, no recalibration r.m.t.c.: in situ recalibration meas. device: calibration yearly opposite re-calibration philosophy: see chapter 2.3

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T e s t t e m p e r a t u r e 4

Row	Column 0	16	17	18
0	Standard	time interval between two calibrations thermocouple	 m.dev. +)	frequency of temperature measurement
1	ISO/DIS 204 (1991)	max. 1 year or before and after test		sufficient recording
2	DIN 50 118 (1982)	S: T ≤ 600: 3 years 600 < T ≤ 800: 2 years 800 < T (°C): 1 year K: shorter interv.		sufficient recording
3	BS 3500 (1969)	b.m.: before reuse r.m.:t<2000 h:anneal only,t>2000 h:anneal + cal.	≤1 year	sufficient recording (continuous recording)
4	EN 123-75 (1975)	(fixed intervals)		every 24 h, exceptionally every 50 h
5	ASTM E 139-83 (1990)	b.m.: no reuse r.m.: periodical calibration		
6	NF A03-355 (1985)	max. 1 year or before and after test		sufficient recording
7	UNI 5111-69 (1969)			sufficient recording (continuous recording)
8	JIS Z 2271/2 (1978)	before reuse		sufficient recording (continuous recording)
9	comments		+) measu- rement device	"sufficient recording" is the normal case
10	minimum requirements for the past			sufficient recording
11	minimum requirements for the future	(°C) T ≤ 600 : 4 years 600 < T ≤ 800 : 2 years 800 < T ≤ 1 350 : 1 year or at the end of each test, sooner for short duration tests	1 year	sufficient rec. of. at min. 1 t.c. per heating zone

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Load application 1

Row	Column 0	20		21	22
0	Standard	constant applied load	stress	tolerance of load ±	time of loading
1	ISO/DIS 204 (1991)	X	X	1 %	as rapid as possible without shock
2	DIN 50 118 (1982)	X		1 %	(max = min (1 h, 1 % of test time)), without shock
3	BS 3500 (1969)	X		1 %	as rapid as possible without shock
4	EN 123-75 (1975)	X		1 %	as rapid as possible without shock
5	ASTM E 139-83 (1990)	X		acc. to ASTM E4	as rapid as possible without shock
6	NF A03-355 (1985)	X		1 %	as rapid as possible without shock
7	UNI 5111-69 (1969)	X		1 %	as rapid as possible without shock
8	JIS Z 2271 cr (1978) JIS Z 2272 r.	X X		0.5 % 1 %	as rapid as possible without shock
9	comments	"constant load" in most cases		"±1%" in most cases	"as rapid as possible" in most cases
10	minimum requirements for the past	constant load		± 1 %	as rapid as possible without shock
11	minimum requirements for the future				≤ 10 min without shock

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L o a d   a p p l i c a t i o n   2

Row	Column 0	23	24
0	Standard	preloading *) in % of load	max. bending stress σ_b and torsion stress
1	ISO/DIS 204 (1991)		bending and torsion minimized
2	DIN 50 118 (1982)	(≤ 10)	DIN 51226: (≤ 10 % of axial strain, for new pull rods)
3	BS 3500 (1969)		bending and torsion minimized
4	EN 123-75 (1975)	(≤ 10)	
5	ASTM E 139-83 (1990)	≤ 10	(≤ 10 % of axial strain) +) avoid nonaxial forces
6	NF A03-355 (1985)		bending and torsion minimized
7	UNI 5111-69 (1969)	≤ 10	
8	JIS Z 2271 cr. (1978) JIS Z 2272 r.	≤ 10	(no excentric load)
9	comments	*) only if an extensometer is used, important for ui.t.	+) max. bending strain at load
10	minimum requirements for the past		
11	minimum requirements for the future	preloading ≤ 10% or first loading at room temperature	$\sigma_b \leq 0.2\ \sigma_o$ torsion minimized

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Supplementary test conditions 1

Row	Column 0	25	26
0	Standard	laboratory air temperature	test duration (h)
1	ISO/DIS 204 (1991)	(variations minimized)	
2	DIN 50 118 (1982)	[(± 3 °C) for strain measur. in i.t.]	
3	BS 3500 (1969)		10 ≤ t ≤ 100 000
4	EN 123-75 (1975)		
5	ASTM E 139-83 (1990)	sufficiently constant, ± 3 °C ui.t.	
6	NF A03-355 (1985)	sufficiently constant	
7	UNI 5111-69 (1969)	sufficiently constant	
8	JIS Z 2271/2 (1978)		
9	comments	not generally ruled	
10	minimum requirements for the past	sufficiently constant	
11	minimum requirements for the future	± 3 °C for extensometer in ui.t. and ± 2 °C for strain measur. in i.t.	

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Supplementary test conditions 2

Row	Column 0	27	28
0	Standard	tolerance of test time	soaking time
1	ISO/DIS 204 (1991)		≥ 1 h
2	DIN 50 118 (1982)	(± 1 %)	≤ 20 h ui.t. ≤ 3 h i.t.
3	BS 3500 (1969)	± 1 %	1 to 24 h heating time included
4	EN 123-75 (1975)		several hours ui.t. as short as poss. i.t.
5	ASTM E 139-83 (1990)	± 1 % for rupture time	≥ 1 h
6	NF A03-355 (1985)		≥ 1 h
7	UNI 5111-69 (1969)		(16 to 24 h) heating time 1 to 4 h
8	JIS Z 2271/2 (1978)		(16 to 24 h) heating time > 1 h
9	comments		
10	minimum requirements for the past		
11	minimum requirements for the future	± 1 %	ui.t.: heat.+soak.t.≤24 h i.t.: heat.t.: ≤ 4 h soak.t.: ≤ 3 h

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T e s t   p i e c e s   1

Row	Column 0	29	30	31	32
0	Standard	cross sectional area S_o (mm^2)	diameter d_0 in gauge length y)	d_0 (mm)	transition radius R
1	ISO/DIS 204 (1991)	≥ 7.00	c.d. g.d.	≥ 3	$R > d_0/4$
2	DIN 50 118 (1982)	≥ 12.57	c.d. g.d.	≥ 4	$R > d_0/4$
3	BS 3500 (1969)	≥ 12.50	c.d.?	≥ 4	$R \geq d_0$
4	EN 123-75 (1975)	(≥ 12.50)	c.d. g.d.	(≥ 4)	R > 0
5	ASTM E 139-83 (1990)	(≤ 123)	c.d.	(≤ 12.5)	R > 0 if necessary
6	NF A03-355 (1985)	≥ 7.00	c.d.	≥ 3	$0.4\ d_0 < R < d_0$
7	UNI 5111-69 (1969)	t.p. ≥ 12.57 round ≥ 16.0 flat	c.d. c.cross section	≥ 4	
8	JIS Z 2271,cr. (1978) JIS Z 2272, r.	28.5, <u>78.5</u>,*) 113 12.6,<u>28.5</u>,*) 78.5, ~~113~~	(c.d.) (c.d.)	10*) 6,8,12 6*) 4,8,10, 12	
9	comments	*) to be prefered y) c.d.:constant diameter g.d.:diam.greater near the ends			
10	minimum requirements for the past	≥ 7	≥ 3		
11	minimum requirements for the future	see col. 31	if g.d.: $L_r \leq 1.1\ L_c$ $d_o \geq 5$, ≥ 6 for special conditions		$\frac{d_0}{2} \geq R \geq \frac{d_0}{4}$ $d_0 > R$ for brittle materials

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T e s t p i e c e s 2

Row	Column 0	33	34	35	36	37
0	Standard	shape tolerance	test piece machining tolerance	diameter tolerance of meas.	reference length minimum value	 tolerance of measurement ±
1	ISO/DIS 204 (1991)	± 0.040 mm $6 < d_0 < 10$ mm (ISO 286-2)	± 0.075 mm $6 < d \le 10$mm	± 0.05 %	$(4.43\ d_0)^{x)}$ $(L_r \le 1.1\ L_c)$	1 %
2	DIN 50 118 (1982)	± 0.020 mm		± 0.01 mm	$3\ d_0$ or 20mm $(5\ d_0)$	0.1 mm 13)14)
3	BS 3500 (1969)	± 0.030 mm	±0.03 mm	± 0.01 mm	$(5\ d_0)$	0.005 %, $\varepsilon \le 0.3$ % 0.01 %, $0.3 < \varepsilon \le 1$ % 13)
4	EN 123-75 (1975)	± 0.040 mm $6 < d_0 < 10$ mm	±0.075 mm $6 < d_0 \le 10$mm		$3\ d_0$	0.25 mm
5	ASTM E 139-83 (1990)	± 0.5 %			$(4\ d_0)$	
6	NF A03-355 (1985)	± 0.040 mm $6 < d_0 < 10$ mm	±0.075 mm $6 < d \le 10$mm		$5\ d_0$ or ≥ 15 mm	1 %
7	UNI 5111-69 (1969)	± 0.015 mm*) $d_0 \le 6$ mm ±0.02 mm $6 < d_0 \le 18$ mm	±0.06 mm*) $d_0 \le 6$ mm ±0.075 mm $6 < d_0 \le 18$ mm		($5d_0$ or $10d_0$) ≥ 25 mm	1 %
8	JIS Z 2271, cr. (1978) JIS Z 2272, r.	± 0.03 mm $d_0 (\le 6$ mm) ± 0.04 mm $d_0 (> 6$ mm)			$5\ d_0$	1 %
9	comments	*) acc. to UNI 556/2		$\frac{dS_0}{S_0} = 2\frac{dd_0}{d_0}$	x) (extensometer gauge length ≥ 10 mm)	13) original gauge length 14) uninterr. test only
10	minimum requirements for the past				$3\ d_0$	1 %
11	minimum requirements for the future	± 0.02 mm for $6 \le d_0 \le 10$ mm	± 0.05 mm $6 \le d_0 < 10$ mm	± 0.05 %	$\ge 3\ d_0$, better $\ge 5d_0$ $L_r \le 1.1\ L_c$	± 0.5 % collars, shoulders: $L_r = L_c + 2\Sigma l_i (d_0/d_i)^{2n}$ take n as near as possible to Norton exponent depending on stress and temperature

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S t r a i n   m e a s u r e m e n t   1

Row	Column 0	38	39
0	Standard	strain measurement	admitted means of strain measurement
1	ISO/DIS 204 (1991)		extensometer other
2	DIN 50 118 (1982)	(on opposite sides)	extensometer other
3	BS 3500 (1969)	on opposite sides +)	extensometer other
4	EN 123-75 (1975)		extensometer other
5	ASTM E 139-83 (1990)	on opposite sides +) (not on load carrying parts)	extensometer
6	NF A03-355 (1985)	(on opposite sides)	extensometer other
7	UNI 5111-69 (1969)		extensometer
8	JIS Z 2271 cr. (1978) JIS Z 2272 r.	on opposite sides	extensometer
9	comments	+) (on the reduced portion of the test piece)	
10	minimum requirements for the past		
11	minimum requirements for the future	on opposite sides	ui.t.: extensometer i.t.: microscope

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Strain measurement 2

Row	Column 0	40	41	42
0	Standard	tolerance of strain /calibration	example for L_r = 40mm and ε = 1%	frequency of strain readings
1	ISO/DIS 204 (1991)	max(±0.01 Δl, ± 3 μm) class 1 extens. /ISO 9513	±0.0075 %	sufficient measurement or continuous recording
2	DIN 50 118 (1982)	max(±0.01 %, ±10 μm)ui.t. max(±0.02 %, ±20 μm) i.t. /cal. is not mentioned	±0.025 % ±0.05 %	sufficient measurement or continuous recording
3	BS 3500 (1969)	Grades B, C ±0.002 % (or) D ±0.005 % /BS 3846	±0.01 % for Grade C	sufficient measurement (continuous recording)
4	EN 123-75 (1975)	±1% of total displacement, $\varepsilon \geq 1$ % ±5% of total displacement, $\varepsilon < 1$ %	±0.01 %	sufficient measurement or continuous recording
5	ASTM E 139-83 (1990)	± 1 μm /ASTM E83	±0.0025 %	at least every 24 h or at 1 % of estimated test duration
6	NF A03-355 (1985)	±0.01 % /cal. is not mentioned	±0.01 %	sufficient measurement or continuous recording
7	UNI 5111-69 (1969)	±1 % of total displacement /cal. is not mentioned	±0.01 %	sufficient measurement or continuous recording
8	JIS Z 2271 cr. (1978) JIS Z 2272 r.	±10 μm /cal. is not mentioned	±0.025 %	sufficient measurement
9	comments			
10	minimum requirements for the past	ui.t.: max(±0.01 %, ±10 μm) i.t.: max(±0.02 %, ±20 μm)	±0.025 % ±0.05 %	
11	minimum requirements for the future	ui.t.: max(±0.01 Δl, ± 3μm) /ISO 9513 i.t.: max(±0.01 Δl, ±10μm) /glass scale + special t.p.	±0.01 % ±0.025 %	fixed time scales

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T e s t   r e s u l t s   1

Row	Column 0	43						44							
0	Standard	ϵ_t	ϵ_f	ϵ_p	ϵ_i	ϵ_e	ϵ_k	$t_{f\epsilon}$ *)	$t_{p\epsilon}$ *)	t_r	$R_{f\epsilon tT}$ *)	$R_{p\epsilon tT}$ *)	R_r	A_r	Z_r
1	ISO/DIS 204 (1991)		X	[X]	[X]	[X]	[X]			X				X	X
2	DIN 50 118 (1982)	X	X	X	X	X	X		X	X		X	X	X	X
3	BS 3500 (1969)	X	X	X	X	X				X			X	X	X
4	EN 123-75 (1975)		X	X	X					X			X	X	X
5	ASTM E 139-83 (1990)	X	X	X	X	X			X	X		X	X	X	X
6	NF A03-355 (1985)		X		X	X				X				X	X
7	UNI 5111-69 (1969)		X	X	X					X			X	X	X
8	JIS Z 2271 cr. (1978) JIS Z 2272 r.		X	X	X					X				X	X
9	comments	[ ] information applicable in the test report *) secondary results not all standards cover i.t.													
10	minimum requirements for the past														
11	minimum requirements for the future	an intern. standard for uninterrupted testing						a definition of basic assessment to obtain secondary results							

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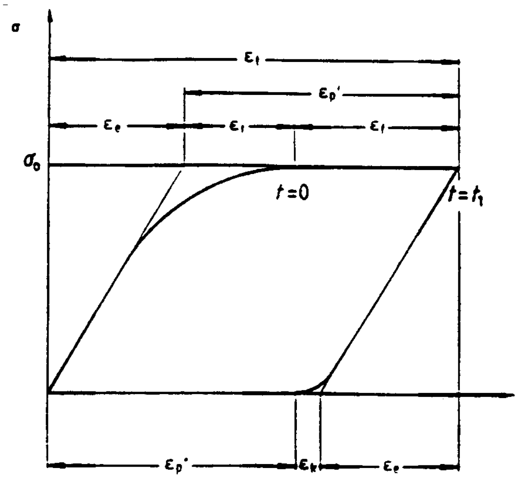
T e s t r e s u l t s 2

Row	Column 0	45
0	Standard	evaluation (bas.assessm.) procedure
1	ISO/DIS 204 (1991)	
2	DIN 50 118 (1982)	X
3	BS 3500 (1969)	
4	EN 123-75 (1975)	
5	ASTM E 139-83 (1990)	X
6	NF A03-355 (1985)	
7	UNI 5111-69 (1969)	(X)
8	JIS Z 2271 cr. (1978) JIS Z 2272 r.	
9	comments	not all standards contain a basic assessment procedure
10	minimum requirements for the past	
11	minimum requirements for the future	see col. 44



Strain results

mostly

$\varepsilon_k = 0$

$\varepsilon_p'' = \varepsilon_p' = \varepsilon_p$

ε_t	total strain
ε_f	creep strain
ε_p'	non-proportional strain
ε_p''	permanent strain
ε_p	total plastic strain
ε_i	initial plastic strain
ε_e	elastic strain
ε_k	anelastic strain

Other results

t_r	time to rupture
$t_{p\varepsilon}$	time to specific plastic strain ε_p
$t_{f\varepsilon}$	time to specific creep strain ε_f
R_r	stress to rupture, rupture strength
$R_{p\varepsilon\,t\,T}$	creep strength to specific plastic strain ε_p for given time t and temperature T
$R_{f\varepsilon\,t\,T}$	creep strength to specific creep strain ε_f for given time t and temperature T
A_r	elongation after rupture
Z_r	reduction of area after rupture

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P a r t n e r s / t e s t p r o c e d u r e s / t e s t m a c h i n e s

Column	0	1	2	3	4
Row	Labora-tory	coun-try	standard used	test procedure ui.t.:uninterr. test i.t.: interr. test*)	machine type used SM: Single m.: 1 t.p. MM: Multi m.: 1 string MSM: Multi spec.m.: >1 str.
1	GEC-A Stein I.	F	NF A03 -355	ui.t.	SM MSM
2	ERA	UK	BS 3500	ui.t. i.t.	SM MM
3	BST Sw.Lab.	UK	BS 3500	ui.t.	SM MSM
4	GECA	UK	BS 3500	ui.t.	SM MSM
5	Sulzer	CH	DIN 50 118	ui.t. i.t.	MM (3 t.p.) MSM
6	SKWU	D	DIN 50 118	ui.t.	SM MSM (3 strings)
7	IfWD	D	DIN 50 118	ui.t. i.t.	SM, MM (2 t.p.) MSM (8 strings)
8	MPAS	D	DIN 50 118	ui.t. i.t.	SM SM, MM
9	IM	S	ASTM E139-83	ui.t.	SM MSM (4 strings)
10	IRB	I	UNI 5111-69	ui.t.	SM
11	comments 10 laboratories 6 countries			*) interruptions for strain measurement ui.t.: 10 labs i.t. : 4 labs	SM : 9 labs MM : 3 labs MSM : 7 labs
12	recommendations				

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A t m o s p h e r e / T y p e o f l o a d a p p l i c a t i o n

Column	0	1	3	4	5	6	7	8	9	10
Row	Labora-tory	coun-try	test	ma-chine	atmosphere	load application dead weight	lever type	spring loaded	other	stan-dard
1	GEC-A Stein I.	F	ui.t.	SM MSM	air	X	X			intern. proc.
2	ERA	UK	ui.t. i.t.	SM MM	air vacuum argon	X	X			EN 10 002
3	BST Sw.Lab.	UK	ui.t.	SM MSM	air	X	X X			BS 1610
4	GECA	UK	ui.t.	SM MSM	air	X X	X X			BS 1610
5	Sulzer	CH	ui.t. i.t.	MM MSM	air	X	X			
6	SKWU	D	ui.t.	SM MSM	air	X X	X X			DIN 51 226
7	IfWD	D	ui.t. i.t.	SM,MM MSM	air	X X	X	X +)*) X +)	Y *)	DIN 51 226
8	MPAS	D	ui.t. i.t.	SM SM,MM	air		X X		Y *)	DIN 51 226
9	IM	S	ui.t.	SM MM	air	X	X		Z *)	ASTM E 139-93
10	IRB	I	ui.t.	SM	air argon	X	X		Z *)	ISO 7500
11	comments					+) DIN 51226 is specified for spring loaded machines *) with servocontrol Y: hydraulic Z: electromechanical				
12	recommendations				air	the need of load calibration is emphasized				

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Test temperature 1

Column 0	1		3	11	12
Row	Labora- tory	coun- try	test	temperature range °C	temperature tolerances (±°C) indicated-specified temp. *) total tolerance
1	Stein	F	ui.t.	≤ 800	3
2	ERA	UK	ui.t. i.t.	≤ 1200	*) 0 < T ≤ 600 °C 2.5 600 < T ≤ 800 °C 3.5 800 < T ≤ 1000 °C 4.5 1000 < T 4.5
3	BST	UK	ui.t.	≤ 1350	*) T ≤ 600 °C 3 600 < T ≤ 800 °C 4 800 < T ≤ 1000 °C 5 1000 < T : by agreement, e.g. 6
4	GECA	UK	ui.t.	< 1000	
5	Sulzer	CH	ui.t. i.t.	< 1100	*) T ≤ 600 °C 3 600 < T ≤ 800 °C 4 800 < T ≤ 1000 °C 5 1000 < T ≤ 1100 °C 6
6	SKWU	D	ui.t.	≤ 1100	
7	IfWD	D	ui.t. i.t.	≤ 1300 ≤ 1000	
8	MPAS	D	ui.t. i.t.	SM ≤ 1300 MM ≤ 700	
9	IM	S	ui.t.	SM ≤ 1200 MSM ≤ 900	*) 2 5
10	IRB	I	ui.t.	≤ 1050	*) T ≤ 600 °C 2 600 < T ≤ 800 °C 2 800 < T ≤ 1000 °C 4 T > 100 °C 4
11	comments				total temperature tolerance is indicated in most cases
12	recommendations			up to 1350°C ui.t. up to 1000°C i.t.	see T. 1/3

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Test temperature 2

Column 0	1	3	13	14	15
Row	Labora-tory	coun-try	test	measurement equipment tolerance (±°C)	resolution	thermocouple r.m.: rare met. b.m.: base met.
1	Stein	F	ui.t.	0.4	0.2	b.m.: K
2	ERA	UK	ui.t. i.t.	0.5	0.1	r.m.: R
3	BST	UK	ui.t.	0.5	0.1	r.m.: R
4	GECA	UK	ui.t.	0.5	0.1	r.m.: R
5	Sulzer	CH	ui.t. i.t.	0.5	0.1	b.m.: K
6	SKWU	D	ui.t.	0.5	0.5	r.m.: S
7	IfWD	D	ui.t. i.t.	i.t. 0.3 ui.t. {0.3 meas. {1 rec.*)	0.1 0.1 1	r.m.: S
8	MPAS	D	ui.t. i.t.			b.m.:K (<500°C) r.m.:S (≥500°C)
9	IM	S	ui.t.	0.5	0.1	r.m.: S
10	IRB	I	ui.t.	0.5	0.5	b.m.: K (short tests) r.m.: S
11	comments			*) rec.: continuous recording		
12	recommendations			see T. 1/4		

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Test temperature 3

Column 0		1	3	4	16	17
Row	Laboratory	country	test	machine	minimum number of thermocouples	time interval between two calibrations
1	Stein	F	ui.t.	SM MSM	- 3/t.p. - 2(1)/t.p. (3/furno)	max. 1 year or before and after test
2	ERA	UK	ui.t. i.t.	SM MM	- 3 - 5 per string	t.c. before and after tests Data logger: 6 mon.
3	BST	UK	ui.t.	SM MSM	2/t.p. L ≤ 50 mm 3/t.p. L > 50 mm - 1/t.p.	max. (between tests, 2 000 h in the same furnace)
4	GECA	UK	ui.t.	SM MSM	3/t.p. L=145 mm c.r. 2/t.p. L= 45 mm r.t.	max (between tests, 1 year)
5	Sulzer	CH	ui.t. i.t.	M MSM	- 3/test piece - 3/string	time interval not specified, new t.c. after ≤ 1 year
6	SKWU	D	ui.t.	SM MSM	- 2(3)/t.p. L≥25(50)mm - 1/heating zone (3)	
7	IfWD	D	ui.t. i.t.	SS SM MSM	- 2 to 3/test piece - 1 to 2/test piece - 1/heating zone (3)	(°C) T ≤ 600: 4 years 600 < T ≤ 800: 2 years 800 < T ≤ 1300: 1 year
8	MPAS	D	ui.t. i.t.	SM MM	- 2/test piece - 3/string	K:new t.c.aft.5000 h S: T ≤ 600: 3 years 600 > T≤ 800: 2 years 800 >T ≤ 1100: 2 years
9	IM	S	ui.t.	SM MSM	- 2/test piece - 1/test piece	
10	IRB	I	ui.t.	SM	- 3/test piece	S:max(between tests, 1 year) K:before test, no reuse
11	comments				in-situ-calibration of r.m.t.c. is not common	
12	recommendations				see T. 1/5	see T. 1/6

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T e s t   t e m p e r a t u r e   4

Column	0	1	3	4	18	19	20
Row	Labora-tory	coun-try	test	ma-chine	temperature calibration	frequency of temperature measurement	ITS
1	Stein	F	ui.t.	MM	classe 1 NF C 42 322 (t.c.), cal. against Pt100 or t.c. type S	scanned and recorded every 5 min.	90
2	ERA	UK	ui.t. i.t.	SM MM	determination of error of thermocouple and of measurement device	suffic. rec.	68
3	BST	UK	ui.t.	SM MSM		suffic. rec. (contin. rec.)	90
4	GECA	UK	ui.t.	SM MSM	BS 4937, device cal. to a NAMAS proc.	scanned every 2 min. rec. every 12 h	68
5	Sulzer	CH	ui.t. i.t.	M MSM	DIN 50 118, comparison with cal. t.c.	contin. reading with computer	68
6	SKWU	D	ui.t.	SM MSM	SM: determ. of error of tc. and of measurement device*) MSM: see SM and addit. diff. betw. test piece and tc.*) DIN 50 118		68
7	IfWD	D	ui.t. i.t.	SS MSM		suffic. rec.	90
8	MPAS	D	ui.t. i.t.	SM MM	determination of error of tc. and of measurement device *)	suffic. rec.	90
9	IM	S	ui.t.	SM MSM	determination of error of tc.*) and of measurement device	scanned every 10 min	90
10	IRB	I	ui.t.	SM	determination of error of tc. against nat. stand. and control of measurement device	suff. rec. rec.every s, if changing ≥ 0.25 °C	90
11	comments				*) in-situ calibration		
12	recommendations				see T. 1/5 repeated determination of the errors of t.c. and meas.device and (for indirect temp. meas.) of the diff. of t.c. and test piece	see T. 1/6	use ITS 90

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L o a d   a p p l i c a t i o n   1

Column 0	1	3		21		22	23
Row	Laboratory	country	test	constant load	applied stress	tolerance of load ± (%)	time of loading
1	Stein	F	ui.t.	X		1	1 to 20 s
2	ERA	UK	ui.t. i.t.	X	X	1	< 5 min
3	BST	UK	ui.t.	X		1	< 5 min
4	GECA	UK	ui.t.	X		1	< 5 min
5	Sulzer	CH	ui.t. i.t.	X		1	as rapid as poss.
6	SKWU	D	ui.t.	X		1	as rapid as poss.
7	IfWD	D	ui.t. i.t.	X		1	0.2 to 5 s EN 10002 P.5: $\dot{\epsilon}_e$=0.1 to 0.5%/min
8	MPAS	D	ui.t. i.t.	X		1	about 1 min
9	IM	S	ui.t.	X		1	2 to 5 min
10	IRB	I	ui.t.	X	X	0.5	as rapid as poss.
11	comments			constant load in nearly all cases			
12	recommendations			see T. 1/7		see T.1/7	see T. 1/7

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L o a d   a p p l i c a t i o n   2

Column	0	1	3	24	25
Row	Labora-tory	coun-try	test	Preloading in % of load, if extens. is used	max. bending stress [spec. methods]
1	Stein	F	ui.t.	230 or 360 N	bending minimized
2	ERA	UK	ui.t. i.t.	-	bending minimized
3	BST	UK	ui.t.	-	[balanced readings of 2 transducers]
4	GECA	UK	ui.t.	< 10 %	[balanced readings of 2 transd, ε_e<5%]
5	Sulzer	CH	ui.t. i.t.	200 N	bending minimized
6	SKWU	D	ui.t.	≤ 10 %	bending minimized [balanced readings]
7	IfWD	D	ui.t. i.t.	≤ 10 %	bending minimized [balanced readings]
8	MPAS	D	ui.t. i.t.	≤ 10 %	[ui.t.: bal.read. of 2 transducers] bending minimized
9	IM	S	ui.t.	-	balanced readings of 2 transducers
10	IRB	I	ui.t.	10 %	bending minimized
11	comments				
12	recommendations			see T. 1/8	see T. 1/8

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Supplementary test conditions 1

Column	0	1	3	26	27
Row	Labora-tory	coun-try	test	laboratory air temperature (°C)	test duration (h) (extreme values)
1	Stein	F	ui.t.	21 ± 2	up to 15 000
2	ERA	UK	ui.t. i.t.	23 ± 2	10 to 100 000 (200 000)
3	BST	UK	ui.t.	22 ± 3	up to 100 000 (200 000)
4	GECA	UK	ui.t.	± 0.5	1 000 to 100 000
5	Sulzer	CH	ui.t. i.t.	partly ± 1 °C partly 23 ± 5 °C	up to 50 000
6	SKWU	D	ui.t.	23 ± 2	1 to 100 000 (300 000)
7	IfWD	D	ui.t. i.t.	MM: 23 ± 3 MSM: 25 ± 5 on 330 days/year 20±2 str. meas sur.	1 to 10 000 300 to 100 000 (200 000)
8	MPAS	D	ui.t. i.t.	22 ± 2	up to 10 000 up to 100 000 (200 000)
9	IM	S	ui.t.	22 ± 1	up to 70 000
10	IRB	I	ui.t.	± 3	up to 30 000
11	comments				
12	recommendations			see T. 1/9	

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Supplementary test conditions 2

Column 0	1	3	28	29	30
Row / Laboratory	country	test	tolerance of test time t	t=0 from $\sigma=\sigma_0$?	soaking time
1 Stein	F	ui.t.	± 0.5 %	yes	1 to 8 h
2 ERA	UK	ui.t. i.t.	± 1 %	yes	1 to 24 h including heating time
3 BST	UK	ui.t.	± 1 %	yes	2 to 3 h + typical heating time
4 GECA	UK	ui.t.	± 0.01 %	yes	1 to 24 h including heating time
5 Sulzer	CH	ui.t. i.t.	± 0.5 h r.t.	yes	1 to 8 h
6 SKWU	D	ui.t.	≤ 1 h	yes	≤ 3 h
7 IfWD	D	ui.t. i.t.	± 1 %	yes	ui.t. 2 to 3 h i.t. 0.5 to 1 h
8 MPAS	D	ui.t. i.t.	≤ 1 h (≤ 0.1 h for short term tests)	yes	ui.t. ≤ 2 h i.t. ≤ 2 h (SM) ≤ 5 h (MM)
9 IM	S	ui.t.	≤ 1 h	yes	1 to 20 h including heating time
10 IRB	I	ui.t.	0.1 h	yes	(°C) T ≤ 600: 4h+20 h 600 < T ≤ 800: 5h+19 h 800 < T ≤ 1000: 7h+18 h 1000 < T *) : : 9h+17 h
11 comments					*) heating time + soaking time
12 recommendations			±1 %		see T. 1/10 partly, ≤ 24 h is recommended

[redacted]

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T e s t   p i e c e s   1

Column 0	1	3	31	32	33	34
Row	Laboratory	country	test	cross sectionel area S_0 (mm^2)	diameter d_0 in gauge length y)	d_0 (mm)	transit. Radius R
1	Stein	F	ui.t.	29.3	c.d.	6	$0.4\ d_0 < R < d_0$
2	ERA	UK	ui.t. i.t.	> 3	c.d.	4.5 8 9	$R \leq d_0$
3	BST	UK	ui.t.	16 to 65	c.d.	8	$R \leq d_0$?
4	GECA	UK	ui.t.	cr.t.: 162 x) r.t.: 65	c.d.	cr.t.: 14.4 r.t.: 9.1	$R \leq d_0$?
5	Sulzer	CH	ui.t. i.t.	15 to 50	c.d.	4.5 to 8	$\frac{d_0}{4} < R < \frac{d_0}{2}$
6	SKWU	D	ui.t.	≥ 19.6	g.d.	≥ 5	$R > d_0/4$?
7	IfWD	D	ui.t. i.t.	49 to 62	g.d.	7.9 to 8.9	$R = 0.3d_0$
8	MPAS	D	ui.t. i.t.	50 to 64	g.d.	8 to 9	$R = 0.3d_0$
9	IM	S	ui.t.	4.9 to 78	c.d.	2.5 to 10	$R = d_0$
10	IRB	I	ui.t.	12.6 to 78.5	c.d.	5,8,10	30°conical transi.
11	comments			y) c.d.: constant g.d.: greater near the ends x) cr.t.: creep test r.t.: rupture test			
12	recommendations			see T. 1/11			

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Test pieces 2

Column	0	1	3	35	35	36	37	38	39
Row	Laboratory	country	test	diameter tolerances (±mm) shape tolerance	machining tolerance	tolerance of meas.	surface quality	reference length L range	(± mm or ^{r}%) tolerance
1	Stein	F	ui.t.	0.03	0.06	0.010		20 to 30 (5 d_0)	± 0.040
2	ERA	UK	ui.t. i.t.	0.030	0.030	0.010	ground	120.5 to 45 (5 d_0)	0.005% $\epsilon \le 0.3$% 0.01% $0.3 \epsilon \le 1$%
3	BST	UK	ui.t.	0.030	0.030	0.010	ground	125 (5 d_0)	0.005% $\epsilon \le 0.3$% 0.01% $0.3 \epsilon \le 1$%
4	GECA	UK	ui.t.		0.010	0.005	ground	cr.t.: 25 (10d_0) r.t.: 45 (5d_0)	0.050
5	Sulzer	CH	ui.t. i.t.	0.020		0.010	turned or ground	3.5 to 5 d_0	0.100
6	SKWU	D	ui.t.		0.010	0.010		30	0.010
7	IfWD	D	ui.t. i.t.	0.010		0.002	ground	42.0 4.7 to 5.3d_0	0.100
8	MPAS	D	ui.t. i.t.			0.005	ground	42.5 5 d_0	0.100
9	IM	S	ui.t.		0.040	0.001	R_a=0.5 µm	20 to 100	0.010
10	IRB	I	ui.t.	0.010	0.050	0.010	fine turned or polished	50 5d_0 for A_r	0.050
11	comments			dS_0/S_0 = 0.33 % dF_0/F_0 = 1 % (load, col.22) $d\sigma_0/\sigma_0$ = $1^2+0.33^2$ = 1 %					
12	recommendations			see T. 1/12				see T. 1/12	see T. 1/12

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Strain measurement 1

Column 0	1	3	40	41	42
Row	Labora-tory	coun-try	test	strain measurement on oppos. sides?	strain measurement cr.t. and r.t. on the same t.p.?	used means of strain measurement
1	Stein	F	ui.t.	no	?	extensom.
2	ERA	UK	ui.t. i.t.	yes	yes, no	extensom. microscope
3	BST	UK	ui.t.	yes	yes, no	extensom.
4	GECA	UK	ui.t.	yes	yes, no	extensom.
5	Sulzer	CH	ui.t. i.t.	yes	no	extensom. microscope
6	SKWU	D	ui.t.	yes	yes	extensom.
7	IfWD	D	ui.t. i.t.	yes	yes	extensom. microscope
8	MPAS	D	ui.t. i.t.	yes	yes	extensom. microscope
9	IM	S	ui.t.	yes	yes	extensom.
10	IRB	I	ui.t.	yes	yes	extensom.
11	comments				cr.t.: creep test r.t.: rupture test	
12	recommendations			see T.1/13	"yes" favours assessment	ui.t.: extensomet. i.t.: microscope

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S t r a i n   m e a s u r e m e n t   2

Column 0 1 3				43	44		45
Row	Labora-tory	coun-try	test	tolerance of strain measurement (% absol.) ± /calibration	tolerance of 1 % strain for L_r (mm)	acc. (%±)	strain readings
1	Stein	F	ui.t.	Extensom. class 0.5/1: max. (0.0015 mm, 0.5 %Δl) /max (0.003 mm, 1 %Δl)	40	class 0.5/1 0.005 %/ 0.010 %	scanned and re-corded every hour, quicker at the begin (6s)
2	ERA	UK	ui.t. i.t.	0.002 % /BS 3846 0.005 %	40 40	0.002 % 0.05 %	suffic.meas.
3	BST	UK	ui.t.	0.010 % /BS 3846,C,D	40	0.010 %	suffic.meas.
4	GECA	UK	ui.t.	0.001 mm /BS 3846	40	0.0025%	frequ. < 24 h than all 12 h
5	Sulzer	CH	ui.t. i.t.	0.001 mm (0.0001) 0.01 mm / no	40	0.0025% 0.025 %	computer rec. suffic.meas.
6	SKWU	D	ui.t.	max (0.01 %, 0.010 mm) /spec.method	40	0.025 %	contin. rec.
7	IfWD	D	ui.t. i.t.	max (0.01 %, 0.010 x) mm) /gauge block max (0.02 %, 0.020 *) mm) /ref.t.p., glass scale	42 42	0.024 % 0.007 % x) 0.05 % 0.02 % *)	contin. rec. suffic.meas.
8	MPAS	D	ui.t. i.t.	0.002(to 0.01) mm /spec.method 0.002(to 0.005) mm /ref. t.p.	42.5 42.5	0.005 (to 0.02) % 0.005 (to 0.01)%	contin. rec. suffic.meas.
9	IM	S	ui.t.	0.001 mm/0.1 µm Laser interferometer	100	0.1 to 0.01 %	suffic. meas.
10	IRB	I	ui.t.	0.001 mm to 0.01 mm /gauge block	50	0.0025 % (best)	suffic. meas. or "intelli-gent"comp.rec.
11	comments			x) 0.003 mm in the future *) 0.010 mm in the future			
12	recommendations			see T. 1/14	see T. 1/14		time scales see chapter 4

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Test results 1

Column	0	1	3	46 strain results						47 other		
Row	Laboratory	country	test	ε_t	ε_f	ε_p	ε_i	ε_e	ε_k	x) $t_{f\varepsilon}$	x) $t_{p\varepsilon}$	t_r
1	Stein	F	ui.t.	X	X	*)	*) $\varepsilon_e + \varepsilon_i$			X		X
2	ERA	UK	ui.t. i.t.	X	X	X X	X	X		(X)	X	X
3	BST	UK	ui.t.	X	X	X	X	X		(X)	(X)	X
4	GECA	UK	ui.t.	X	X	X	X	X		X	X	X
5	Sulzer	CH	ui.t. i.t.	X	X	X X	X	X			X X	X X
6	SKWU	D	ui.t.	X	X	X	X	X	X		X	X
7	IfWD	D	ui.t. i.t.	X	X	X X	X	X	X		X X	X X
8	MPAS	D	ui.t. i.t.	X	X	X X	X	X	X		X	X
9	IM	S	ui.t.	X	X	X	X	X			X	X
10	IRB	I	ui.t.		X	X	X	X	X		X	X
11	comments			*) with ε_i from hot tensile test, ε_p and from there $t_{p\varepsilon}$ can be determined x) not part of test procedure								
12	recommendations			see T. 1/15, col. 44								

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Test results 2

Column	0	1	3	48					49	50	51
Row	Laboratory	country	test	x) $R_{f\varepsilon tT}$	x) $R_{p\varepsilon tT}$	x) R_r	A_r	Z_r	evaluation procedure	accredition	comparison tests
1	Stein	F	ui.t.				X	X	no		no
2	ERA	UK	ui.t. i.t.		X	X	X	X	various	obtained NAMAS	occ.
3	BST	UK	ui.t.	X	X	X	X	X	graph.	obtained NAMAS	occ.
4	GECA	UK	ui.t.	X	X	X	X	X	various	within 3 years	occ.
5	Sulzer	CH	ui.t. i.t.		X X	X X	X X	X X	graph. DIN 50 118		not in the last years
6	SKWU	D	ui.t.		X	X	X	X	graph., DESA DIN 50 118	within 3 years?	occ.
7	IfWD	D	ui.t. i.t.		X X	X X	X X	X X	graph., DESA DIN 50 118	within 3 years	occ.
8	MPAS	D	ui.t. i.t.		X	X	X	X	graph. DIN 50 118	within 3 years	occ.
9	IM	S	ui.t.		X	X	X	X	various	not yet	occ.
10	IRB	I	ui.t.			X	X	X	various	running	occ.
11	comments			x) not part of test procedure							
12	recommendations								see T. 1/15 col. 44	recommended	recommended

APPENDIX 2

REVIEW OF STRESS RELAXATION TESTING STANDARDS AND PRACTICES

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APPENDIX 2

REVIEW OF STRESS RELAXATION TESTING STANDARDS AND PRACTICES

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APPENDIX 2 to VOL 3

REPORT ON STRESS RELAXATION TESTING STANDARDS AND PRACTICES

Prepared for ECCC-WG1

by H. Theofel, MPA Stuttgart, Germany
with the aid of the members of WG1 (compare cover sheet of Vol. 3)

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1 Introduction

This report deals with a review of existing standards and draft standards for two methods of stress relaxation testing, Annex 1 and 2, and reviews the practices currently adopted in several European laboratories, Annex 3. The two test methods are uniaxial stress relaxation testing and model bolt stress relaxation testing, which are described in Volume 2, Terms and Terminology, §2.4.

2 Standards for uniaxial stress relaxation testing

2.1 Reviewed standards (Annex 1, Table 1)

There are fewer stress relaxation testing standards than exist for creep testing. The tables in Annex 1 summarise the requirements from four standards for stress relaxation testing with tensile specimens /1-4/. One of them (SEP) is only available as a draft.

Generally, it can be noticed that in these standards only a few regulations are given under topics such as temperature measurement, strain measurement and specimen details. For these cases it can be assumed, that regulations from corresponding standards for (uninterrupted) creep testing, as reported in Appendix 1 to Vol 3, are applicable. For example, in ASTM E328 it is said, that temperature measurement should be made in accordance with ASTM E139.

2.2 Test equipment and environment (Annex 1, Table 1)

Most regulations (SEP, ASTM(1986) and JIS) require servo-controlled testing machines. Control mode is not mentioned in the BS standard, but servo-control *or* manual control is allowed, because the method shall be recorded together with the test results.

The JIS standard refers to a "Step-down-test", which was also included in an older ASTM-version (1978) as "Flow Rate Test". Such tests are manually controlled and the relaxation curve is approximated by stepwise load reduction. There is only good agreement between the flow rate test and the stress relaxation test if the stepwise load reductions are small in the former test.

Manually controlled stress relaxation tests have to be carefully conducted (not simply as 'flow rate tests' with rough steps of load reduction). Just after the beginning of the test, load reductions are frequently necessary to hold the given total elongation within the specified limits. This normally requires adjustments around the clock until the frequency reaches ≤ 2 loadsteps per day.

As a consequence of these circumstances relaxation tests up to shorter or medium testing times, i.e. up to about 3 000 h, are usually conducted as automatically controlled tests. In the case of longterm testing the manual mode becomes more useful. The necessary adjustments are small and, in addition to cost aspects, the advantage of manual controlled tests is their lower susceptibility to interferences.

At present the use of servo and/or manual control on one machine throughout the whole test duration is recommended. Interruptions should not be tolerated unless absolutely essential. The effects of interruptions are being studied in the current BCR project No. 3127 /6/, after which it should be clearer, how they should be controlled and exactly what influence they have on the stress relaxation behaviour. In future, a combined method is conceivable involving a machine change to use the positive aspects of both procedures. Then, after starting in a servocontrolled machine, the test could be continued as manually controlled test using a single creep testing machine with lever weights.

The environmental conditions are not stated in the standards. Air can be assumed and recommended for uniaxial tests.

2.3 Temperature control and measurement (Annex 1, Table 2)

For most aspects of temperature measurement, thermocouples and calibrations the regulations for creep tests can be equally applied for uniaxial stress relaxation testing. Single specimens are tested and they are longer than usual specimens for creep tests. Therefore 3 thermocouples per specimen are recommended.

Heating should be better specified, as well as the soaking time for uniaxial tests, see ann.1/t.3.

2.4 Load application (Annex 1, Table 3)

The load in uniaxial relaxation tests can be applied to reach either a specified total strain or a specified initial stress (the other parameter vice versa is part of the test results).

The loading procedure can be selected as loading with constant strain rate or with constant load/stress rate. This will cause a different behaviour above the elastic regime, see fig. 1. In tests with a small amount of plastic strain their will be no influence. But in tests, where a remarkable amount of plastic strain appears, at time t_0 the initial stress will be reached with different actual strain rates, and this will influence the following unloading sequence.

Nevertheless, when both loading procedures can be applied, the allowed stress rate or strain rate must be better stated or limited. Within a test series it should be the same rate for all tests.

Bending should be minimised by preloading at ambient temperature and the reading of both extensometers separately. Preloading is also recommended at test temperature, to prevent settling effects before setting the extensometers and starting the strain measurement. It is considered that this preload has no influence on the specimen, when it is limited to 10 % of the yield strength at test temperature.

2.5 Specimen details (Annex 1, Table 4)

The general rules for specimen details are as for the creep tests. Examples for the shape of specimens are shown in fig. 2.

It is recommended, to use a long specimen shape ($L_0 \geq 10d_0$), otherwise control of ε_t during test is not precise. Although a diameter $\geq$ 5 mm is allowed for future data, it should be better $\geq$ 8 mm (together with a L_0/d_0 ratio of $\geq$ 10 and a preferred parallel length of $\geq$ 100 mm).

To take into account the actions of shoulders or collars of the specimens within the measurement length of the extensometer, the reference length has to be determined according to the formula in Appendix 1 (after DIN 50 118 and DIS 204). At the beginning of a stress relaxation test the total strain is predominantly elastic. Therefore it is recommended to calculate L_r with an exponent of n = 1. Inaccuracies in this determination for stress relaxation test specimens will obviously have a smaller influence than at creep test specimens, because the collars/shoulders are smaller and the shaft is longer (L/d greater).

2.6 Strain measurement (Annex 1, Table 5)

The implementation of strain measurement for uniaxial tests is usually by a double sided extensometer using an average value as control parameter.

The tolerance for strain measurement should be given by the limits ±1 % (relative) resp. 0.0025 % (absolute), whichever is the greater.

For extensometric reasons the laboratory room temperature, see ann.1/t.3, should be held in a limited range of ±3 °C during the test.

2.7 Test parameters and test results (Annex 1, Table 6)

Alternatively ε_t or σ_0 can be selected as initial test parameter. In addition to this the stress rate resp. the strain rate is another important test parameter, see 2.4. Both parameters, ε_t (or σ_0) and stress rate (or strain rate) must be reported, also the test temperature as the third basic parameter.

The aim of stress relaxation tests is to determine the relaxed stress as a function of time. The other values, which are mentioned in the standards, are derived from the relaxed stress and the initial stress (normalised or as difference), or are the differentiation of the stress/time-curve. For future testing it should not be mandatory, to report such secondary values. They should only be reported in exceptional cases.

An important value for characterising the stress/strain-behaviour is the Young's modulus at the test temperature. It can be determined either as part of the hot loading sequence or during a tensile test on the same test material. This static Young's modulus is used to calculate the elastic and plastic components of the strain achieved as

$$\varepsilon_{e0} = \sigma_0 / E_{T(S)} \quad \text{and}$$

$$\varepsilon_{p0} = \varepsilon_t - \varepsilon_{e0}.$$

If the static Young's modulus is determined by a hot tensile test, the same loading rate as in the relaxation test shall be applied.

The following test results shall mandatory be reported:

- initial stress σ_0 (when a given ε_t is set)
  [or ε_t (when σ_0 is an initial parameter)]
- remaining or residual stress σ_R (values versus test duration)
- Young's modulus at test temperature $E_{T(S)}$
- initial elastic and permanent components of strain ε_{e0} and ε_{p0} .

3 Standards for stress relaxation testing with model bolts

Model bolt tests provide an alternative to uniaxial methods for determining longterm stress relaxation properties.

3.1 Reviewed standards (Annex 2, table 1)

For stress relaxation testing with model bolts only one draft standard, SEP 1260 /5/, could be reviewed.

3.2 Test equipment and environment (Annex 2, Table 1)

In the SEP-draft two types of model bolt tests are described. They have different principles to measure strain or elongation during loading and unloading: a) with a mechanical extensometer from end face to end face, or b) with strain gauges.

For type a) the reference length must be determined, to calculate strain from the overall elongation. This can be done by comparison measurements at RT with strain gauges on the shaft, to take into account the actions of collars at the bolt and effects from other parts of the model and of their geometry. This reference length represents the situation during the fully elastic loading and it is used to tighten the model bolt up to the required value of ε_t. For type b) the strain during loading / unloading is directly measured at the shaft. For both types of models the proportions will be slightly different at the test temperature, when small portions of plastic deformation in the shaft and transition appear.

The environmental conditions are not stated, air can be assumed and recommended for model bolt tests.

3.3 Temperature control and measurement (Annex 2, Table 2)

Temperature gradients between the different parts of a model bolt during heating and cooling must be prevented. Therefore, heating and cooling rates should be carefully controlled.

For model bolts, where several specimens are annealed together in a furnace, the number and the location of thermocouples has to be chosen in a manner, to guarantee the specified tolerances, i.e. the total temperature deviations within the used zone of the furnace must be observed. To have relatively large zones with constant temperature, the use of furnaces with forced air draft is recommended.

3.4 Load application (Annex 2, Table 3)

For model bolts it is required to load the bolt 3 times to the fully total elongation (elastic deformation at RT) to accommodate settling effects in threads and contact surfaces. For misalignment strain compare 3.5.

The bolt and flange should be held such that no torsion occurs during nut rotating.

3.5 Specimen details (Annex 2, Table 4)

The ratio of the cross section area of the flange and bolt has an influence on the relaxation behaviour and must therefore be stated. For future data a ratio of $S_{0[flange]}/S_{0[bolt]} > 5$ is required.

For the type a) models, for measurements with mechanical extensometer, a relative long bolt should be used. The bolt of type b) models have a shorter cylindrical length. Here the strain is measured directly at the shaft with the strain gauges.

Bending in the bolt is negligible, when the end faces of the flange are parallel to each other and have concentric centres with the nuts, compare fig. 3 for a model of type a.

3.6 Strain measurement (Annex 2, table 5)

For model bolt tests (a) mechanical extensometer measurements or (b) strain gauges measurements are used to determine the total initial strain at the beginning of the test and the remaining elastic strain after the test. The tolerance for strain measurement should be at ±1 %.

During the length measurements before and after loading respectively and before and after unloading of the models, the laboratory air temperature, see ann.2/t.3, should be held in a limited range of ±2 °C.

3.7 Test parameters and test results (Annex 2, Table 6)

For the model bolt tests, the Young's modulus is needed for the calculation of stresses. The static Young's modulus is used to estimate the initial stress by the expression

$$\sigma_0^* = \varepsilon_{eRT} \cdot E_{T(S)}$$

(with ε_{eRT} determined from elongation measurements before and after loading, following /5/).

The remaining stress, σ_R, has traditionally been calculated using $E_{T(S)}$ by the expression

$$\sigma_R = \varepsilon_{eRT} \cdot E_{T(S)}$$

(in this case with ε_{eRT} determined due to unloading, following /5/).

There is emerging evidence to indicate that σ_R should be determined using the dynamic modulus, $E_{T(D)}$, ie.

$$\sigma_R = \varepsilon_{eRT} \cdot E_{T(D)} .$$

While existing and new model bolt stress relaxation data is being collated which has been determined using either $E_{T(S)}$ or $E_{T(D)}$, the type of modulus employed in the σ_R calculation should be quoted with all test results. The remaining stress σ_R is the test result, that has to be reported.

4 Stress relaxation testing practices

The testing practices of nine European laboratories from four countries are given in the tables of annex 2.

4.1 Laboratories, used standards and test equipment (Annex 3, Table 1)

Eight of the nine laboratories conduct uniaxial stress relaxation tests. Five have experiences with model bolt tests. As generality, the laboratories refer to their national standards. However, IRB (Italy) and SI (Switzerland) respectively use the American and the German regulations.

Often servocontrolled testing machines are used, but also manual controlled equipments. Manual tests are the cheaper for long term tests and it can clearly be seen in column A27 (Ann.3/t.6), that those labs lead their uniaxial relaxation tests to ten times longer test durations. Therefore otherwise model bolt tests are conducted for the determination of longterm properties.

4.2 Temperature (Annex 3, Table 2)

The temperature measurement for uniaxial tests is mostly similar to those for creep tests in the same laboratory. This is also the case for Model bolt tests in most aspects, despite of the different types of furnace, where a temperature control within the used zone is necessary.

4.3 Load application for uniaxial stress relaxation tests (Annex 3, Table 3 and 4)

Loading is conducted in the load/stress controlled mode as well as in the strain controlled mode. Some labs can apply both methods, as required.

Normally a relaxation specimen only should be steady unloaded, when the required total elongation is held constant. But short term temperature deviations, although they do not exceed ±1 °C in the labs reviewed, cause temperature induced changes in length. The amount of this deviation can be greater, than the smallest possible change in length, corresponding to the sensitivity in load control (smallest possible step in load). To prevent frequent small up- and downward load changes in the servo-controlled mode, which means to ignore temperature induced changes in length, it is recommended to use a less sensitive adjustment. With this control behaviour the test is to be held within ± 1 % of the set strain value.

Preloading at the test temperature is mostly used and should be recommended for future test practices. In the question of loading time the labs are not as far from another, as the given limits from the standards allow. The limits should be closer in an improved standard.

4.4 Loading and unloading of model bolts (Annex 3, Table 5)

During the loading procedure, i.e. tensioning the bolt to a given elongation at RT, it is possible to observe the total length with a mechanical extensometer, or to measure the strain directly with strain gauges on the shaft of the bolt. Both methods are used by the labs, involved in this query.

For the unloading procedure, mostly done by destroying the nut, the same method for strain or length measurement is used.

4.5 Miscellaneous and specimen details (Annex 3, Table 6-8)

In all labs, where uniaxial relaxation tests are conducted, air-conditioning is installed, to hold the air temperature within tolerable limits, as needed for extensometry. Most laboratories use specimens with a constant diameter within the gauge length. Amongst them are specimens with small collars, whose influence on the reference length should not be neglected (cf. 2.5).

4.6 Strain measurement (Annex 3, Table 9)

Strain measurement in uniaxial stress relaxation tests is similar to that of creep tests. For model bolts two different principles for strain measurement are used, mechanical extensometry (type a) or strain gauges (type b).

4.7 Test parameter and test results (Annex 3, Table 10)

The indicated test parameters and test results, that directly can be taken from the test, are nearly completely given by all labs. Additionally some labs control the final plastic strain after the test (method as for interrupted creep tests) and compare it with the directly measured value. Derived values are also given as test results from most labs.

5 Conclusions

The stress relaxation testing standards for uniaxial tests (Annex 1) and model bolt tests (Annex 2) and the practices adopted by nine European Laboratories (Annex 3) have been reviewed.

On the basis of the survey, recommendations for the minimum requirements for (i) existing data and (ii) future data are proposed

6 Standards and draft standards

/1/ SEP-Entwurf, 1984, Entspannungsversuch an Stählen bei erhöhter Temperatur unter einachsiger Zugbeanspruchung (Doc. 5524/WG1/ 16)

/2/ BS 3500, part 6 (Doc. 5524/WG1/ 19)

/3/ ASTM E328 - 86 Standard Methods for Stress Relaxation Tests for Materials and Structures (Doc. 5524/WG1/ 27)

/4/ JIS Z 2276 - 1975, Japanese Industrial Standard, Method of Relaxation Test for Metallic Materials (Doc. 5524/WG1/ 43)

/5/ SEP 1260, Entwurf 12.93, Relaxationsversuch bei erhöhter Temperatur mit Schraubenverbindungsmodellen (Doc. 5524/WG1/ 17)

/6/ BCR-project No. 3127: Development of a standardised European methodology for stress relaxation testing of metals, co-ordinated by ERA Technology Ltd.

7 Figures (and tables as annex 1 - 3)

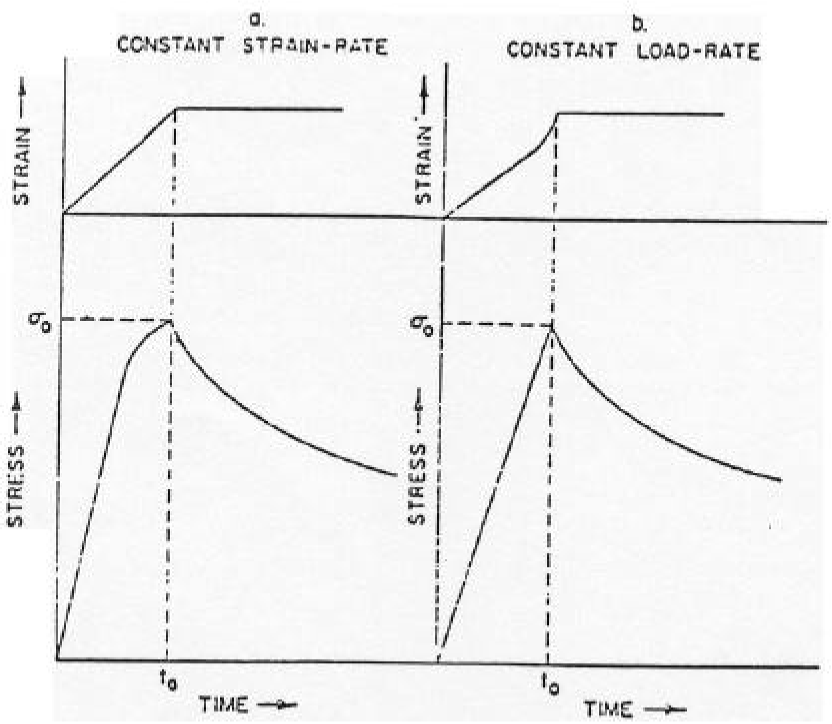

Fig. 1: Different behaviour during the loading period in an uniaxial relaxation test, depending from the strain- or stress-controlled loading mode

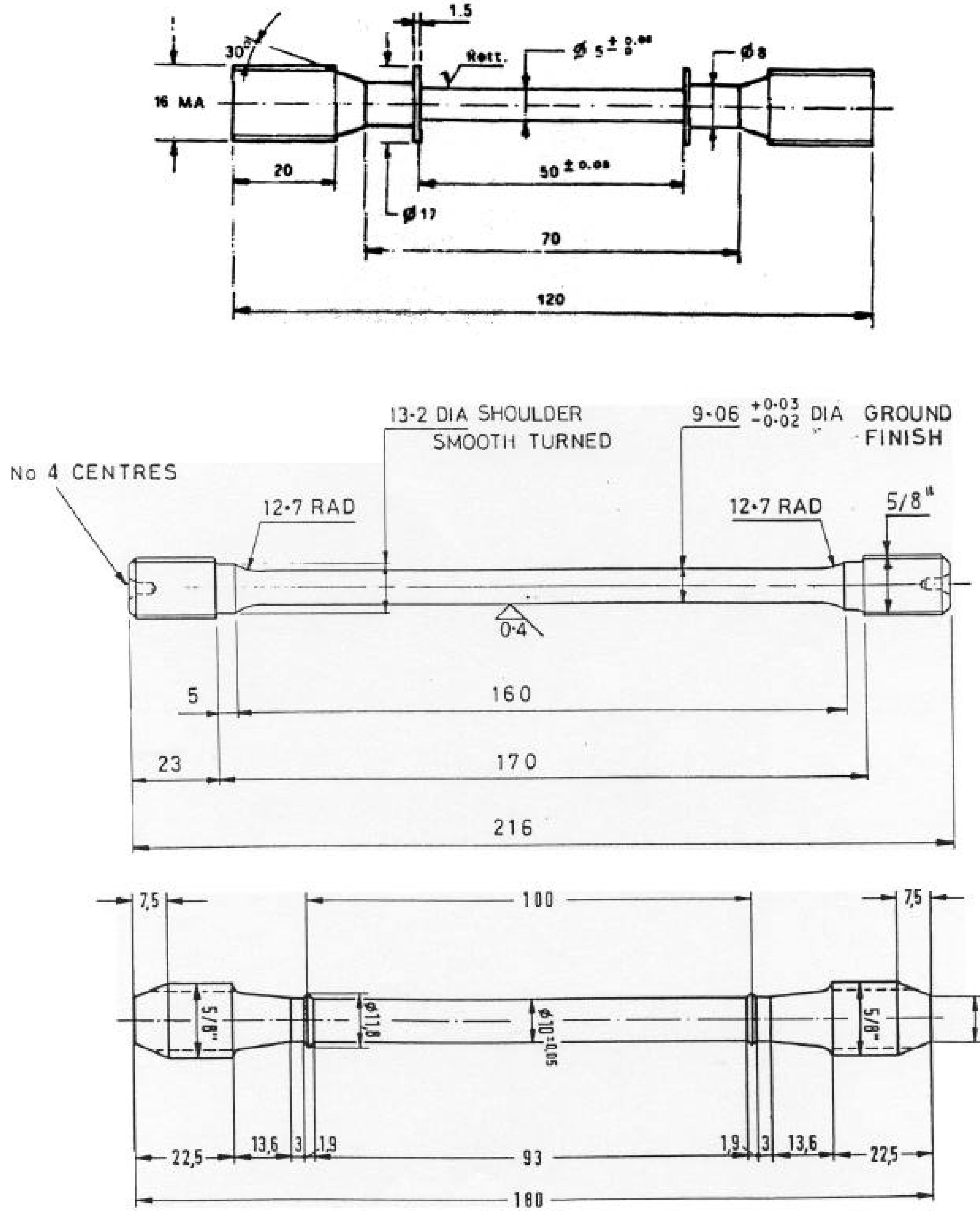

Fig. 2: Shape of specimens used for uniaxial stress relaxation tests.

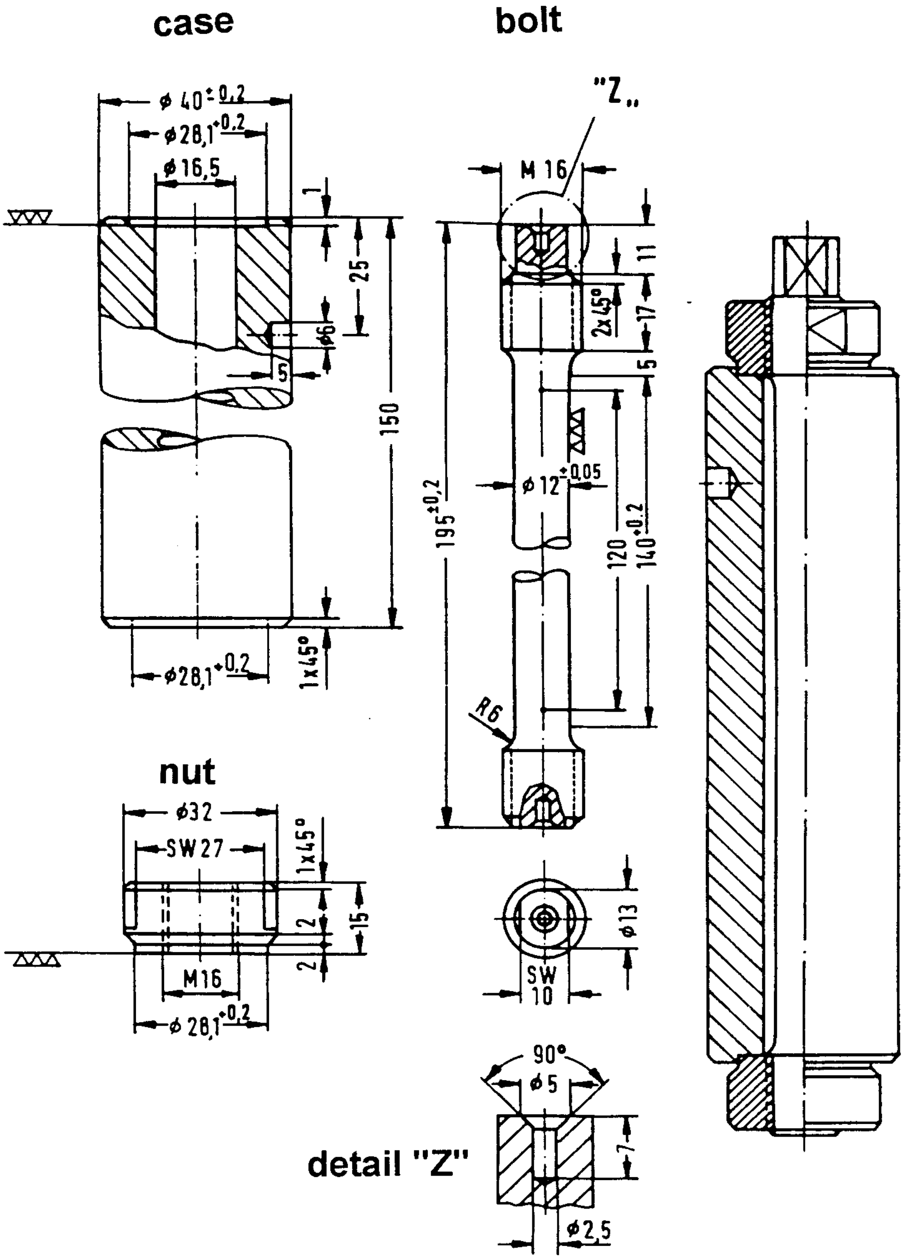

Fig. 3: Shape of the bolt, flange and nut of a model bolt type a (for mechanical extensometry)

Standards, Tests and Machine Type

	0	1	2	3	4	5	6	7
0	Standard	SEP, Relaxation Test, uniaxial	BS 3500, part 6	ASTM E328-86	JIS Z 2276	Comments	Min. Requirements for Existing Data	Min. Requirements for Future Data
0	Standard	Entspannungsversuch ... unter einachsiger Zugbeanspruchung, SEP-Entwurf, 1984	BS 3500, part 6, 1969 (approved 1987)	ASTM E328-86 Stress Relaxation Tests	JIS Z 2276 - 1975 Tensile Stress Relaxation Test	3 standards, 1 draft standard		
1	Doc. 5524/WG1/	16	19	27	43			
2	Test procedure	stress relaxation tests, uniaxial (RU), using tensile testpieces						
4	Machine type	Equipment for relaxation testing, servocontrolled	automatic or manual load adjustment	automatic control to maintain constant constraint	automatic or manual load adjustment	lever-manual, lever-auto, servo-electric, servo-hydraulic	all types (practical limits on test duration for servo-hydraulic)	all types (practical limits on test duration for servo-hydraulic)
5	Atmosphere	air assumed	air assumed	air assumed	air	air	air assumed	air assumed

Temperature Treatment and Measurement

	0	1	2	3	4	5	6	7
0	Standard	SEP, Relaxation Test, uniaxial	BS 3500, part 6	ASTM E328-86	JIS Z 2276	Comments	Min. Requirements for Existing Data	Min. Requirements for Future Data
6	Temperature range	up to 1000°C (no limit given)	up to 1000°C (or above)	up to 1000°C (no limit given)	RT - (>)1000°C (no limit given)			
7	Temperature tolerances	≤600°C : ±3°C ≤800°C : ±4°C ≤1000°C : ±6°C	≤600°C : ±3°C ≤800°C : ±4°C ≤1000°C : ±6°C (for t > 100h)	≤600°C : ±3°C ≤800°C : ±4°C ≤1000°C : ±5°C	≤600°C : ±3°C ≤800°C : ±4°C ≤1000°C : ±6°C		±3°C (indicated) ±4°C (indicated) ±6°C (indicated)	±3°C (total) ±4°C (total) ±5°C (total)
8	Temp measurement equipment tolerance			acc. to ASTM E139				±0.5°C
9	Measurement equipment resolution		≤0.5°C					±0.1°C
10	Thermocouple (tc) type	long-term or above 500°C: rare metal (r.m.)	(b.m.) r.m.; small wire diam recommended		sufficiently durable for long times at temp		base metal (b.m.) or rare metal (r.m.)	new b.m. only for ≤400°C & ≤1000h, else r.m.
11	Min. number of tcs.	3/testpiece	3/testpiece (L<50mm: 2/tp)		3/testpiece		2/testpiece (depending on gauge length)	3/testpiece
12	Calibr. interval, tc.	r.m.: ≤600°C: 3yr 600-800°C: 2yr >800°C: 1yr b.m.: more often	as BS 3500, p 3					b.m.: only new, r.m.: 4yr (<600°C), 2yr (600-800°C), 1yr (800-1000°C)
13	Temperature calibration	in situ			/ JIS C 1602			acc to IEC584-2 (1989) Class 1 or against fixed point cal. tc traceable to Intern. unit
14	Cal. interval, Temp measuring device	regularly	≤1yr					1yr
15	Frequency of temp.-measurement	cont. recording		continously or periodically			sufficient	sufficient

Loading procedure, Load control and Miscellaneous

	0	1	2	3	4	5	6	7
0	Standard	SEP, Relaxation Test, uniaxial	BS 3500, part 6	ASTM E328-86	JIS Z 2276	Comments	Min. Requirements for Existing Data	Min. Requirements for Future Data
16	Initial conditions	to spec. value of ε_i	to spec. value of const. strain or initial stress		to spec. value of ε_i or σ_i	ε_i or σ_i permissible		
17	Load tolerance	±1%	±1%	±1%	±0.5% (up to 20t)		±1%	±1%[17)]
18	Limits on target strain. ε_t : $\Delta l/L_0$ (%)	±0.0025%		±0.0025%	{at RT: ≤ 1μm}			±0.0025%
19	Loading time/ loading rate	max. 30 min, without impact or vibration	without shock (loading rate should be the same in a test series)	with constant strain- or stress rate rapidly, with-out shock	without shock	loading rate may have influence, 30 min is too long	<30 min, without shock or vibration	<10 min, without shock/vibration[19)]; rate same through-out test series ($\dot{\sigma}$ or $\dot{\varepsilon}$ should be stated)
20	Preloading				$\leq 0.1 \cdot \sigma_i$			
21	Misalignment strain		check at RT: ≤10% diff. between opp. transducers	≤15% diff. between two transducer readings	minimised			≤10% difference between ε readings from opposite transducers[21)]
22	Lab. air temp.			±3 °C				±3°C
23	Test duration							
24	Tol. of test time		±1 %					±1%
25	Heating/soaking time	max. 20h (heating T/2 to T: 0.5-5h)	≤1h at T (24h with heating)	suff. to reach thermal equilibrium	16 to 24h (heat-ing time >1 h)	range too wide from ≤1h up to 16 - 24h		<24h, with >1h at T

17) the ±1% tolerance should be for the expected $\sigma_e > \sigma > \sigma_R$ range

19),21) to be reconsidered on availability of results from BCR stress relaxation programme

Specimen details

	0	1	2	3	4	5	6	7
0	Standard	SEP, Relaxation Test, uniaxial	BS 3500, part 6	ASTM E328-86	JIS Z 2276	Comments	Min. Requirements for Existing Data	Min. Requirements for Future Data
26	Cross section area S_0 (mm^2)	≥12.5						
27	Diameter d_0 (mm)	≥4			10 (also 6, 8, 12)		≥4	≥5 (≥ 8 preferred)
28	Transition radius R (mm)	$\geq d_0/4$						$d_0/2 \geq R \geq d_0/4$
29	Shape tolerance			eccentricity thread/gauge l. ≤0.01 mm				±0.02mm
30	Variation of diameter in gauge length	±0.02mm		$d_0$12.7: ±0.2% 9.5 : ±0.3% 6.4 : ±0.4% 2.5 : ±0.5%	±0.04mm			see 29
31	Test piece machining tolerance							see 29
32	Diameter measuring tolerance	0.01mm	0.01mm		0.2% (0.02mm for d_0=10mm)		0.01mm	0.005mm
33	Reference length L_r (mm)	$\geq 3d_0$ (prefer $5d_0$); (but ≥20mm)			100mm (≥50mm)		$\geq 5d_0$	$\geq 10d_0$ (≥100mm preferred) [33)]
34	Tolerance of L_r	±0.1mm						≤1%

[33)] L_r calculated with n = 1

Strain measurement

	0	1	2	3	4	5	6	7
0	Standard	SEP, Relaxation Test, uniaxial	BS 3500, part 6	ASTM E328-86	JIS Z 2276	Comments	Min. Requirements for Existing Data	Min. Requirements for Future Data
35	Strain measurement		on opposite sides	on opposite sides				on opposite sides
36	Strain measurement device / type		extensometer, averaged m. from both sides					
37	Strain tolerance /calibration		/acc. BS 3846: for ε_t $\leq$0,2%: grade B $\leq$0,5%: grade C >0,5%: grade D		1 µm (at RT)			± max[0.01Δl, 3µm] (ISO 9513)
38	Tolerance of ε_t, as control value	relative, $\Delta\varepsilon/\varepsilon_t$: ±1 %	relative: ±1% {= ±2µm for ε_t=0,2% and L= 100mm}	absolute: 0.0025%	relative: ±1.5% {Δε ≤[±?]8µm for „step-down test"; results may prov. be used}		±1.5%	± max[0.01ε_t, 0.0025% absolute]
39	Frequency of load/stress readings	continous record/ suffficient readings	continous / sufficient frequ.		continous/ sufficient frequ.		sufficient	sufficient

Results

	0	1	2	3	4	5	6	7
0	Standard	SEP, Relaxation Test, uniaxial	BS 3500, part 6	ASTM E328-86	JIS Z 2276	Comments	Min. Requirements for Existing Data	Min. Requirements for Future Data
40	Test parameter ε_t loading rate	 ✓ 	 ✓ ✓	 ✓ 			 ✓ 	 ✓ ✓ (or strain rate)
41	Test results σ_0 σ_R	 ✓ as f(t)	 ✓ as f(t)	 ✓ as f(t)	 ✓ as f(t)		 ✓ ✓	 ✓ ✓
42	Derived test results[42a)] σ_{rel} (= σ_0-σ_R) rel. rate $\Delta\sigma/\Delta t$ (σ_0-σ_R)/σ_0 [42b)]			 ✓	 ✓ ✓ 			
43	Other results to report	plot stress-strain-diagram during loading >> $E_{T(S)}$	plot stress-strain-diagram during loading	meas. of "elastic springback"	plot stress-strain-diagram during loading >> $E_{T(S)}$			σ–ε–diagram ; eval. of $E_{T(S)}$ [43)]

42a) as requ. by standard and/or customer
42b) "fraction initial relaxed stress" (ASTM E328-86)
43) to be within ±10% of expected value for material

Standards, Tests and Machine Type **table 1**

	0	1	2	3	4
0	Standard	SEP 1260, Model Bolt	Comments	Min. Requirements for Existing Data	Min. Requirements for Future Data
0	Standard	Relaxationsversuch ... mit Schraubenverbindungsmodellen, SEP 1260, Entwurf 1993	draft standard		
1	Doc. 5524/WG1/	17			
2	Test procedure	model bolt relaxation tests (MB)	isothermal exposure of tightened model bolts		
4	Equipment	furnace		furnace: all types	furnace: all types (forced air draft furnace preferred)
5	Atmosphere	air assumed	air assumed	air	air

Temperature Treatment and Measurement **table 2**

	0	1	2	3	4
0	Standard	SEP 1260, Model Bolt	Comments	Min. Requirements for Existing Data	Min. Requirements for Future Data
6	Temperature range	up to 800 °C			
7	Temperature tolerances	≤600°C : ±3°C ≤800°C : ±4°C		±3°C (indicated) ±4°C (indicated)	±3°C (total) ±4°C (total)
8	Temp measurement equipment tolerance				±0.5°C
9	Measurement equipment resolution				±0.1°C
10	Type of thermocouple (tc.)			base metal (b.m.) or rare metal (r.m.)	new b.m. only for ≤400°C & ≤1000h, else r.m.
11	Min. number of tcs.	temp. control within used zone of furnace		≥3/furnace (depending on furnace size)[11]	≥5/furnace[11] or 3/testpiece
12	Calibr. interval, tc				b.m.: only new, r.m.: 2yr (<500°C) 1yr (>500°C)[12]
13	Temperature calibration				acc. to IEC584-2 (1989) Class 1 or against fixed point cal. tc traceable to Intern. unit
14	Cal. interval, Temp measuring device				1yr
15	Frequency of temp.-measurement				sufficient

[11] sufficient to guarantee permitted temperature limits within the working zone of the furnace (tcs on dummy tps)

[12] shorter recalibration times due to potential deterioration of tcs due to bolt thread lubricant fumes

Loading procedure, Load control and Miscellaneous **table 3**

	0	1	2	3	4
0	Standard	SEP 1260, Model Bolt	Comments	Min. Requirements for Existing Data	Min. Requirements for Future Data
16	Initial conditions	loading to reqd ε_t by tightening nut (at RT), wrt strain gauge or over-all length measurements, then heating	prevent torsion during loading [unloading by destroying nut or flange (at RT)]		
17	Load tolerance	-	load calculated		
18	Limits on target strain ε_t : $\Delta l/L_0$ (%)			±1%	±1%
19	Loading time/rate	-	no meaning at RT		
20	Preloading	3 times to ε_t (at RT)			3 times to ε_t
21	Misalignment strain				
22	Lab. air temp.	load/unload: RT			±2°C, for strain measurement
23	Test duration	recom.: 0.1 to 30kh (2/decade)			
24	Tol. of test time				±1%
25		max. heating (and cooling) rate 100°C/h		50-100°C/h	100°C/h

Specimen details **table 4**

	0	1	2	3	4
0	Standard	SEP 1260, Model Bolt	Comments	Min. Requirements for Existing Data	Min. Requirements for Future Data
26	Cross section area S_0 (mm^2)				$S_{0[flange]} > 5 \cdot S_{0[bolt]}$
27	Diameter d_0 (mm)	a) 12[27)] b) 15			≥8
28	Transition radius R (mm)				$d_0/2 \geq R \geq d_0/4$
29	Shape tolerance				±0.02mm (±0.15% for longer bolts)
30	Variation of diameter in gauge length				see 29
31	Test piece machining tolerance				see 29
32	Diameter measuring tolerance			0.01mm	0.005mm
33	Length to diameter ratio				a) $L_r / d > 10$ [33)] b) $L_c / d > 5$
34	Tolerance of L_r				

[27) 33)] two test types a) and b); refer to rows 35,36

Strain measurement **table 5**

	0	1	2	3	4
0	Standard	SEP 1260, Model Bolt	Comments	Min. Requirements for Existing Data	Min. Requirements for Future Data
35	Strain measurement	a) between end faces b) on opp. sides			a) axial b) 2 sides
36	Strain measurement device / type	a) mechanical extensometer b) strain gauges		both acceptable	both acceptable
37	Strain tolerance /calibration	resolution: a) 1 μm[37)] b) 1 μm/m			resolution: a) 1 μm[37)] b) 1 μm/m
38	Tolerance of ε_t (initial value at RT)				±1%
39	Frequency of load/stress readings	1 value per model[39)]		1 value for model	1 value for model

[37)] on dial gauge
[39)] standard practice for model bolt stress relaxation tests

Results **table 6**

	0	1	2	3	4
0	Standard	SEP 1260, Model Bolt	Comments	Min. Requirements for Existing Data	Min. Requirements for Future Data
40	Test parameter ε_0 loading rate			✓ -	✓ -
41	Test results σ_0* σ_R	$\sigma_R = E_T \cdot \varepsilon_{eRT}$ [41)]		- ✓	- ✓
42	Derived test results σ_{rel} (= σ_0-σ_R) rel. rate $\Delta\sigma/\Delta t$			- -	- -
43	Other results to report				$E_{T(S)}$ or $E_{T(D)}$ [44)]
44	Add. remarks	same type of material for bolt, flange and nuts			

[41),44)] state, whether $E_{T(S)}$ or $E_{T(D)}$ was used and how it was evaluated (to be within ±10% of expected value for material)

Overview: Labs, standards, test and machine types

	column 0	1	2	3	4	6
row	laboratory	coun-try	used standard	type of test-ing[3)]	type of test machine[4)]	atmos-phere
1	Istituto Ricerce Breda (IRB)	I	ASTM E328	RU	EM / HD / WL(manual control)	air
2	Inst. f. Werk-stoffk. Darm-stadt (IfWD)	D	„Entspannungsvers.“, ASTM E328 ; SEP 1260, Entw. 3.94	RU MB	EM	air
3	Sulzer-Innotec (SI)	CH	„Entspannungsvers.“	RU	WL (weight moved along lever, servocontroled) / PN	air
4	GEC Alsthom (GECA)	UK	BS 3500, part 6	RU MB	EM / WL (weight moved along lever, manual and/or automated)	air
5	ERA Technology	UK	BS 3500, part 6	RU	WL (manual control) / EM	air
6	British Steel, Swinden Labs (BS)	UK	BS 3500, part 6	RU	WL (weight moved along lever; manual control)	air
7	MPA Stuttgart	D	„Entspannungsvers.“; SEP 1260, Entw. 3.94	RU MB	WL (weight moved along lever, servocontroled) *MB: annealing furnace*	air
8	Siemens KWU	D	„Entspannungsvers.“; SEP 1260, Entw. 3.94	RU MB	WL (weight moved along lever, servocontroled)	air
9	MAN Energie	D	SEP 1260, Entw. 3.94	MB	*MB: furnace with air circulation*	air
10	comments 9 labs: 8 x RS, 5 x MB			3) RU = relaxation test, uniaxial MB = model bolts 4) EM = servocontrol, electromechanical, HD = ~, hydraulic, PN = ~, pneumatic WL = weights/levers		
11	recommen-dations					

Relaxation Testing Practices App 2 to Vol 3 [i2], 26.09.1995 **annex 3 / table 2**

Temperature measurement (dim. in °C) {*italics*}= details for MB, if different

col.	0&1	11	12	13	14	15	16	17	18	19
r o w	lab (coun-try)	temp. range (°C)	tot. temp toler-ance (±)	measurement equipment ~ tolerance|	resol.	type of thermo-couple	no. of tcs.	calibration interval	manner of cali-bration	tm frequ-ency
1	IRB (I)	≤1050	≤800: 2	0.5	0.5	S (K for short t)	3/sp.	S: 1y K: before test	contr. of tc&dev. error	suff. rec.
2	IfWD (D)	≤1000	≤600: 3 ≤800: 4 ≤1000: 5	0.3	0.1	S	3/ sp.	≤600: 4y ≤800: 2y ≤1000: 1y	in situ	suff. rec.
3	SI (CH)	≤1100	"" " "", >1000: 6	0.3	0.1	K	3/sp.	new tc: < 1y	comp. with cal. tc	cont. reading
4	GECA (UK)	≤700	3	0.5	0.1	R	3/sp.	1y (or between tests)	BS4937 (NAMAS proc.)	2 min (rec.: 12 h)
5	ERA (UK)	≤1150	≤600:2.5 ≤800:3.5 >800:4.5	0.5	0.1	R	3/sp.	1y (or between tests)	against nat.stan-dard ref.	10 min
6	BS (UK)	≤700	3	0.5	0.1	R	3/sp.	duration of test	in simi-lar imm. depth	1 h (rec.: 8 h)
7	MPA (D)	≤650 (possib. ≤1000)	as 2	0.3	0.1	K (future: S)	3/sp. {*0.5 to 3/MB**}	4000 h (dep. from T)	in situ	suff. rec.
8	KWU (D)	≤1100	as 2 , >1000:5	0.3	0.1	S	3/sp.	before test	comp. with cal. tc	suff. rec.
9	MAN (D)	≤650	≤650: 3 ≤650: 4	0.5	0.1	K / S	5/ furnace	6 month	in situ	cont. rec.
10	com-ments	RU: up to 1150					*dep. on no. of MB's			
11	recom-menda-tions						3/sp (or 2/sp for short L_0)			

Loading --- A) Uniaxial Tests (RU)

col.	1&2	A20	A21	A22a	A22b	A22c
row	lab (country)	indicated ΔT (short term)	Loading procedure	Load tolerance	Sensitivity, smallest step in load ΔF (caused Δl_{con})[22b)]	Δl_{tem}, caused by ΔT (short term)
1	IRB (I)	no	HD(EM): strain controlled; WL: mixed mode	HD: ±1%	WL: 10 N (0.04 μm)	no
2	IfWD (D)	±1	stress or strain controlled	±1%	$\Delta l = 0.3 \mu m$ ($\Delta F = 31$ N)	2 μm
3	SI (CH)	-	load/stress or strain controlled possible	±1%	10 N (0.05 μm)	--
4	GECA (UK)	<0.5	load/stress controlled	≤ 1% {± ?}	10 N (0.06 μm)	0.9 μm
5	ERA (UK)	-	load/stress or strain controlled	±1%	10 N (0.10 μm)	--
6	BS (UK)	0.5	load/stress or strain controlled, as required	±1%	22 N (0.28 μm)	0.8 μm
7	MPA (D)	±1	load/stress controlled	±1%	4 N (0.03 μm)	2.5 μm
8	KWU (D)		load/stress or strain controlled	±1%	10 N (0.08 μm)	
9						
10	comments				[22b)] $\Delta l_{con} = \Delta F \cdot L_0 / E \cdot S_0$ (with E = 155 000 MPa) [22c)] $\Delta l_{tem} = \alpha \cdot \Delta T \cdot L_0$ (with $\alpha = 12.5 \cdot 10^{-6}$/K)	
11	recommendations		load/stress or strain control is applicable			

Loading --- A) Uniaxial Tests (RU)

col.	1&2	A23	A24	A25	
row	lab (country)	loading time	Preloading	method to minimize bending	
1	IRB (I)	≤ 30 sec ≈5 min	HD(EM): 0 WL: $0.1 \cdot F_{max}$	- alignment proc. (strain gauge based) - universal joints	
2	IfWD (D)	≤ 30 sec (0.3-0.7 %/min)	$\leq 0.1\sigma_c$	contr. testpiece with strain gauges before test / balanced readings of 2 transducers	
3	SI (CH)	max. 180 N/s possible	200 - 1000 N (d_0=8[?]: 4 - 20 MPa)	no	
4	GECA (UK)	< 3 min	250 N	bal. readings of 2 transducers (at RT and T), diff. must be ≤5%	
5	ERA (UK)	< 5 min	500 N (7.7 MPa)	at RT determination and adjustment	
6	BS (UK)	≤ 10 min	at RT to check extensometer	balanced readings of 2 transducers	
7	MPA (D)	< 3 min	800 N (10.5 MPa)	balanced readings of 2 transducers	
8	KWU (D)	< 5 min	200 N	balanced readings of 2 transducers	
9					
10	comments				
11	recommendations				

Loading, Unloading--- B) model bolts (MB)

col.	1&2	B21a	B21b	B21c	B23
row	lab (country)	Loading procedure, tensed up to ε_t <u>at RT</u>	Tolerance of ε_t (± in %)	Unloading procedure	time for heating up to test temperature
1					
2	IfWD (D)	control of length during tightening with mech. extensometer	±1 %	nut destroyed by boring, length meas. before and after	heating up with ≤100 K/h
3					
4	GECA (UK)	using hydraulic jack [1], length measured using extensometer before and after	±1 %	using hydraulic jack, length measured before and after	<24 h
5					
6					
7	MPA (D)	control of total length during tightening with mech. extensometer	±1 %	nut destroyed by mill-cut, length meas. before and after	heating up with 75 K/h
8	KWU (D)			nut destroyed by eroding, length meas. before and after	
9	MAN (D)	strain controlled during tightening with 2 strain gauges		nut destroyed by drilling, strain meas. [2] before and after	2 to 4 h
10	comments	[1] tension on bolt to screw the nut without friction		[2] new gauges after annealing	
11	recommendations			destroying of nut or flange is recommended in SEP 1260	

Miscellaneous (columns with A: for RU only - columns with B for MB only)

col.	1&2	26	A27	B27	28	A29		A30
r o w	lab (coun-try)	laboratory air temperature (°C)	test duration		tolerance of test time	loading up to given $\varepsilon_t \mid \sim \sigma_0$ is reached		soaking time
1	IRB (I)	EM/HD: 28 ±3 WL: 25 ±3	-- ≤ 1 000 h -- ≤ 10 000 h		-- 0.01 h -- 0.1 h	X		16 - 24 h (heating included)
2	IfWD (D)	24 ±3	as long as needed, typical range 100 - 3000 h	up to 30 000 h	A: 1% B: max (1%,1h)	X	X	2 - 4 h
3	SI (CH)	23 ±1				X		
4	GECA (UK)	contr. within ±0.5	up to 30 000 h (mostly below 600 °C)	up to 30 000 h (<600°C)	<<1%		X	< 24 h
5	ERA (UK)	22	35 000^{+} / >800 °C: >1000h		0.1 h	X	X	1 - 24 h
6	BS (UK)	20 ±2	≤ 40 000 h		±1%	X	X	1 h
7	MPA (D)	22 ±2	as long as needed (typical ≤ 3000 h)	max. 45 000 h	1h (short term <1%)	X		2 to 4 h
8	KWU (D)	20 ±2	as long as needed (typical ≤ 1000 h)		<1%	X	X	4 h
9	MAN (D)	RT		up to 30 000 h (60 000 h)	<1%			
10	com-ments	(shields can be used to prevent draught from extensometer)						
11	recom-menda-tions	±3 for extensiometry						

Test Specimen A) Uniaxial Tests (RU)

col.	1&2	A31	A32,33	A34	A35	A36	A37	A38	A39
row	lab (country)	S_0 (mm^2)	d_0 (shape within gauge l. [32]) (mm)	R (mm)	shape tol. (±mm)	mach. tol. (±mm)	meas. tol. (±mm)	ref. lgth. L_r (mm)	tolerance of L_r (±mm)
1	IRB (I)	19.6 to 78.5	5, 8, <u>10</u> (c.d.)	conical 30°	0.010	0.050	0.010	50 ($5d_0$)	0.05
2	IfWD (D)	49 to 62	7.9 to 8.9 (g.d.)	≈0.3 d_0	0.010		0.002	80 (≈$10d_0$)	0.10
3	SI (CH)	15 to 50	4.5 to 8 (c.d.)	0.25 to 0.5·d_0	0.020		0.010	(3.5 to 5·d_0)	0.10
4	GECA (UK)	162	14.4 (c.d.)	$R \leq d_0$	0.02	0.01	0.005	125 ($10d_0$)	0.05
5	ERA (UK)	64.5	≈9 (c.d.)	≈d_0	0.03	0.013	0.005	101.6 ($11.2d_0$)	0.1
6	BS (UK)	63.6	9 (c.d.)	$R \leq d_0$	0.03	0.03	0.01	125 ($14d_0$)	0.1 ÷ 0.15
7	MPA (D)	78.5	10 (c.d.)	conical 6°	0.02		0.01	100 ($10d_0$)	0.01
8	KWU (D)	78.5	10 (c.d.)		0.01		0.01	100 ($10d_0$)	0.1
9									
10	comments		[32] c.d.: const. diameter g.d.: greater diam. near the ends						
11	recommendations								

Test Specimen B) model bolts (MB)

col.	1&2	B31	B32,B33	B33a	B34	B35	B36	B37	B38	B39
r o w	lab (coun-try)	S_0 (mm^2)	d_0 (shape [32]) (mm)	ratio $\frac{S_{0[flange]}}{S_{0[bolt]}}$	R (mm)	shape tol. (±mm)	mach. tol. (±mm)	meas. tol. (±mm)	ref. lgth. L_0 (mm)	tolerance of L_0 (±mm)
1										
2	IfWD (D)	113	12 (g.d.)	2.7 9.1 or other	6	0.010		0.002	153 87 or other	0.1
3										
4	GECA (UK)	2262	OD 57,2 ID 19,8	16		0,06		0,01	254	
5										
6										
7	MPA (D)	113	12 (c.d.)	9.22	0.5d_0	0.02		0.01	153 (l_{cyl}=140)	
8	KWU (D)									
9	MAN (D)	176.7	15 (c.d.)			0.01		0.01	10 [9]	-
10	com-ments								[9] strain gauges used	
11	recom-menda-tions									

Strain Measurement, readings -- A) Uniaxial Tests (RU)

col.	1&2	A40	A42	A43	A45
row	lab (country)	s.m. on opposit sides?	s.m. device/ type	tolerance of s.m. in % absolut, ± (calibration)	frequency of load/stress readings
1	IRB (I)	yes	extensometer	EM/HD: 0.0005 mm WL: 0.0001 mm	-- continously -- sufficient r.
2	IfWD (D)	yes	extensometer	max (0.01%,0.010mm) {max (0.01%,0.003mm) in future}, (gauge block)	continuous recording
3	SI (CH)	yes	extensometer	0.001 mm	autom. reading via computer, can be selected
4	GECA (UK)	yes	extensometer	0.001 mm {0.0069 %} (BS 3846)	<1h: frequently, 1/h to 24 h; 3/day to 72 h; 1/day thereafter
5	ERA (UK)	yes	extensometer	0.002 % (BS 3846)	sufficient meas., dependent on material and temperature
6	BS (UK)	yes	extensometer	0.010 % (BS 3846)	As required to adjust ε_t within ±1%
7	MPA (D)	yes	extensometer	{Δl=0.002mm} 0.002%	cont. recording
8	KWU (D)	yes	extensometer	0.001 mm	sufficiant meas.
9					
10	comments				
11	recommendations				

Test results -- A) Uniaxial Tests (RU)

col.	1&2	A46a	A46b	A47a	A47b	A47c	A47d	A47e	A48a	A48b
		Test parameter		Test results					T. res., derived	
row	lab (country)	E	$E_{T(S)}$	ε_{e0}	ε_i	$\varepsilon_p(t)$	ε_p, contr. at RT	σ_0, $\sigma_R(t)$	σ_{rel}	σ_{rel} / t
1	IRB (I)	X	X		X	X	X	X	X	
2	IfWD (D)	X	X	X (from hot tensile test)	X			X	X	X
3	SI (CH)		X	X	X	X	X	X	X	X
4	GECA (UK)	X	X	X	X	X		X	X	X
5	ERA (UK)	X	X	X	X	X	X	X	X	X
6	BS (UK)	X	X	X	X	X		X	X	
7	MPA (D)	X	X	X	X	X	X	X	X	
8	KWU (D)		X	X	X	X		X	X	
9										
10	comments									
11	recommendations									

Test results -- B) model bolts (MB)

col.	1&2	B46	B47a	B47e	B47d	
row	lab (country)	used value for $E_{T(S)}$	$\varepsilon_{e\text{-end}}$	$\sigma_{R\text{-end}}$	ε_p, meas. at RT	
1						
2	IfWD (D)	determined for test material	X	X		
3						
4	GECA (UK)	determined for test material	X	X	X	
5						
6						
7	MPA (D)	determ. for test material or acc. to standards	X	X	X	
8	KWU (D)					
9	MAN (D)	acc. to mat. standards	X	X	X	
10	comments					
11	recommendations					