TECHNICAL REPORT

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Thermoplastics pipes for the transport of fluids — Methods of extrapolation of hydrostatic stress rupture data to determine the long-term hydrostatic strength of thermoplastics pipe materials

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Tubes thermoplastiques pour le transport des fluides — Méthodes d'extrapolation des essais de rupture sous pression, en vue de la détermination de la résistance à long terme des matières thermoplastiques pour les tubes

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Foreword

ISO (the International Organization for Standardization) is a world-wide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The main task of ISO technical committees is to prepare International Standards. In exceptional circumstances a technical committee may propose the publication of a Technical Report of one of the following types:

- type 1, when the required support cannot be obtained for the publication of an International Standard, despite repeated efforts;

- type 2, when the subject is still under technical development or where for any other reason there is the future but not immediate possibility of an agreement on an International Standard.

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- type 3, when a technical committee has collected data of a different kind from that which is normally published as an International Standard ("state of the art"), for example).

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Technical Reports of types 1 and 2 are subject to review within three years of publication, to decide whether they can be transformed into International Standards. Technical Reports of type 3 do not necessarily have to be reviewed until the data they provide are considered to be no longer valid or useful.

ISO/TR 9080, which is a Technical Report of type 2, was prepared by Technical Committee ISO/TC138 "Plastics pipes, fittings and valves for the transport of fluids".

This Technical Report is the result of considerable discussion within task group 10 of working group 5 of technical committee 138 of the International Organization for Standardization (ISO) (referred to hereafter as ISO/TC138/WG5/TG10) which was entrusted with generation of the Report and is an agreed compromise which incorporates features of several accepted National procedures.

Furthermore it is emphasized that these standard extrapolation methods (SEM) are not intended to be used to disqualify existing procedures to arrive at design stresses or allowable pressures for pipelines from plastics materials nor to disqualify pipelines from materials proven by such procedures which have shown to be satisfactory over long years of experience. The SEM are generally meant to be used to qualify a material for pipes by the introduction of such a material on the market.

At present the SEM are considered to be at a stage where they need to be tested with real data. Therefore the publication as a Technical Report, type 2, was considered to be justified.

The Committee wishes to have comments which will be based on analysis of pipe stress rupture data using one or both of the procedures. By generating constructive criticism the SEM can be improved and, if necessary, modified.

Comments of a general nature, for example, pertaining to the theoretical basis for the concept of the SEM, are unlikely, at this stage, to be useful. Many such submissions have already been considered within the study. The need is for pragmatic appraisal of the proposals.

This document is being issued in the type 2 Technical Report series of publications (according to subclause G.6.2.2 of part 1 of the IEC/ISO Directives) as a "prospective standard for provisional application" in the field of thermoplastics pipes for the transport of fluids because there is an urgent need for guidance on how standards in this field should be used to meet an identified need.

This document is not to be regarded as an "International Standard". It is proposed for provisional application so that information and experience of its use in practice may be gathered. Comments on the content of this document should be sent to the ISO Central Secretariat.

A review of this type 2 Technical Report will be carried out not later than two years after its publication with the options of: extensions for another two years; conversion into an International Standard; or withdrawal.

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Annexes A to F form an integral part of this Technical Report. Annex G is for information only.

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Introduction

0.1 General principles

The suitability for use of a plastics pressure pipe is in the first instance determined by the performance under stress of its material of construction taking into account the envisaged service conditions (e.g. temperature).

It is conventional to express this by means of the hoop stress to which a plastics pipe made of the material under consideration is expected to be able to withstand fifty years at an ambient temperature of 20 °C, using water as the test environment.

In certain cases it is necessary to estimate the value for this hoop stress at either shorter life times or higher temperatures, or on occasion both.

The methods given in this report are designed to meet the needs for both estimations. The result obtained will generally indicate the average expected value of hoop stress which can cause failure in the stated time at a stated temperature (the ultimate hoop stress).

In most cases it is necessary to obtain a design value rather than the ultimate value, therefore it is necessary to define an appropriate factor taking into account other relevant material properties as well as aspects of the specific application envisaged.

This technical report provides a definitive procedure incorporating extrapolation by using test data at different temperatures, analysed by curve fitting techniques in conjunction with linear regression analysis.

Those curve fitting techniques are of mathematical character, but the formula used is based on the Eyring deviation of so-called rate processes (see annex G).

In order to assess the predictive value of the model used, it has been considered necessary to make use of the estimated 97,5 % lower confidence limit where the 97,5 % lower confidence limit is equivalent with the lower confidence limit of the 95 % confidence interval. This convention is used in the mathematical calculations to be consistent with literature. This aspect has necessitated the use of statistical techniques. It is recognized that such procedures previously have not been specifically quantified and it is presumed this will be accounted for within the consideration of the choice of the value of the factor to be used to convert the ultimate circumferential stress to a design stress.

The methods can provide a systematic basis for the interpolation of stress rupture characteristics at working life temperature conditions different from the conventional 50 years at 20 °C.

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These methods are not applicable if any chemical attack or degradation effect, such as oxidation or consummation of additives such as stabilisers or anti-oxidants, has been found to occur during the pipe testing programme.

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It is essential that the medium used for pressurizing the pipe has no other effect. In general water is considered to be such a medium. The effect of chemical attack on plastics pressure pipes is a subject of study by ISO/TC138/SC3.

The study necessary to prepare a 'standard extrapolation method' (SEM) has been undertaken by members of ISO/TC138/WG5/TG10, which was first convened as an ad hoc group of WG5 in March 1976. Membership included invited individual experts from France, Germany, the Netherlands, Switzerland, the United Kingdom and the United States of America. In the course of the deliberations it has studied the relevance of procedures identified by Larson Miller and the Goldfein derivation for plastics, National Standards, published technological papers from different countries including the United States of America, the United Kingdom, Canada, Germany, Sweden, the Netherlands, France, and Switzerland. In addition specific statistical tasks have been commissioned from experts in France, the Netherlands, the United Kingdom, the United States of America and Finland. A total of over 200 working documents, the majority of which have been highly technological, have been examined in the course of this study.

Long consideration has been given to resolve which variable should be taken to be the independent variable to calculate the long-term hydrostatic stress. The choice was between time and stress. The basic question to which the method has to give an answer can be formulated in two ways as follows.

a) What is the maximum stress (or pressure) that a given pipe system can withstand at a given temperature for a defined time?

This question is answered if time is chosen to be the independent variable to calculate the long-term hydrostatic strength (σ_{LTHS}).

b) How long will a pipe system last when subjected to a defined stress (pressure) at a given temperature?

This question is answered if the stress (pressure) is chosen as the independent variable to calculate the long-term hydrostatic strength (σ_{LTHS}).

Both questions may be asked by users of existing pipe systems and by intending users, and of new systems. Both questions have equal validity.

When the test data on the pipe under study do not show any scatter and when the pipe material can be described perfectly by the chosen empirical model, the regression with either time independent or stress independent will be identical. This is never so, because testing circumstances are never ideal and the material will not be 100 % homogeneous, therefore the observations will show scatter. Moreover, the model is an idealisation. The calculated regressions will not be identical and the difference between the calculated values will increase as the scatter increases.

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It can be shown that the regression of log time on log stress always gives a lower, more conservative, result than the regression of log stress on log time, caused by the scatter of the data. The choice between the two methods of carrying out the regression analysis (time-independent or stress independent) for the SEM should not allow a possibly unjustified optimistic value.

In order to achieve this all SEM calculations are made using stress as the independent variable.

0.2 Use of the methods

0.2.1 These SEM methods are designed to meet basically two requirements. These are:

a) to estimate the mean hoop stress which a pipe made of the material under consideration is able to withstand for 50 years at an ambient temperature of 20 °C using water as the test environment;

b) to estimate the value for the mean hoop stress at either shorter life times, or higher temperatures, or on occasion both.

0.2.2 There are several extrapolation models in existence, which have different degrees of freedom or a different number of variables, as indicated in figure 0.1. It was decided that the SEM will only consider the models QI and QII, RI and RII as shown in figure 0.1.

In models RI and RII a fourth coefficient has been added. The addition of this fourth coefficient inevitably leads to a better correlation coefficient and lack-of-fit values, because of the additional degree of freedom. It was necessary to add this fourth coefficient, because it has been shown that for certain materials (PVC, PVC-C) this leads to better fit.

For other materials (PE and PP) however, good fit is already reached with the model with three coefficients. To add more coefficients will improve the correlation, but leads to more uncertain extrapolation and has therefore not adopted.

0.2.3 Method I of the SEM describes a method to estimate such a mean hoop stress whether a knee is found or not, in accordance with models QI, QII, RI and RII of figure 0.1.

This method is intended for new materials or for materials not previously evaluated for pipe production.

0.2.4 Method II of the SEM describes a method for estimation of the hoop stress at 50 years at a chosen temperature for pipe materials and variations thereof already widely used and under consideration in ISO/TC138 for water and/or gas transport and for industrial pressure pipe applications. This method can only be used if model QI has shown to be applicable.

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0.2.5 The materials have to be tested in pipeform to enable the method to be applied.

0.2.6 The end result of the SEM for a specific material is the value for the long-term hydrostatic strength (σ_{LTHS}) and lower confidence limit (σ_{LCL}).

0.2.7 Methods for use of the σ_{LTHS} and/or σ_{LCL} to arrive at allowable design stresses still have to be considered.

Service factors or safety factors have to be introduced.

An estimate for a safety factor taking into account the effects of testing and estimating stress by extrapolation could be the ratio of the 97,5 % lower confidence level (l.c.l.) and the extrapolated mean hoop stress.

I. Models with constant slope

II. Models with discontinuous change of constant slope

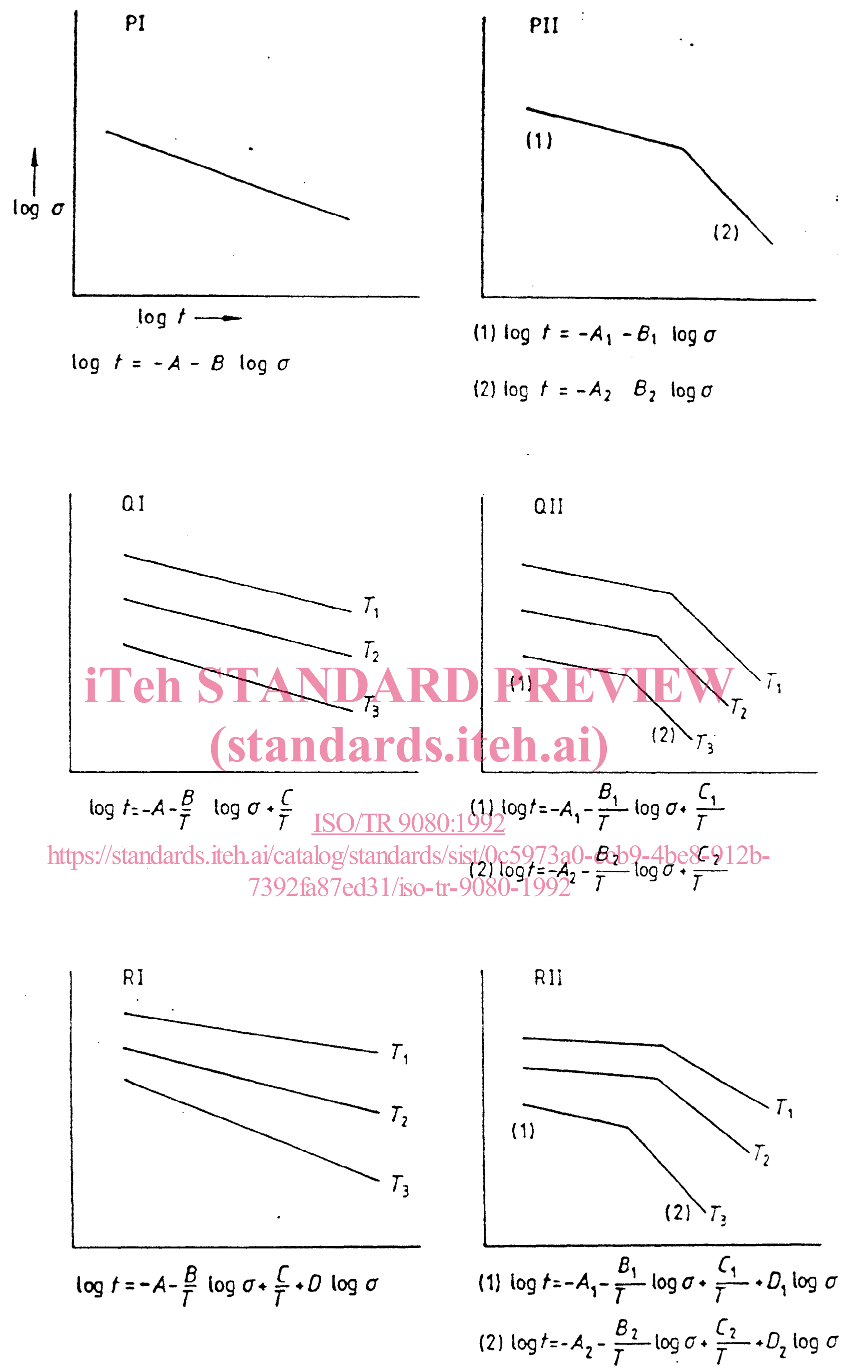

Figure 0.1: Scheme of material behaviour models

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Thermoplastics pipes for the transport of fluids — Methods of extrapolation of hydrostatic stress rupture data to determine the long-term hydrostatic strength of thermoplastics pipe materials

1 Scope

This Technical Report describes methods for estimation of the long-term hydrostatic strength of thermoplastics materials.

The methods are applicable to all known types of thermoplastics and cross-linked thermoplastics pipes at any temperature and to any practicable test medium. The methods were developed on the basis of test data from pipes of relatively small sizes. The pipe sizes to be tested are specified in the relevant product standard.

These methods do not cover effects which are caused by oxidation, hydrolysis, or exhaustion of additives such as anti-oxidants within or outside the testing times. If such effects occur, then other test methods may be appropriate.

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2 Normative references

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The following standards contain provisions which, through reference in this text, constitute provisions of ISO/TR 9080. At the time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on ISO/TR 9080 are encouraged to investigate the possibility of applying the most recent editions of the standards listed below. Members of IEC and ISO maintain registers of currently valid international standards.

ISO 1167 - 1973: Plastics pipes for the transport of fluids - Determination of the resistance to internal pressure

ISO 3126 - 1974: Plastics pipes - Measurement of dimensions

3 Definitions, symbols and abbreviations

For the purposes of this Technical Report, the following definitions apply:

3.1 internal pressure (P): Force per unit area exerted by the medium in the pipe.

3.2 stress (σ): Force per unit area in the wall of the pipe in the hoop direction due to internal pressure. The stress is denoted as σ and derived from the internal pressure using the following equation:

$$\sigma = \frac{P\ (D_{m,max.} - e)}{2 e_{min.}}$$

where

$D_{m,max.}$ is the maximum mean outside diameter;

$e_{min.}$ is the minimum wall thickness.

3.3 test temperature (T): The temperature at which stress rupture data have been determined.

3.4 service temperature (T_s): The temperature at which the pipe will be used.

3.5 failure: Physical breakdown of pipe as manifested by ductile bursting, brittle cracking, splitting or weeping (seepage of liquid through the pipe wall) during testing.

3.6 time-temperature dependent hydrostatic strength (σ_{tTHS}): A quantity with the dimensions of stress which can be considered as a a property of the material under consideration. It is denoted as:

$$\sigma_{tTHS} = \sigma_{(T,\ \log t,\ \alpha)}$$

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where

T is a temperature, in kelvins;

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t is a time, in hours;

α is a factor related to the chance that a pipe, made from the material under study, will survive without failure during a time t when submitted to a stress σ, at a constant temperature.

NOTE - The σ_{tTHS} is derived from the available test data by using one of the methods I or II in accordance with clause 5.

3.7 long-term hydrostatic strength (σ_{LTHS}): A quantity with the dimensions of stress which represents the 50 % lower confidence limit (LCL) for the long-term hydrostatic strength and can be considered as a property of the material under consideration. It equals the mean (average) strength or predicted (average) mean strength at a temperature T and a time t when the factor α has a value of 0,5 (see 3.6). It is denoted as:

$$\sigma_{LTHS} = \sigma_{(T,\ \log t,\ 0{,}5)}$$

3.8 lower confidence limit long-term hydrostatic strength (σ_{LCL}): A quantity with the dimensions of stress which represents the 97,5 % lower confidence limit of the long-term hydrostatic strength and can be considered as a property of the material under consideration. It equals the mean (average) strength or predicted mean (average) strength at a temperature T and a time t when the factor α has a value of 0,975 (see 3.6). It is denoted as:

$$\sigma_{LCL} = \sigma(T, \log t, 0{,}975)$$

3.9 knee: The transition point between two probably different modes of failure represented by a change of slope on a log stress versus log time plot of hydrostatic stress rupture data.

4 Acquisition of test data

4.1 Test conditions

The pipe stress rupture data shall be determined using the procedure described in ISO 1167 - 1973 except that in the case of conflict between that standard and the provisions of this SEM, the provisions of this SEM shall apply.

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The pressure medium inside the pipe shall be water or any other liquid. The outside environment shall be air, water or any other liquid. The inside medium and the outside environment shall be mentioned in the test report. The inside and the outside environment shall be maintained within ± 1 °C, but preferably within ± 0,5 °C of the test temperature during a conditioning period, extending from 15 min before the beginning of the test, and during the test period.

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The mean outside diameter and minimum wall thickness of each pipe test piece shall be determined in accordance with ISO 3126.

4.2 Distribution of pressure levels

For each selected temperature a minimum of 25 failure stress-time points above 10 h shall be obtained, spread over at least 5 pressure levels and such that at each pressure level at least one failure point is recorded. (For statistical reasons it is recommended that more failure points are recorded at each pressure level.) If possible, the pressure levels shall be selected so that at least eight failures will occur between 10 h and 100 h, at least eight failures between 100 h and 1000 h and at least nine failures above 1000 h; however, one shall have at least four of these points above 7000 h and at least one of these points above 9000 h.

Test pieces which have not failed at the lowest pressure levels shall be used in the calculations as failure points if they increase the value of σ_{LTHS}, if not then they shall be deleted.

NOTE - To be able to take advantage of advanced statistical methods it is recommended that the differences between successive pressure levels is arranged to follow the relationship : (delta) log (stress) is constant.

5 Procedure

5.1 Selection of method for data gathering and analysis

Select and perform a method of determination of a long-term hydrostatic strength in the light of the following information.

Two methods for obtaining the long-term hydrostatic strength, σ_{LTHS}, are presented. They are designated as method I, detailed in 5.2 and for which a flow chart is given in annex A, and method II, detailed in 5.3.

Both methods are based on linear regression and supported as applicable by reference to appropriate calculation details given in annex B and a validation test for linearity given in annex C. The choice of method may be specified by a relevant product standard in reference to this Technical Report, and depends on the indication of a knee in the data pattern, for which a statistical test is provided in annex D, and/or on the purpose of the evaluation, as follows.

- **Method I** is the most complete and decisive method for determining burst pressure characteristics. It requires observations at several temperatures and times over one year or longer and is applicable whether or not indications are found in the test data of the presence of a knee. The consequent procedural alternatives are selected as indicated in annex A. The risk that in the extrapolation range the real behaviour will deviate from the predicted behaviour, e.g. because of another change of slope in the burst pressure characteristics, is considered to be minimal, although not zero. Method I is the appropriate method for determining the burst pressure characteristics of new materials.

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- **Method II** is a method in which the required range of experiments is more restricted in the number of temperature levels than in Method I and the observations shall not show any sign of a knee. This method is more suitable for testing new varieties of well-known materials where the polymer itself has not changed.

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5.2 Method I

(See also annex A.)

5.2.1 Required test data

Obtain test data in accordance with clause 4 and using at least three temperatures T_1, T_2, T_3, ...; where $T_1 < T_2 < T_3 < ...$ and the following conditions also apply:

a) each pair of adjacent temperatures shall be separated by at least 10 K;

b) the highest test temperature, $T_{max.}$, shall not exceed the glass transition temperature minus 20 K in amorphous or predominantly amorphous polymers, or the melting temperature minus 15 K in crystalline or semi-crystalline polymers;

c) the number of observations and the distribution of pressure levels per temperature shall comply with 4.2;

d) the maximum test temperature, $T_{max.}$, shall be selected taking into account for each material the maximum temperature at which the material can be used and the highest possible test temperature;

e) the number of observations of class 2 n_2, as given in B.5.2 of annex B, shall at least be 20.

NOTE - To obtain an optimal estimation of a σ_{LTHS} value, it is recommended that the range in test temperatures is selected in such a way that it covers the service temperature or range in service temperatures.

5.2.2 Detection of a knee; validation of data and model

5.2.2.1 Apply linear regression to the observations at every test temperature separately and determine at every test temperature the slope of the regression line and the stress at which 50 % and 2,5 % failure is predicted after 50 years.

For the procedure to calculate these values, see B.3 of annex B.

5.2.2.2 If at one or more temperatures the slope of the regression line b is positive, consider the test data at that temperature or at those temperatures unsuitable.

5.2.2.3 Apply the test for a knee in accordance with annex D. If the presence of a knee is confirmed, apply 5.2.4. Otherwise apply 5.2.2.4.

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5.2.2.4 If the ratio of the slope of the regression line at the lowest temperature, $b_{T\ min.}$ and the slope of the regression line at the highest test temperature, $b_{T\ max.}$, exceeds the value of three, i.e.:

$$\frac{b_{T\ min.}}{b_{T\ max.}} > 3$$

consider this as the possible indication of a knee within the experimental range and apply 5.2.4.

5.2.2.5 If the ratio of the 97,5 % lower confidence limit long-term hydrostatic strength, $\sigma_{(T,\ \log t,\ 0,975)}$ at a time, t_1, of one increment in log time, in hours, beyond the longest testing time and the long-term hydrostatic strength, $\sigma_{(T,\ \log t,\ 0,5)}$ at that time, both at the highest temperature, has a value equal to or below 0,85 i.e.:

$$\frac{\sigma(T_{max.}, \log t, 0{,}975)}{\sigma(T_{max.}, \log t, 0{,}5)} \leq 0{,}85$$

consider this as a possible indication of a knee within the experimental range of the highest test temperature data and apply 5.2.4.

5.2.2.6 Inspect, visually the time-to-failure/stress data points when plotted on a log (time)-log (stress) basis. If a knee appears to be present, apply 5.2.4.

5.2.2.7 If the conditions given in 5.2.2.4, 5.2.2.5 and 5.2.2.6 were not fulfilled, assume that there is no indication of the presence of a knee within the experimental range and apply 5.2.3.

5.2.3 Calculation of log σ_{LTHS} when no knee is found

5.2.3.1 In accordance with the relevant referring product specification or otherwise based on the information given in 5.1 and annex E, apply multiple linear regression to find the coefficients *A*, *B*, *C* and *D* in one of the following equations where the procedure to calculate these values for equation (1) is outlined in B.4 and comparable calculations can be made by applying appropriate mathematics to formula (1a).

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$$\log t = -A - \frac{B}{T} \log \sigma_{LTHS} + \frac{C}{T} \qquad \ldots (1)$$

$$\log t = -A - \frac{B}{T} \log \sigma_{LTHS} + \frac{C}{T} + D \log \sigma_{LTHS} \qquad \ldots (1a)$$

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If the values of A, B and C are not positive, consider the data unsuitable.

5.2.3.2 Calculate the mean strength, $\sigma_{(T, \log t_e, 0{,}5)}$, and the 97,5 %

lower confidence limit (LCL) of the mean strength, $\sigma_{(T, \log t_e, 0{,}975)}$, at a life time t_e and a temperature *T*; and as outlined in B.4, and equation 1a providing that extrapolation time limits given in 5.2.5 are complied with.

5.2.3.3 Apply the lack-of-fit test in accordance with annex C. If the hypothesis of linearity is rejected, reject the model used.

Reject a model if *F* > 20, where *F* is the coefficient of lack-of-fit of the model to the data.

If the linear model (models) is (are) not rejected, apply 5.2.3.4.

5.2.3.4 Choose the model with the lowest value for *F* (lack-of-fit) to describe the experimental data.

With this model calculate the values for the σ_{LTHS} and σ_{LCL} at various times and temperatures.