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INTERNATIONAL STANDARD

NORME INTERNATIONALE

Guide for the statistical analysis of ageing test data –
Part 1: Methods based on mean values of normally distributed test results

Guide pour l'analyse statistique de données d'essais de vieillissement –
Partie 1: Méthodes basées sur les valeurs moyennes de résultats d'essais normalement distribués

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CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

GUIDE FOR THE STATISTICAL ANALYSIS OF AGEING TEST DATA –

Part 1: Methods based on mean values of normally distributed test results

FOREWORD

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International Standard IEC 60493-1 has been prepared by IEC technical committee 112: Evaluation and qualification of electrical insulating materials and systems.

This second edition cancels and replaces the first edition, published in 1974, and constitutes a technical revision.

The main changes with respect to the first edition are that, besides a complete editorial revision, censored data sub-group are considered.

The text of this standard is based on the following documents:

CDV	Report on voting
112/172/CDV	112/192/RVC

Full information on the voting for the approval of this standard can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all the parts in the IEC 60493 series, published under the general title *Guide for the statistical analysis of ageing test data,* can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

INTRODUCTION

Procedures for estimating ageing properties are described in specific test procedures, or are covered by the general documents on test procedures for ageing tests with a specific environmental stress (e.g. temperature, radiation, partial discharges).

In many cases, a certain property is determined as a function of time at different ageing stresses, and a time to failure based on a chosen end-point criterion is found at each ageing stress. A plot of time to failure versus ageing stress may be used to obtain an estimate of the time to failure for similar specimens exposed to a specified stress, or to obtain an estimate of the value of stress which will cause failure in a specified time.

The physical and chemical laws governing the ageing phenomena may often lead to the assumption that a linear relationship exists between the property examined and the ageing time at fixed ageing stresses, or between certain mathematical functions of property and ageing time, e.g. square root or logarithm. Also, there may be a linear relationship between time to failure and ageing stress, or mathematical functions of these variables.

The methods described in this part of IEC 60493 apply to such cases of linear relationship. The methods are illustrated by the example of thermal ageing wherein the case of a simple chemical process it may be assumed that the degradation obeys the Arrhenius law, i.e. the logarithm of time to failure is a linear function of the reciprocal thermodynamic temperature. Numerical examples demonstrating the use of the methods in this case are given in IEC 60216-3 [1][1].

The calculation processes specified in this standard are based on the assumption that the data under examination are normally distributed. No test for normality of the data is specified, since the available tests are unreliable for small sample groups of data. However, the methods have been used for a considerable time without undesirable results and with no check on the normality of the data distributions.

1 Figures in square brackets refer to the bibliography.

GUIDE FOR THE STATISTICAL ANALYSIS OF AGEING TEST DATA –

Part 1: Methods based on mean values of normally distributed test results

1 Scope

This part of IEC 60493 gives statistical methods which may be applied to the analysis and evaluation of the results of ageing tests.

It covers numerical methods based on mean values of normally distributed test results.

These methods are only valid under specific assumptions regarding the mathematical and physical laws obeyed by the test data. Statistical tests for the validity of some of these assumptions are also given.

This standard deals with data from both complete test sets and censored test sets.

This standard provides data treatment based on the concept of "data sub-group" as defined in Clause 3. The validity of the coefficients used in the calculation processes to derive statistical parameters of the data groups are described in [1].

2 Normative references

None.

3 Terms, definitions and symbols

3.1 Terms and definitions

For the purposes of this document, the following terms, definitions and symbols apply.

3.1.1
ordered data
set of data arranged in sequence so that in the appropriate direction through the sequence each member is greater than or equal to its predecessor

Note 1 to entry: "Ascending order" in this standard implies that the data is ordered in this way, the first being the smallest.

3.1.2
order-statistic
each individual value in a set of ordered data is referred to as an "order-statistic" identified by its numerical position in the sequence

3.1.3
incomplete data
ordered data, where the values above and/or below defined points are not known

3.1.4
censored data
incomplete data, where the number of unknown values is known

Note 1 to entry: If the censoring is begun above/below a specified numerical value, the censoring is Type I. If it is begun above/below a specified order-statistic, it is Type II. This standard is concerned only with Type II.

3.1.5
truncated data
incomplete data where the number of unknown values is not known

Note 1 to entry: This report is not concerned with truncated data.

3.1.6
Saw coefficient
one of the coefficients developed by J.G. Saw for calculating the primary statistical functions of a single sub-group

Note 1 to entry: There are four coefficients used in this standard. Saw originally defined five, the fifth being intended for estimating the variance of the variance estimate (see [7]).

3.1.7
degrees of freedom
number of data values minus the number of parameter values

3.1.8
variance of a data group
sum of the squares of the deviations of the data from a reference level

Note 1 to entry: The reference level may be defined by one or more parameters, for example a mean value (one parameter) or a line (two parameters, slope and intercept), divided by the number of degrees of freedom.

3.1.9
central second moment of a data group
sum of the squares of the differences between the data values and the value of the group mean, divided by the number of data in the group

3.1.10
covariance of data groups
for two groups of data with equal numbers of elements where each element in one group corresponds to one in the other, the sum of the products of the deviations of the corresponding members from their group means, divided by the number of degrees of freedom

3.1.11
regression analysis
process of deducing the best-fit line expressing the relation of corresponding members of two data groups by minimizing the sum of squares of deviations of members of one of the groups from the line

Note 1 to entry: The parameters are referred to as the regression coefficients.

3.1.12
correlation coefficient
number expressing the completeness of the relation between members of two data groups, equal to the covariance divided by the square root of the product of the variances of the groups

Note 1 to entry: The value of its square is between 0 (no correlation) and 1 (complete correlation.

3.1.13
data sub-group
single set of data which may be used with other sub-groups to form a compound group

3.2 Symbols

Symbol	Definition
a, b	Regression coefficient
e	Sample (point) estimate of e
e_1	Lower confidence limit of e
e_2	Upper confidence limit of e
f	Number of degrees of freedom
$f(x)$	Probability density
$f_1(t)$, f_3 t)	Arbitrary function of time
$f_2(\theta)$	Arbitrary function of stress
$f_4(p)$	Arbitrary function of property
F	Fisher-distributed stochastic variable
$F(x)$	Cumulative probability distribution
i	Order No. of partial sample
j	Order No. of specimen in partial sample No. i
k	Number of partial samples in total sample
m	Order No. of specimen
n	Number of observations in sample
n_i	Number of specimens in partial sample No. i
N	Total number of specimens
p	Arbitrary property of test specimens
$P(X \leq x)$	Probability that $X \leq x$
s^2	Sample variance
s_1^2	Variance within sets
s_2^2	Variance about regression line
s_{11}^2	Partial sample variance
t	Student-distributed stochastic variable
u	Standardized normal (Gaussian) distributed stochastic variable
x	Independent variable (for example $1/\theta$)
x_i	Partial sample value of x
$\bar{x}$	Sample mean
$\bar{x}$	Weighted mean of x
$\tilde{x}$	Sample median
X	Stochastic variable, specified value of x
y	Dependent stochastic variable (for example log v)
y_{ij}	Individual specimen value of y
$\bar{y}_i$	Partial sample mean of y
$\bar{y}$	Total sample mean of y
Y	Specified value of y
α	Significance level
ε	Arbitrary population parameter
Θ	Thermodynamic temperature/Kelvin
θ	Ageing stress (for example temperature)

Symbol	Definition
ξ	Mean value of X
$\bar{\xi}$	Median value of X
σ	Standard deviation of X
σ^2	Variance of X
χ^2	Chi-square-distributed test variable
$1 - \alpha$	Confidence level

4 Calculation procedures

4.1 General considerations

For these calculations:

– n is the number of values known in subgroup;

– m is the total number in subgroup (= n for complete data group);

– α, β, μ and ε are the "Saw" coefficients for these values of m and n.

For an uncensored subgroup, the values of the "Saw" coefficients are as follows:

$$\alpha = 1/(n-1) \quad (1)$$

$$\beta = -1/(n(n-1)) \quad (2)$$

$$\mu = 1 - 1/n \quad (3)$$

$$\varepsilon = 1 \quad (4)$$

If convenient, these coefficients may be used to calculate the primary statistical functions (mean and standard deviation) of complete data groups, using the formulae of 4.2.3 (in place of the usual formulae as in 4.2.2). "Saw" coefficients are given in Table B.1.

4.2 Single sub-group – Difference of mean and specified value

4.2.1 General

The purpose of the procedure is to test the significance of the difference between the sub-group mean and a specified numerical value.

4.2.2 Complete data sub-group

Calculate sub-group mean

$$\bar{y} = \sum_{i=1}^{n} y_i / n \quad (5)$$

Calculate sub-group variance

$$\sigma^2 = \frac{\left(\sum_{i=1}^{n} y_i^2 - n\bar{y}^2\right)}{(n-1)} \quad (6)$$

Calculate t $$t=\bar{y}/\sqrt{\sigma^2/n} \tag{7}$$

Compare the value of t with the tabulated t values.

4.2.3 Censored data sub-group

Calculate sub-group mean $$\bar{y}=(1-\mu)y_n+\mu\sum_{j=1}^{n-1}\frac{y_j}{(n-1)} \tag{8}$$

Calculate sub-group variance $$\sigma^2=\alpha\sum_{j=1}^{n-1}\left(y_n-y_j\right)^2+\beta\left[\sum_{j=1}^{n-1}\left(y_n-y_j\right)\right]^2 \tag{9}$$

Calculate adjustment for t $$a=\frac{(1-n/m)}{(6{,}2+n/6{,}4-(m-n)/10{,}7)} \tag{10}$$

Calculate t $$t=\bar{y}/\sqrt{\varepsilon\sigma^2/n} \tag{11}$$

Calculate t_a $$1/t_a=1/t+a \tag{12}$$

Compare the value of t_a with the tabulated t values.

4.3 Two subgroups – Difference of means

4.3.1 General

The purpose of this procedure is to test the significance of the difference between the sub-group means.

For these calculations:

– n_i is the number of values known in subgroup i;

– m_i is the total number of values in subgroup i;

– α_i β_i μ_i and ε_i are the "Saw" coefficients for these values of m and n.

For a complete sub-group, ε_i =1.

4.3.2 Both sub-groups complete

Calculate sub-group means $$\bar{y}_i=\sum_{j=1}^{n_i}y_{ij}/n_i \tag{13}$$

Calculate sub-group variances $$\sigma_i^2=\frac{\left(\sum_{j=1}^{n_i}y_{ij}^2-n\bar{y}_i^2\right)}{(n_i-1)} \tag{14}$$

Calculate the group value of ε

$$e=\left(\frac{\varepsilon_1}{n_1}+\frac{\varepsilon_2}{n_2}\right) \quad (15)$$

Calculate the merged variance σ^2

$$\sigma^2=\frac{\left((n_1-1)\sigma_1^2+(n_2-1)\sigma_2^2\right)}{(n_1+n_2-2)} \quad (16)$$

Calculate t

$$t=\frac{(\bar{y}_1-\bar{y}_2)}{\sqrt{e\sigma^2}} \quad (17)$$

Determine probability by reference to tabulated values of t.

4.3.3 One or both subgroups censored

Calculate sub-group variances

$$\sigma_i^2=\alpha_i\sum_{j=1}^{n_i-1}\left(y_{in_i}-y_{ij}\right)^2+\beta_i\left[\sum_{j=1}^{n_i-1}\left(y_{in_i}-y_{ij}\right)\right]^2 \quad (18)$$

Calculate sub-group means

$$\bar{y}_i=(1-\mu_i)y_{in_i}+\mu_i\sum_{j=1}^{n_i-1}\frac{y_{ij}}{(n_i-1)} \quad (19)$$

Calculate the group value of ε

$$e=\left(\frac{\varepsilon_1}{n_1}+\frac{\varepsilon_2}{n_2}\right) \quad (20)$$

Calculate the merged variance σ^2

$$\sigma^2=\frac{\left((n_1-1)\sigma_1^2+(n_2-1)\sigma_2^2\right)}{(n_1+n_2-2)} \quad (21)$$

Calculate t

$$t=\frac{(\bar{y}_1-\bar{y}_2)}{\sqrt{e\sigma^2}} \quad (22)$$

Calculate adjustment, a

$$a=\frac{p}{(n_1+n_2)^2}\left[\frac{n_1}{m_1}-\frac{n_2}{m_2}\right]\left[\left(\frac{(n_1+n_2)}{20}\right)^2+2\right] \quad (23)$$

where p is the smaller of n_1 and n_2.

Apply adjustment

$$t_a=\frac{1}{\left(\frac{1}{t}+a\right)} \quad (24)$$

Determine probability by reference to tabulated values of t.

4.4 Two or more subgroups – Analysis of variance

Individual sub-groups may be complete or censored.

For these calculations:

n_i	is the number of values known in subgroup i;
m_i	is the total number in subgroup i;
α_i, β_i, μ_i and ε_i	are the “Saw” coefficients for these values of m and n;
k	is the number of subgroups;
c	is the intermediate value for χ^2 calculation;
A	is the adjustment factor for χ^2 calculation.

Calculate the total number of values $$M = \sum_{i=1}^{k} m_i \quad (25)$$

Calculate the total number of values known $$N = \sum_{i=1}^{k} n_i \quad (26)$$

Calculate subgroup means:

$$\bar{y}_i = (1-\mu_i) y_{in_i} + \mu_i \sum_{j=1}^{n_i-1} \frac{y_{ij}}{(n_i-1)} \quad \text{(Censored data)}$$

$$\bar{y}_i = \frac{\sum_{j=1}^{n_i} y_{ij}}{n_i} \quad \text{(Complete data subgroup)} \quad (27)$$

Calculate group general mean $$\bar{\bar{y}} = \frac{\sum_{i=1}^{k} n_i \bar{y}_i}{N} \quad (28)$$

Calculate sub-group variances:

$$s_i^2 = \alpha_i \sum_{j=1}^{n_i-1} \left(y_{in_i} - y_{ij}\right)^2 + \beta_i \left[\sum_{j=1}^{n_i-1} \left(y_{in_i} - y_{ij}\right)\right]^2$$

$$s_i^2 = \frac{\sum_{j=1}^{n_i} \left(y_{ij}^2 - n_i \bar{y}_i^2\right)}{(n_i-1)} \quad \text{(Complete data subgroup)} \quad (29)$$

Calculate mean variance factor $$\varepsilon = \frac{\sum_{i=1}^{k} \varepsilon_i}{k} \quad (30)$$

Calculate variance of means
$$s_N^2 = \frac{\left[\sum_{i=1}^{k} n_i \bar{y}_i^2 - N\,\bar{\bar{y}}^2\right]}{(k-1)} \qquad (31)$$

Calculate residual variance
$$s_D^2 = \frac{\varepsilon\left[\sum_{i=1}^{k} s_i^2 (n_i - 1)\right]}{(N-k)} \qquad (32)$$

Test equality of subgroup variances:

Calculate c
$$c = 1 + \frac{\left[\sum_{i=1}^{k} \frac{1}{(n_i - 1)} - \frac{1}{(N-k)}\right]}{3(k-1)} \qquad (33)$$

Calculate adjustment factor
$$A = 1 + \frac{\left(1 - \frac{N}{M}\right) \times \left(1 - \frac{12}{M}\right)}{2} \qquad (34)$$

Calculate χ^2
$$\chi^2 = \frac{A}{c}\left[(N-k)\ln\left(\frac{s_D^2}{\varepsilon}\right) - \sum_{i=1}^{k}(n_i - 1)\ln\left(s_i^2\right)\right] \qquad (35)$$

Test equality of residual variance and variance of subgroup means.

Calculate F
$$F = \frac{s_N^2}{s_D^2} \qquad (36)$$

Degrees of freedom for F $N - k$ (denominator), k *-1* (numerator)

Calculate significance of general mean:

Calculate t
$$t = \bar{\bar{y}}\sqrt{\frac{N}{s_T^2}} \qquad (37)$$

Adjust t for censoring
$$1/t_a = 1/t + a \qquad (38)$$

Determine probability by reference to tabulated values of t with N-1 degrees of freedom.

4.5 Three or more subgroups – Regression analysis

4.5.1 Regression analysis – General considerations

These data differ from those of (4.4) in that the y-values in each subgroup are associated with a value of another variable, referred to in this section as x_i. The objective of the analysis is to determine whether there is a linear relationship between x and y and, if so, its parameters and properties.