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Hydraulic fluid power — Methods to assess the reliability of hydraulic components

Part 1: General procedures and calculation method

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British Standards

National foreword

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General procedures and calculation method

Transmissions hydrauliques — Méthodes d'évaluation de la fiabilité des composants hydrauliques —

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Contents

Page

Foreword

ISO (the International Organization for Standardization) is a worldwide 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.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

In exceptional circumstances, 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), it may decide by a simple majority vote of its participating members to publish a Technical Report. A Technical Report is entirely informative in nature and does not have to be reviewed until the data it provides are considered to be no longer valid or useful.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO/TR 19972-1 was prepared by Technical Committee ISO/TC 131, *Fluid power systems*, Subcommittee SC 8, *Product testing*.

ISO/TR 19972 consists of the following parts, under the general title *Hydraulic fluid power — Methods to assess the reliability of hydraulic components*:

— *Part 1: General procedures and calculation method*

It is possible that other parts will be developed in the future.

Introduction

In hydraulic fluid power systems, power is transmitted and controlled through a liquid or gas under pressure within an enclosed circuit. Fluid power systems are composed of components, and are an integral part of various types of machines and equipment. Efficient and economical production requires highly reliable machines and equipment.

Machine producers need to know the reliability of the components that comprise their machine's fluid power system. Once they know the reliability characteristic of the component, the producers can model the system and make decisions on service intervals, spare parts inventory and areas for future improvement.

There are different methods used to investigate component reliability.

A preliminary design analysis is useful to identify potential failure modes and to reduce their effect on reliability. In addition, calculation of failure rates is possible. When prototypes are available, in-house laboratory reliability tests are run and initial reliability can be determined. Reliability testing is often continued into the initial production run and throughout the production lifetime as a continuing evaluation of the component. Collection of field data is possible when products are operating and data on their failures are available. This, in turn, can be utilized for reduced lab testing on improvements to the products or similar, new products. These methods also offer the user an opportunity to choose the most economical and practical procedure to measure reliability for a given application.

Hydraulic fluid power — Methods to assess the reliability of hydraulic components —

Part 1:
General procedures and calculation method

1 Scope

This part of ISO/TR 19972 provides a means for determining the reliability of hydraulic fluid power components using:

a) estimates from a design analysis;

b) analysis of laboratory testing to failure or suspension;

c) analysis of field data;

d) analysis of a substantiation test.

These methods apply to the first failures without repairs, but exclude certain infant mortality failures. Specific component test procedures and exclusions will be provided in subsequent parts of ISO/TR 19972.

This part of ISO/TR 19972 also provides calculation methods, reporting descriptions and examples of reliability calculations.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 1000, *SI units and recommendations for the use of their multiples and of certain other units*

ISO 5598, *Fluid power systems and components — Vocabulary*

ISO 9110-1, *Hydraulic fluid power — Measurement techniques — Part 1: General measurement principles*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 5598 and the following apply.

3.1
B_{10} **life**
L_{10} **life**
life of the component or assembly that has not been altered since its production, where its reliability is 90 %; or time at which 90 % of the population has survived

NOTE The cumulative failure percentage is 10 %.

3.2
component
individual unit (e.g. cylinder, motor, valve, filter, but excluding piping) comprising one or more parts designed to be a functional part of a fluid power system

3.3
mean time to failure
MTTF
mean lifetime of a component that has not been repaired since its production, based on a statistical mean, using times to failure as the definition of failure

3.4
mean cycles to failure
MCTF
mean life, expressed as number of cycles, of a component that has not been repaired since its production, based on a statistical mean, using cycles to failure as the definition of failure

3.5
reliability
probability that a component can perform continuously, without failure, for a specified interval of time when operating under stated conditions

3.6
failure
state at which a component reaches the threshold level or terminates its ability to perform a required function

3.7
termination cycle count
number of cycles on a specimen when it reaches any threshold level for the first time

3.8
threshold level
the value of a performance characteristic (e.g. leakage, flow and current) against which the component's test data is compared

NOTE This is an arbitrary value defined by the experts as the critical value for performance comparisons, but not necessarily indicative of the end of component operation.

4 Units of measurement and symbols

Units of measurement are in accordance with ISO 1000, except for Clause 7 and Annex A, which are based on *The Handbook of Reliability Prediction Procedures for Mechanical Equipment* [9] and use imperial units.

Symbols for the Weibull parameters:

β = Slope

η = Characteristic life

t_0 or x_0 = Minimum life

5 Reliability concept

Reliability is the probability (a percentage) that a component will not exceed the threshold level for a specified interval of time or number of cycles when it operates under stated conditions. This probability can be determined by any of the methods described in Clause 6. There are many different statistical distributions that describe the population of failures that result from these methods. Mean time to failure and B_{10} life are common terms used for expressing reliability.

It is also necessary to associate some confidence with a reliability result. This takes into account the fact that results will vary if the process is repeated many times, and the confidence describes probability bounds to the distribution of failures.

To determine reliability scientifically, it is necessary to define failure. This can be evident in field failures, but for the other methods the concept of threshold levels is defined for various performance characteristics. This is necessary because the value of some of these characteristics (e.g. leakage) might not represent a total failure of the component.

Examples of analytical methods and test parameters for which threshold levels might need to be established include:

a) dynamic leakage, both internal and external;

b) static leakage, both internal and external;

c) changes in performance characteristics (e.g. loss of stability, increase in minimum operating pressure, deterioration of flow rate, increase in response time, change in electrical characteristics, performance degradation due to contamination and breakdown of accessory functions).

In addition to these threshold levels, failure can also occur from catastrophic events such as burst, breakage, fatigue or loss of function.

6 Means for determining reliability

6.1 General

Environmental aspects for any of the methods discussed in this part of ISO/TR 19972 will have an influence on the results. Therefore, it is important to record the assumptions used in 6.2, follow the requirements specified for 6.3, record the observations obtained in 6.4, and use the original historical conditions in 6.5.

6.2 Design analysis

Calculation methods can be used to quantify the reliability of hydraulic components. In cases where neither field data or test data are available or tests cannot be carried out economically, calculation methods are recommended to estimate component reliability.

Predicting the reliability of mechanical equipment requires consideration of its exposure to the environment and subjection to a wide range of stress levels (e.g. impact loading). The approach to predicting reliability of mechanical equipment considers the intended operation environment, and determines the effect of that environment at the lowest part level where the material properties can also be considered. The combination of these factors permits the use of engineering design parameters to determine the design life of the equipment in its intended operating environment, and the rate and pattern of failures during design life.

An analysis of a design for reliability and maintenance (R and M) can identify critical failure modes and causes of unreliability as well as providing an effective tool for predicting equipment behaviour. The design evaluation programme includes a methodology for evaluating a design for R and M that considers the material properties, operating environment and critical failure modes at component level. In *The Handbook of Reliability Prediction Procedures for Mechanical Equipment* [9], 19 mechanical components have been identified for which reliability prediction equations have been developed. If a hydraulic component includes more than one mechanical component, the individual mechanical component reliabilities can be combined to establish the total equipment reliability.

A great advantage of this method is that the influence of parameters on the life of a component can be determined. This allows the engineer to improve the design in an early phase of development.

6.3 Laboratory test to failure or suspension

One of the major difficulties encountered in specifying a reliability test is the time it takes to cause a failure without accelerating the test. Accelerated testing, with environmental conditions above those for which the component is rated, is sometimes necessary in order to keep the test time at a reasonable length. The goals and objectives of the test method should be clearly defined.

The primary criterion for determining test acceleration factors is that the failure mode or failure mechanism should not change or be different from that expected from a non-accelerated test.

Two other important factors are the test stand and measurement of parameters. The test stand should be designed to operate reliably within the planned environmental conditions. Its configuration should not affect the results of the test being run on the component. Evaluation and maintenance of the test stand during the reliability test programme is critical. The accuracy of parameter measurement and control of parameter values should be within the specified tolerances to assure accurate and repeatable test results.

Proper test planning is essential in order to have results that accurately predict the component's reliability under specified conditions. The goals and objectives of the test programme should be clearly defined if a supplier and user agree to apply this part of ISO/TR 19972.

6.4 Collection of field data

Collection of field reliability data is an essential element of an effective product reliability programme. It is one of the most valuable sources of data since it represents actual customer/user product experience under working conditions.

Failures occur as a result of manufacturing and material deviations, product overstress in use, design deficiencies, cumulative wear and degradation, and random occurrences. Factors such as product misapplication, operating environment, installation and maintenance practices directly impact product life. Hence the collection of field data is necessary to assess these factors. Therefore, it is very important that details such as product lot identification, date codes and the specific operating environment be recorded.

Communication of objectives and the qualifications of personnel involved in the reporting process are crucial to the success of the data collection effort. It should be recognized that information to be extracted can only be obtained from the data collected. It is essential to be clear about objectives.

Since field data collection relies on people, it is subject to errors, personal biases, omissions and misunderstandings. It is therefore critically important to collect all data using a formal structured procedure and format.

The importance that appropriately trained qualified operations and maintenance personnel can contribute to the completeness and correctness of the data should not be underestimated. However, the design of the data collection system should minimize any bias that could be introduced by the personnel involved.

NOTE It is important to consider the individual's position, experience and objectivity when developing the collection procedures.

Selection of the data to be collected depends on the kind of performance metrics to be evaluated or estimated. The data collection system should provide at least

a) basic product identification information, including total number of units in service,

b) equipment environmental class,

c) environmental conditions,

d) operating conditions,

e) performance measurements,

f) maintenance support conditions,

g) failure description,

h) system changes implemented following occurrence of failure,

i) corrective action and specific details of replacement or repair, and

j) date, time and/or cycles to each failure.

6.5 Substantiation testing

Substantiation testing, based on statistical methods, is an efficient means used to validate the reliability of small sample test populations using historical data to define a population failure distribution.

NOTE This is also known as the Weibayes method.

This method validates a minimum level of reliability for a new population similar to an existing one, but does not result in an explicit value for its reliability. Instead, the testing validates that the reliability of the new population is greater than, or equal to, the reliability target of the test.

The procedure consists of selecting a Weibull shape or distribution factor, β, and calculating the test length required to support substantiation (historical data has shown that β tends to be consistent for a specific failure mode criterion). A test programme is then conducted on a sample of the new population. If the test is successful, the minimum level of reliability is substantiated.

7 Procedures for analysing a design concept

7.1 General

Based on handbooks for mechanical and electronic equipment, failure rates can be calculated for all critical parts of a hydraulic component that can fail in service (see Figure 1). For mechanical equipment, failure rates are calculated with reliability prediction equations that consider material properties, operating environment and design parameters. To predict the reliability of a complete component, the single failure rates are simply added to a component failure rate. The MTTF is the reciprocal of the failure rate.

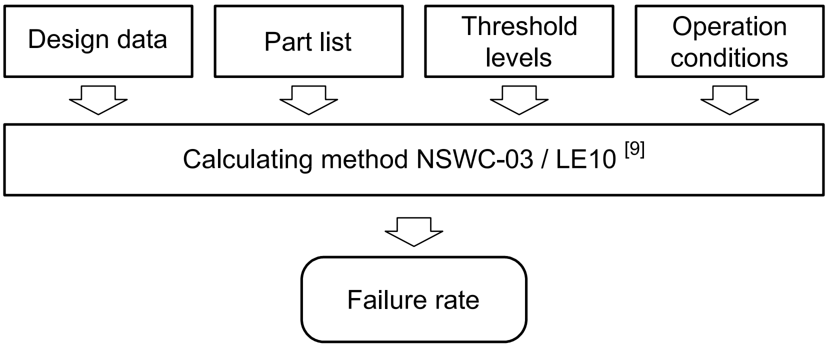

Figure 1 — Flow chart for calculating failure rates

Where integrated electronics are part of a hydraulic component, the failure rate of the electronics can be calculated by using MIL-STD-756B [7], MIL-HDBK-217F [6] or the Telcordia Technologies Special Report SR332 data bank [8].

The Handbook of Reliability Prediction Procedures for Mechanical Equipment [9] is recommended for mechanical parts. This reference is a summary of experiments that have led to an analytical method based on empirical values obtained from that source.

7.2 Design evaluation

Critical components can be identified by simply comparing the parts of the design with the components listed in *The Handbook of Reliability Prediction Procedures for Mechanical Equipment* [9], for example:

a) seals and gaskets;

b) springs;

c) solenoids;

d) valve assembles;

e) bearings;

f) gears and splines;

g) actuators;

h) pumps;

i) filters;

j) brakes and clutches;

k) compressors;

l) electric motors;

m) accumulators and reservoirs;

n) threaded fasteners;

o) mechanical couplings;

p) slider-crank mechanisms;

q) sensors and transducers.

Typical failure modes and failure rate models are defined for each component. The part list should identify all components and the number of parts in a design for the calculation of failure rates.

7.3 Threshold levels

For some components, threshold levels (e.g. allowable leakage) have to be defined in order to calculate the failure rate.

7.4 Operational conditions

Operational conditions have an important influence on the life of a component. All parameters (e.g. fluid pressure, fluid viscosity, temperature, contamination and externally applied loads) are needed to calculate the failure rate of a component.

7.5 Failure rate calculation

For each component there exists a characteristic equation to calculate the failure rate. Also, a base failure rate is given for each component. A generalized equation that adjusts the base failure rate can be established. These characteristics and equations are given in the reference used for the analysis.

For electronic parts, the Telcordia Technologies Special Report SR332 [8] can be used to calculate the failure rate.

The failure rate of the total assembly is the sum of the failure rates calculated for each individual component. Then, the MTTF or MCTF is the reciprocal of the failure rate, λ. An example calculation is given in Annex A.

7.6 Validation statement

Several test programmes were conducted during the development of *The Handbook of Reliability Prediction Procedures for Mechanical Equipment* [9] to verify the identity of failure modes and validate the engineering approach being taken to develop the reliability equations. For example, valve assemblies were procured and tested at the Belvoir Research, Development and Engineering Center in Ft. Belvoir, Virginia. The number of failures for each test was predicted using the equations presented in the Handbook. Failure rate tests were performed for several combinations of stress levels and results compared to predictions. Typical results are shown in Table 1.

Table 1 — Sample test data for validation of reliability

Test [a] series	**Valve number**	**Test cycles to failure**	**Actual failures/ 10^6 cycles**	**Average failures/ 10^6 cycles**	**Predicted failures/ 10^6 cycles**	**Failure [b] mode no.**
15	11	68 322	14,64	14,64	18,02	3
24	8	257 827	—	—	—	1
24	9	131 126	7,63	10,15	10,82	1
24	10	81 113	12,33	—	—	1
24	11	104	—	—	—	2
24	12	110 488	9,05	—	—	1
24	13	86 285	11,59	—	—	1
25	14	46 879	21,33	19,67	8,45	2
25	15	300	—	—	—	3
25	18	55 545	18,00	—	—	1

[a] Test parameters:
System pressure: 3 500 psi
Fluid flow: 100 % rated
Fluid temperature: 90 °C
Hydraulic fluid: MIL-H-83282.

[b] Failure modes:
1 Spring fatigue;
2 No apparent failure mode;
3 Accumulated debris.

8 Procedures for laboratory testing to failure or suspension

8.1 Minimum testing requirements

Testing should be carried out in accordance with the provisions of the relevant part of ISO/TR 19972 applicable to the component to be evaluated, and should include:

a) the statistical analysis method to be employed;

b) the test parameters to be measured in a reliability test and the threshold level for each parameter. Several parameters can be selected for any component and threshold levels can also be classified in groups;

c) the class of measurement accuracy in accordance with ISO 9110-1;

d) the number of specimens to be tested. This can be determined by practical methods (e.g. experience or cost) or by statistical (e.g. analytical) methods. The specimens should be representative of the population and should be selected randomly;

e) any preliminary measurements or bench tests that can be necessary to establish baseline measurements;

f) a determination of whether production assembly testing is permissible or necessary before starting a reliability test;

g) the conditions for the reliability test (e.g. supply pressure, cycle rate, loads, duty cycle, environmental conditions and component orientation);

h) the frequency of test parameter measurement (e.g. at specific intervals or continuous monitoring).

i) any repairs permitted on the samples during the reliability test;

j) a disposition if the samples experience a failure that is not defined by one of the parameters being measured;

k) the minimum number of specimens that should reach a termination cycle count (e.g. 50 %);

l) the maximum number of specimen suspensions allowed before the test is ended and to define whether a minimum number of cycles is necessary before a specimen can be classified as a suspension or discounted as a specimen;

m) any final examinations that are to be performed on the specimens, and on the test instruments at the end of the test and any influence these examinations can have on the test data. Confirm the validity of the data and any pass or fail conclusions (e.g. a failed solenoid might not be observed during a cycling test until it is separately examined or a hairline crack might not be observed unless separately examined).

8.2 Data analysis

The resulting data shall be evaluated for estimating the reliability. One of the most commonly used methods is the Weibull analysis because of its versatility in modelling various statistical distributions. Other methods are possible if the distribution can be determined, or if an assumption for a distribution can be justified.

Typically, the following steps are performed during data analysis.

a) Record the cycle count at which a specimen reaches the threshold level for any parameter; this is the termination cycle count for that specimen. The specimen may continue to be tested if there is interest for other parameters, but it will not be counted any further in the analysis;

b) Plot a statistical distribution from the test data. If a Weibull analysis is employed, use median ranks. If suspensions are included, use the modified Johnson formula and Bernard's equation for the plotting positions. See the example data analysis shown in Annex B;

c) Using a best-fit plot of the data, determine the characteristic values of the distribution. If a Weibull analysis is used, this includes the minimum life, t_0 or x_0, the slope, β, and characteristic life, η. In addition, the desired level of confidence specified for the design is to be plotted using a type 1 Fisher Matrix;

NOTE Commercial software can be helpful for this purpose.

d) If a Weibull analysis is used, determine the B_i life at the confidence level for which the reliability values will be determined.

9 Procedures for collecting field data

9.1 General

Reliability data collection can be based on events or on monitoring/inspection time intervals. Both methods are established practice. Statistical methods are available to analyse data for either method used. A structured approach should be adopted for assigning responsibilities, identifying data needed and developing procedures for data collection methods for analysis and reporting.

Recording of the data can be manual, but automated and interactive data collection systems are recommended. Reporting should include information on the conditions of use. Where the items are under multiple usage (e.g. operation, configuration, standby, storage, transportation, test), it is necessary to collect data on each usage type.

A fully relational database is recommended to permit storage and retrieval of required data, and facilitate data analysis. The database includes records on all reported failures, failure analysis and failure resolution. Analysis capabilities for efficient retrieval and analysis of the data to produce failure trends, failure summary and status reports, failure history and corrective action should be incorporated. Any database needs an in-depth study of its specific requirements, in order to define the most suitable methods of data checking, error correction and updating.

Regardless of the design of the data collection procedure and the method of data storage, checks should be made on the validity of data before entry. Data accepted for inclusion in the database should be validated and checked for consistency. Validation depends on a clear definition of acceptable data. At a basic level, this can be a check on whether or not a numeric value falls within a permitted range. However, data, unless erroneous, should be retained even if outside a predetermined range.

Data stored for retrieval should be structured to maintain confidentiality of the source. Data should be distributed only in composite form.

The goal of the data collection system is to convert large amounts of data into useable knowledge. Obviously the nature of the product and marketplace needs will be a major consideration in deciding how extensive the data collection and analysis system should be.

Frequently, one of a number of types of statistical distribution will underlie the collected data. Three principal methods are available to identify a particular distribution:

a) engineering judgement, based on an analysis of the physical process generating the data;

b) graphical methods using special charts, leading to the construction of nomographs (e.g. see ISO 8258 [1]);

c) statistical tests providing a measure of the deviations between the sample and the assumed distributions; such a test is given for the exponential distribution in IEC 60605-6 [3]; for other distributions, where there are no international standards, information can be found in the technical literature;

Unfortunately, no single standard method or system for the analysis of field reliability data exists. Often, the interpretation and analysis of field data require combining technical expertise, intuition and knowledge based upon experience in order to achieve meaningful results.

The technical literature provides numerous methods for both graphical and analytical methods of presenting field reliability data. A combination of graphical and analytic methods is often most informative. However, graphical methods are the simplest, while analytic methods are generally mathematically rigorous in statistical techniques. Some of the methods employed for data analysis are:

a) Pareto plots;

b) pie charts;

c) histograms;

d) time series plots;

e) custom charts;

f) non-parametric statistical techniques;

g) cumulative probability plots;

h) statistical methods and probability distribution functions;

i) Weibull analysis;

j) extreme value probability methods.

There are a number of commercially available software packages that support the analysis of field reliability data and include many of the preceding analysis methods.

9.2 Methods for estimating reliability from field survey data

The MTTF, or the MCTF, for field data can be calculated in the same manner as for laboratory data. Use the methods described in 8.2, with examples shown in Annex B. Supplementary information is given in Annex C.

10 Procedure for a substantiation test

10.1 General

Substantiation test procedures such as zero failure and zero/one failure test plans are derived from statistical distribution procedures using a null hypothesis for the reliability of a component that is less than or equal to the specification requirement, with zero failures (or one failure) in a binomial distribution. These test procedures are particularly applicable for small sample test programmes.

In a zero failure test procedure, a specified B_i life is demonstrated if no failures occur during the test.

The zero/one failure test plan is similar to a zero failure test plan, except that one failure is allowed during the test programme. A zero/one failure test accepts a higher cost (due to more testing) for a reduced risk of rejecting an acceptable design. One advantage of the zero/one failure plan occurs when specimens are tested in groups (e.g. due to test capacity restrictions). If all of the specimens up to the last specimen do not fail, then the last specimen does not need to be tested. This is a basic part of the assumption that accounts for one failure to occur while still validating the reliability requirement.

For the following analysis, the Weibull distribution method is assumed.

10.2 Zero failure method

10.2.1 Select a Weibull slope value for the component to be tested, based on known historical data. Then, determine either the test duration or the number of samples from Equation (1) (see Annex D for its development):

$$t = t_i \left[\frac{\ln(1-C)}{n \times \ln(R_\mathrm{i})} \right]^{\frac{1}{\beta}} = t_i \left[\left(\frac{1}{n} \right) \frac{\ln(1-C)}{\ln R_\mathrm{i}} \right]^{\frac{1}{\beta}} = t_i \left(\frac{A}{n} \right)^{\frac{1}{\beta}} \quad \text{or} \quad n = A \left(\frac{t_i}{t} \right)^{\beta} \qquad (1)$$

where

t is the test duration expressed in time, cycles, or distance;

t_i is the reliability objective in time, cycles, or distance;

β is the Weibull slope, obtained from historical data;

R_i is the reliability goal $(100 - i)/100$;

i is the variable index for % cumulative failure (e.g. $i = 10$ for B_{10} life);

n is the number of specimens;

C is the test confidence level;

A is obtained from Table 2 or calculated from Equation (1).

Table 2 — Values of A

C	R_i				
	R_1	R_5	R_{10}	R_{20}	R_{30}
95 %	298,1	58,40	28,43	13,425	8,399
90 %	229,1	44,89	21,85	10,319	6,456
80 %	160,1	31,38	15,28	7,213	4,512
70 %	119,8	23,47	11,43	5,396	3,376
60 %	91,2	17,86	8,70	4,106	2,569

10.2.2 Conduct a test on the samples using procedures in other parts of ISO/TR 19972. The test duration will be t as defined above, and all samples shall survive the test.

10.2.3 If the test is successful, the reliability can be stated as follows.

The B_i life of (component) has been substantiation tested to demonstrate a minimum life of at least t_i (e.g. cycles, hours or kilometres) at a confidence level of C based on a zero failure Weibayes method.

10.3 Zero/one failure method

10.3.1 Select a Weibull slope value for the component to be tested, based on known historical data.

10.3.2 Determine the test duration from Equation (2) (see Annex D).

$$t_0 = t_j \left(\frac{\ln R_0}{\ln R_j} \right)^{\frac{1}{\beta}} \qquad (2)$$

where:

t_0 is the test duration expressed in time, cycles, or distance;

t_j is the reliability objective in time, cycles, or distance;

β is the Weibull slope obtained from historical data;

R_j is the reliability goal (100 – i)/100;

R_0 is the reliability root value for zero/one failures (see Table 3);

j is the variable index percent cumulative failure (e.g. $j = 10$ for B_{10} life);

n is the number of specimens;

C is the confidence level.

Table 3 — Values of R_0

C	n								
	2	3	4	5	6	7	8	9	10
95 %	0,025 3	0,135 3	0,248 6	0,342 5	0,418 2	0,479 3	0,529 3	0,570 8	0,605 8
90 %	0,051 3	0,195 8	0,320 5	0,416 1	0,489 7	0,547 4	0,593 8	0,631 6	0,663 1
80 %	0,105 6	0,287 1	0,417 6	0,509 8	0,577 5	0,629 1	0,669 6	0,702 2	0,729 0
70 %	0,163 4	0,363 2	0,491 6	0,578 0	0,639 7	0,685 7	0,721 4	0,749 8	0,773 0
60 %	0,225 4	0,432 9	0,555 5	0,635 0	0,690 5	0,731 5	0,762 9	0,787 7	0,807 9

10.3.3 Conduct a test on the specimens using procedures in other parts of ISO/TR 19972. The test duration will be t_0 as determined using Equation (2) and no more than one specimen may fail the test. If all specimens cannot be tested at one time, the last specimen need not be tested if all of the other specimens survive the test.

10.3.4 If the test is successful, the reliability can be stated as follows.

The B_j life of (component) has been substantiation tested to demonstrate a minimum life of at least t_j (e.g. cycles, hours, kilometres) at a confidence level of C, based on a zero/one failure Weibayes method.

Annex A
(informative)

Example calculation for analysing a design concept

A.1 Example design evaluation procedure

A hydraulic valve assembly will be used to illustrate an approach to predicting the reliability of mechanical equipment.[1] Developing reliability equations for all the different types of hydraulic valve available would be an impossible task. For example, some valves are named after the function they perform (e.g. check valve, regulator valve and unloader valve). Others are named after a distinguishing design feature (e.g. globe valve, needle valve and solenoid valve). From a reliability standpoint, dropping down one indenture level provides two basic types of valve assembly, poppet valves and sliding action valves.

The assembly chosen for this analysis example is a poppet valve consisting of a poppet assembly, spring, seals and housing.

A.2 Poppet assembly

The functions of a poppet valve would indicate the primary failure mode to be incomplete closure of the valve resulting in leakage around the poppet seat. This failure mode can be caused by contaminants being wedged between the poppet and seat, wear of the poppet seat and corrosion of the poppet/seat combination. External seal leakage, sticking valve stem and damaged poppet return spring are other failure modes which should be considered in the design of the valve.

A new poppet assembly can be expected to have a sufficiently smooth surface for the valve to meet internal leakage specifications. However, after a period of time, contaminants will cause wear of the poppet assembly until the leakage rate is beyond tolerance. The leakage rate at which the valve is considered to have failed will depend on the application and to what extent leakage can be tolerated.

The failure rate of a poppet assembly can be calculated using Equation (A.1).

$$\lambda_{\mathrm{P}} = \lambda_{\mathrm{P,B}} \frac{2x10^{-2} D_{\mathrm{MS}} f^{3} \left(P_1{}^2 - P_2{}^2\right)}{Q_{\mathrm{f}} \nu_{\mathrm{a}} L_{\mathrm{w}} \left(S_{\mathrm{s}}\right)^{1.5}} K_1 \tag{A.1}$$

where:

λ_{P} is the failure rate of the poppet assembly, expressed in the number of failures per million cycles;

$\lambda_{\mathrm{P,B}}$ is the base failure rate for poppet assembly, expressed in the number of failures per million cycles;

D_{MS} is the mean seat diameter, expressed in inches;

f is the mean surface finish of opposing surfaces, expressed in inches;

P_1 is the upstream pressure, expressed in pounds per square inch;

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[1] As stated in Clause 4, units of measurement are in accordance with ISO 1000, except for Annex A and Clause 7, which are based on *The Handbook of Reliability Prediction Procedures for Mechanical Equipment* [9] and use imperial units.

P_2 is the downstream pressure, expressed in pounds per square inch;

Q_f is the leakage rate considered to be a valve failure expressed in cubic inches per minute;

ν_a is the absolute fluid viscosity expressed as pound minute per square inch;

L_w is the radial seat land width expressed in inches;

S_s is the apparent seat stress expressed in pounds per square inch;

K_1 is a constant which considers the impact of contaminant size, hardness and quantity of particles.

Values used to determine the failure rates for the parts used in this example are listed in Table A.1.

Failure rate equations for each component and part are then translated into a base failure rate using a series of multiplying factors to modify the base failure rate to match the operating environment being considered. For example, Equation (A.1) can be rewritten as shown in Equation (A.2).

$$\lambda_\mathrm{PO} = \lambda_\mathrm{PO,B} \times C_\mathrm{P} \times C_\mathrm{Q} \times C_\mathrm{F} \times C_\mathrm{v} \times C_\mathrm{N} \times C_\mathrm{S} \times C_\mathrm{DT} \times C_\mathrm{SW} \times C_\mathrm{W} \tag{A.2}$$

where:

λ_PO is the failure rate of the poppet assembly expressed in the number of failures per million operations;

$\lambda_\mathrm{PO,B}$ is the base failure rate of the poppet assembly expressed in the number of failures per million operations;

C_P is the multiplying factor which takes into account the effect of fluid pressure on the base failure rate;

C_Q is the multiplying factor which takes into account the effect of allowable leakage on the base failure rate;

C_F is the multiplying factor which takes into account the effect of surface finish on the base failure rate;

C_v is the multiplying factor which takes into account the effect of fluid viscosity on the base failure rate;

C_N is the multiplying factor which takes into account the effect of contaminants on the base failure rate;

C_S is the multiplying factor which takes into account the effect of seat stress on the base failure rate;

C_DT is the multiplying factor which takes into account the effect of seat diameter on the base failure rate;

C_SW is the multiplying factor which takes into account the effect of seat land width on the base failure rate;

C_W is the multiplying factor which takes into account the effect of fluid flow rate on the base failure rate.

The parameters in the failure rate equation can be located on an engineering drawing, through knowledge of design standards or by actual measurement. Other design parameters which have a minor effect on reliability are included in the base failure rate as determined from field performance data.

A.3 Spring assembly

Depending on the application, a spring can be in a static, cyclic, or dynamic operating mode. For this example the spring will be considered to be in a cyclic mode. The operating life of a mechanical spring is dependent upon the susceptibility of its materials to corrosion and the stress levels (e.g. static, cyclic or dynamic) experienced in service. The two most common spring failure modes are fracture due to fatigue and excessive loss of load due to stress relaxation. Other failure mechanisms and causes can be identified for a specific application. Typical failure rate considerations include applied load, operating temperature, cycling rate and corrosiveness of the fluid environment.

The failure rate of a spring depends upon the stress and the relaxation properties of the spring material. The load on the spring is equal to the spring rate multiplied by the change in load per unit deflection and calculated using Equation (A.3).

$$P_\mathrm{L} = K\left(L_1 - L_2\right) = \frac{G_\mathrm{M}\left(D_\mathrm{W}\right)^4\left(L_1 - L_2\right)}{8\left(D_\mathrm{c}\right)^3 N_\mathrm{a}} \tag{A.3}$$

where:

P_L is the maximum load expressed in pounds;

K is the spring rate expressed in pounds per inch;

L_1 is the initial length expressed in inches;

L_2 is the final length expressed in inches;

G_M is the modulus of rigidity expressed in pounds per square inch;

D_C is the mean diameter of the spring coil expressed in inches;

D_W is the mean diameter of the spring wire expressed in inches;

N_a is the number of active spring coils.

Stress in the spring will be proportional to the applied load as shown by the relationship in Equation (A.4).

$$S_\mathrm{G} = \frac{8P_\mathrm{L}D_\mathrm{C}}{\pi\left(D_\mathrm{W}\right)^3}K_\mathrm{W} \tag{A.4}$$

where:

S_G is the actual stress expressed in pounds per square inch;

K_W is the Wahl stress correction factor given by Equation (A.5).

$$K_\mathrm{W} = \frac{4r-1}{4r-4} + \frac{0.615}{r} \tag{A.5}$$

where:

$$r = \frac{D_\mathrm{C}}{D_\mathrm{W}}$$

This equation allows the expected life of the spring to be determined by plotting the material S-N curve on a modified Goodman diagram. In this example, the spring force and the failure rate remain constant. This projection is valid if the spring does not encounter temperature extremes. The anticipated failure rate as a function of time is shown in Figure A.1. Corrosion is a critical factor in spring design because most springs are made of steel which is susceptible to a corrosive environment. In this example the fluid medium is assumed to be non-corrosive and the spring is always surrounded by the fluid, thus a corrosion factor need not be included. If the valve were a safety device and subjected intermittently to a steam environment, a corrosion factor would have to be applied which took account of any corrosion protection applied to the spring.

The failure rate can then be calculated using Equation (A.6).

$$\lambda_{SP} = \lambda_{SP,B}\left(\frac{S_G}{T_S}\right)^3 \tag{A.6}$$

where:

λ_{SP} is the spring failure rate expressed as the number of failures per million cycles;

$\lambda_{SP,B}$ the spring base failure rate expressed as the number of failures per million cycles;

S_G is the spring stress expressed in pounds per square inch;

T_S is the material tensile strength expressed in pounds per square inch.

A.4 Seal assembly

The primary failure mode of the seal is leakage and Equation (A.7) adopts a similar approach to that developed for evaluating the poppet design.

$$\lambda_\mathrm{SE} = \lambda_\mathrm{SE,B}\frac{K_1\left(P_1^2 - P_2^2\right)}{Q_\mathrm{f}\nu_\mathrm{a}P_2}\times\frac{r_\mathrm{o}+r_\mathrm{i}}{r_\mathrm{o}-r_\mathrm{i}}\times H^3 \quad \text{and} \quad H = 0.233\left(\frac{M}{C}\right)^{1.5}\times f^{2/3} \tag{A.7}$$

where:

λ_SE is the seal failure rate expressed as the number of failures per million cycles;

$\lambda_\mathrm{SE,B}$ is the seal base failure rate expressed as the number of failures per million cycles;

P_1 is the system pressure expressed in pounds per square inch;

P_2 is the standard atmospheric pressure or downstream pressure expressed in pounds per square inch;

Q_f is the allowable leakage rate under conditions of usage expressed in cubic inches per minute;

ν_a is the absolute fluid viscosity expressed in pound minute per square inch;

r_i is the inside radius of circular interface expressed in inches;

r_o is the outside radius of circular interface expressed in inches;

H is the conductance parameter (Meyer hardness M, contact pressure C, surface finish f);

K_1 is the multiplying factor taking into account the effects of contaminants, temperature.

In the case of an O-ring seal, the failure rate will increase as a function of time due to the gradual hardening of the rubber material. A typical failure rate curve for an O-ring is shown in Figure A.1.

A.5 Combination of failure rates

The addition of individual part failure rates to determine the total valve failure rate depends on the life of the valve and the maintenance philosophy established. If the valve is to be discarded upon the first failure, a time-to-failure can be calculated for the particular operating environment.

However, if the valve is to be repaired on failure, then the individual failure rates should be combined for different time phases throughout the life expectancy until the wear-out phase has been reached. The effect of part replacement and overhaul is a tendency toward a constant failure rate at system level and will have to be considered in the prediction for the total system.

Once the failure rates are determined for each component part, they are summed to determine the failure rate of the complete valve assembly. As some of the parameters in the failure rate equation are time dependent (i.e. the failure rate changes as a function of time) the total failure rate should be determined for particular time intervals. For a poppet assembly, nickel plating is assumed with an initial surface finish of 35 µ in. The change in surface finish over a time period of one year for non-acidic fluids (e.g. water, mild sodium chloride solutions and hydraulic fluids) will be a deterioration to 90 µ in. In the case of the O-ring seal, the hardness of the rubber material will change with age. This combination of failure rates is shown in Figure A.1.

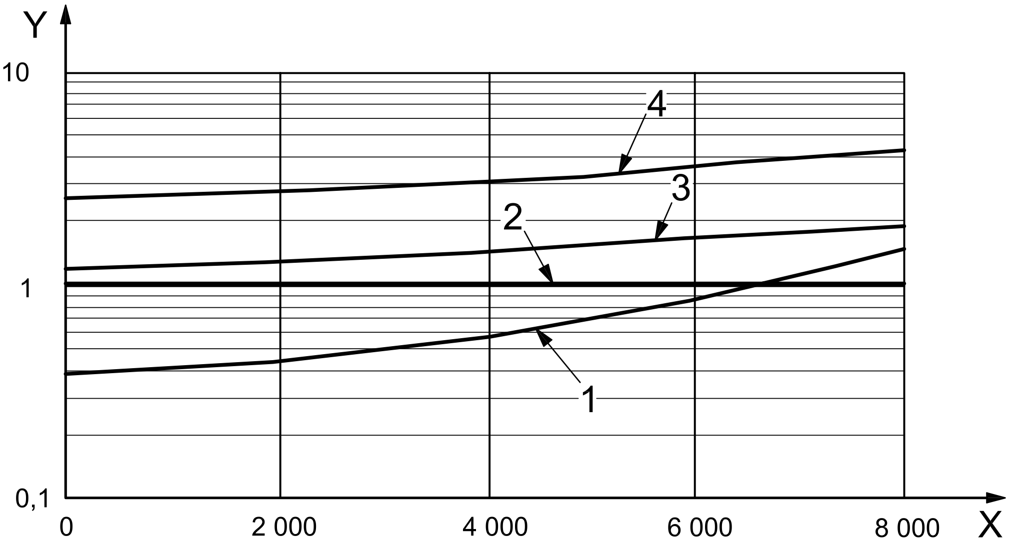
The housing will exhibit an insignificant failure rate, usually verified by experience or by finite element analysis. Typical values assumed for the example equations are listed in Table A.1.

Table A.1 — Typical values for failure rate equations

Poppet		Spring		Seal	
Parameter	**Value**	**Parameter**	**Value**	**Parameter**	**Value**
λ_{PB}	1,40	$\lambda_{\mathrm{SP,B}}$	23,8	$\lambda_{\mathrm{SE,B}}$	2,40
Q_{f}	0,06	L_1	3,35	Q_{f}	0,06
D_{MS}	0,70	L_2	2,28	P_1	3 000
f[a]	35×10^{-6}	G_{M}	$11,5 \times 10^{6}$	P_2	15
P_1	3 000	D_{C}	0,58	v_{a}	2×10^{-8}
P_2	15,0	D_{W}	0,085	r_{i}	0,17
v_{a}	2×10^{-8}	N_{a}	14,0	r_{o}	0,35
L_{W}	0,18	T_{S}	245×10^{3}	M/C [b]	0,55
S_{S}	20	P_{L}	29,40	f	35×10^{-6}
K_1	1,00	S_{G}	$86,191 \times 10^{3}$	K_1	$3,27 \times 10^{-4}$
λ_{P}	0,39	λ_{SP}	1,036	λ_{SE}	1,187

[a] Initial value = 35 µ in; after 1 year (500,000 operations) surface finish will equal 90 µ in.

[b] Initial value = 0,55 (hardness, $M = 500$ psi; contact stress, $C = 910$ psi); after 1 year M estimated to be 575 psi ($M/C = 0{,}63$).



Key

X life in hours

Y failure rate, in failures per million hours

1 poppet failure rate [a]

2 spring failure rate [a]

3 seal failure rate [a]

4 valve assembly failure rate [a]

[a] Failure rates are calculated for a specific time interval.

Figure A.1 — Combination of component failure rates

Annex B
(informative)

Calculation examples for laboratory test to failure data analysis

B.1 General

The underlying distribution of failure data can be unknown. The value of the Weibull method lies in its flexibility. Other distributions such as exponential or normal are subsets of the Weibull. It has application as a model for a wide variety of life data. The Weibull distribution is a parametric one; it consists of a family of distributions.

The Weibull distribution can have three parameters that define the distribution:

a) η the characteristic life;

b) β the shape factor (or slope);

c) t_0 the minimum life parameter.

NOTE When $\beta < 1$, the distribution has a decreasing failure rate, when $\beta = 1$ the failure rate is constant and when $\beta > 1$ the failure rate is increasing.

B.2 Example of data analysis without suspensions

Consider a test run on a sample of seven specimens of a component and five parameters (a, b, c, d and e) are measured during a reliability test. Raw data for each parameter are collected at various cycle counts as the test progresses. At some point, the threshold level for one of the parameters is reached, and the cycle count at that point is recorded, as shown in Table B.1. The termination cycle count for each specimen (shown in the shaded table cells) is the first time that the specimen reaches the threshold level for any parameter. The test is considered complete when at least half of the specimens, in this case four, have reached a termination cycle count.

Table B.1 — Test specimen parameter thresholds and data

Termination cycle count	Threshold				
	Parameter a: 100 cm^3/min.	Parameter b:	Parameter c:	Parameter d:	Parameter e:
$11{,}8 \times 10^6$			Specimen No. 5		
$21{,}5 \times 10^6$		Specimen No. 1			
$30{,}2 \times 10^6$					Specimen No. 2
$31{,}6 \times 10^6$	Specimen No. 2			Specimen No. 5	
$39{,}8 \times 10^6$					Specimen No. 1
$41{,}1 \times 10^6$		Specimen No. 5			
$42{,}9 \times 10^6$	Specimen No. 6				
$42{,}9 \times 10^6$	Test ended – Specimen Nos. 3, 4, 7 terminated.				

This example illustrates how the specimens can reach threshold levels for other parameters if they continue to be tested beyond their termination cycle count. The termination cycle count (shaded cell) is the point at which the specimen reaches the first threshold.

NOTE Some specimens did not reach a threshold and were terminated at the end of the test.

A Weibull plot is then made from the data shown in Table B.2:

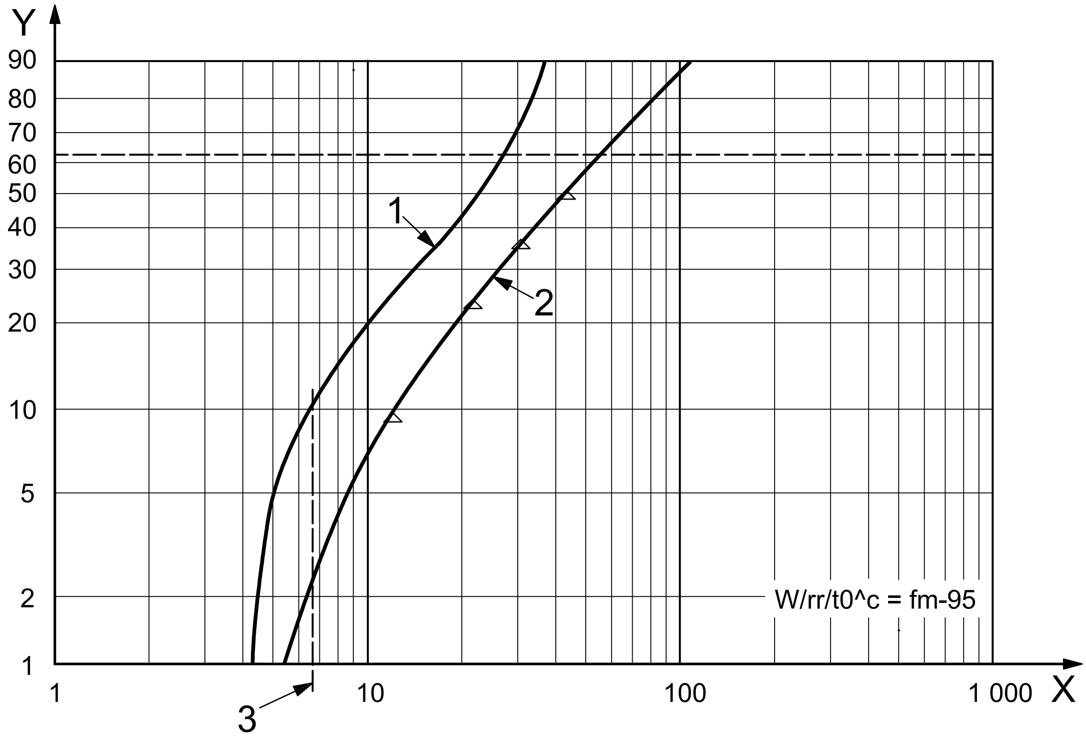
Table B.2 — Weibull plot data

Cycle count	Median ranks
$11{,}8 \times 10^6$	0,094 3
$21{,}5 \times 10^6$	0,228 5
$30{,}2 \times 10^6$	0,364 1
$42{,}9 \times 10^6$	0,500 0

NOTE Median rank values are based on the total number of specimens (in this case, seven). Median rank values in this example use the Beta Binomial method of calculation.

It is not necessary to use the Johnson and Bernard equations for the terminated specimens in this case because they occurred at the end of testing. See Clause B.2 for an example of data analysis in which suspensions occurred during the course of testing and have to be taken into account.

The approximate results are given in Figure B.1.



Key

X	number of recorded cycles ×10^6
Y	cumulative failure, expressed as a percentage
1	lower confidence bound single sided 95 %
2	median rank for the three-parameter Weibull distribution
3	B_{10} life at 95 % confidence level

NOTE Minimum life = 4,14 × 10^6 cycles; Characteristic life = 55,8 × 10^6 cycles; Slope = 1,21.

The 95% confidence bound is obtained from a Type 1 Fisher Matrix method.

Figure B.1 — Weibull plot for example 1

A calculation for x from the three-parameter Weibull equation [see Equation (B.1)], with $F(x) = 0{,}1$, and substituting the values shown in Figure B.1 will yield a B_{10} life based on the median curve as:

$$F\left(x\right) = 1 - e^{-\left(\frac{x - x_0}{\eta - x_0}\right)^{\beta}} \qquad \text{(B.1)}$$

$$0{,}1 = 1 - e^{-\left(\frac{x - 4{,}14 \times 10^6}{55{,}8 \times 10^6 - 4{,}14 \times 10^6}\right)^{1{,}21}}$$

$$x = \left(55{,}8 \times 10^6 - 4{,}14 \times 10^6\right)\left[\ln\left(\frac{1}{0{,}9}\right)\right]^{\frac{1}{1{,}21}} + 4{,}14 \times 10^6$$

x = 12 198 520 cycles B_{10} life at a 50 % confidence level (median curve).

A graphical interpretation of the lower confidence bound yields a B_{10} life of 6 500 000 cycles at a 95% confidence level.

NOTE The Weibull curve has a bend in its lower part, indicating that a minimum life value is likely. This suggests that the three-parameter Weibull equation is justified.

B.3 Example of data analysis with suspensions

This example illustrates a case in which some specimens are removed from the test before they fail, while others continue to be tested. Reasons for such removal should not be related to the objective of the test; acceptable reasons include equipment failures, external damage (e.g. fire, falling object), removal for inspection, or any other reason. Any specimen that is removed should not be returned to the test programme, it is then classified as a suspended specimen.

Consider the data in Table B.3. The shaded table cells show the cycle count at which a specimen reached a threshold level for the first time.

Table B.3 — Test specimen parameter thresholds and data

Termination cycle count	Threshold				
	Parameter a: 100 cm^3/min.	**Parameter b:**	**Parameter c:**	**Parameter d:**	**Parameter e:**
$11,8 \times 10^6$			Specimen No. 5		
$21,5 \times 10^6$		Specimen No. 1			
$25,0 \times 10^6$	Specimen No. 4 removed from test				
$30,2 \times 10^6$					Specimen No. 2
$31,6 \times 10^6$	Specimen No. 2			Specimen No. 5	
$35,0 \times 10^6$	Specimen No. 3 removed from test				
$39,8 \times 10^6$					Specimen No. 1
$41,1 \times 10^6$		Specimen No. 5			
$42,9 \times 10^6$	Specimen No. 6				
$42,9 \times 10^6$	Testing ended – Specimen No. 7 removed from test				

The plotting positions are calculated using the modified Johnson formula [Equation (B.2)] as:

$$\text{Plotting position} = \frac{(\text{Reverse sequence})\,(\text{Previous position number}) + (N + 1)}{(\text{Reverse sequence} + 1)} \tag{B.2}$$

Calculate the Median ranks using Bernard's approximation [Equation (B.3)] as:

$$\text{Median rank} = \frac{(\text{Plotting position} - 0{,}3)}{(N + 0{,}4)} \tag{B.3}$$

where N is the number of specimens tested (7 in this example).

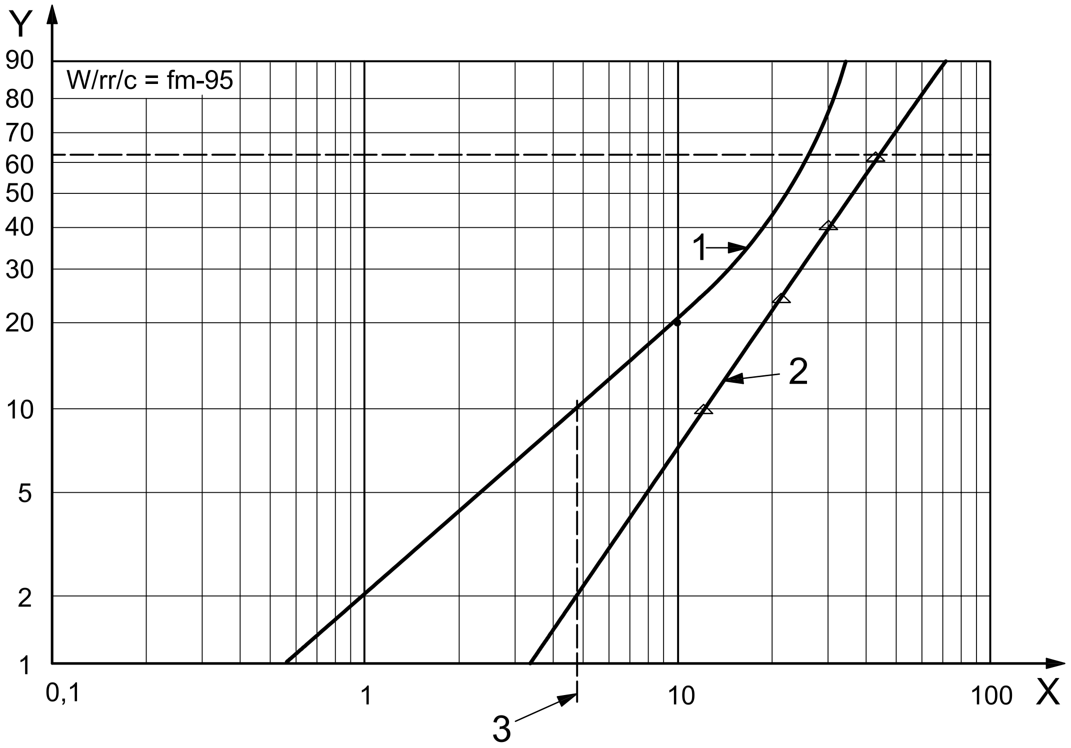
Table B.4 describes these calculations.

Table B.4 — Calculations for plotting positions and median ranks for test data with suspensions

Termination cycle count	Specimen no.	Sequence	Reverse sequence	Status	Plotting position	Median rank
$11{,}8 \times 10^6$	5	1	7	Fail	1	0,094 6[a]
$21{,}5 \times 10^6$	1	2	6	Fail	2	0,229 7[a]
$25{,}0 \times 10^6$	4	3	5	Suspend	—	—
$30{,}2 \times 10^6$	2	4	4	Fail	3,20	0,391 9
$35{,}0 \times 10^6$	3	5	3	Suspend	—	—
$42{,}9 \times 10^6$	6	6	2	Fail	4,80	0,608 1
$42{,}9 \times 10^6$	7	7	1	Terminated	—	—

[a] The first two entries do not require calculation by the modified Johnson equation. Their median ranks could be determined from a standard table, or they could be calculated from Bernard's approximation, which was used in this example in order to be consistent.

Using the calculated plotting positions and Median ranks, a Weibull plot is developed. The results are given in Figure B.2.



Key

X number of recorded cycles $\times 10^6$

Y cumulative failure, expressed as a percentage

1 lower confidence bound single sided 95 %

2 median rank for the two-parameter Weibull distribution

3 B_{10} life at 95 % confidence level

NOTE Minimum life = 0 cycles; Characteristic life = $45{,}1 \times 10^6$ cycles; Slope = 1,74. The 95% confidence bound is obtained from a Type 1 Fisher Matrix method.

Figure B.2 — Weibull plot for Example 2

A calculation for x from the two-parameter Weibull equation [see Equation (B.4)], with $F(x) = 0{,}1$, will yield a B_{10} life based on the median curve as follows:

$$F(x) = 1 - e^{-\left(\frac{x}{\eta}\right)^{\beta}} \tag{B.4}$$

$$0{,}1 = 1 - e^{-\left(\frac{x}{45{,}1 \times 10^{6}}\right)^{1{,}74}}$$

$$x = \left(45{,}1 \times 10^{6}\right)\left[\ln\left(\frac{1}{0{,}9}\right)\right]^{\frac{1}{1{,}74}}$$

$X =$ 12 408 020 cycles B_{10} life at a 50 % confidence level (median curve).

A graphical interpretation of the lower confidence bound yields a B_{10} life = 4 800 000 cycles at a 95 % confidence level.

NOTE The Weibull curve is straight in its lower part, indicating that a minimum life value is close to zero. This suggests that the two-parameter Weibull equation is justified.

B.4 Example of interval testing

B.4.1 General

During a reliability test, monitoring of the specimen condition is usually not possible (threshold). Thus, inspections in defined intervals are needed to assess the condition (failures). If a component fails during an interval, a certain lack of information has to be accepted since the exact time to failure is not known (i.e. the component might have failed at the beginning or at the end of an interval). Therefore it is recommended that a reasonable time for test intervals be chosen.

The typical type of data for interval testing is censored data, which can include left censored and right censored types (suspensions).

Life data types are as follows:

- complete data: life data (time to failure) for each specimen of a sample is available;
- censored data, e.g.
    - right censored data: specimen of a sample did not fail at the observation (suspended)
    - interval censored data: specimen failed during an interval
    - left censored data: specimen of a sample failed between the start and the observation

NOTE 1 A data set may contain more than one type of censored data.

The use of maximum likelihood estimation (MLE) for data analysis instead of rank regression method (or least squares method, RRX) is recommended. MLE does not consider ranks or plotting positions, but rather uses each unique time to failure or suspension. As a rule of thumb, MLE should be used for heavy and/or mixed censoring, or large sample sizes (>30). RRX should be used for complete data and small samples sizes.

B.4.2 Example

A sample with 30 specimens has been tested, but the test was abandoned after half of the specimens failed. One specimen was suspended during the test due to incorrect handling. The time interval between inspections was fixed at 400 h. During these inspections, failures were observed due to malfunction or exceeding the threshold levels. Results are shown in Table B.5.

Table B.5 — Test results

Number in state	Last inspected h	State F or S	State end time h	Censoring	Unit No.
1	0	F	400	left censored	3
2	400	F	800	interval censored	21; 14
1	800	F	1 200	interval censored	5
2	1 200	F	1 600	interval censored	9;13
2	1 600	F	2 000	interval censored	27;10
1	2 000	S	2 400	right censored	22 [a]
2	2 400	F	2 800	interval censored	17
3	2 800	F	3 200	interval censored	6; 11; 19
2	3 200	F	3 600	interval censored	1; 24
15	3 600	S	3 600	right censored	2; 4; 7; 8; 12; 15; 16; 18; 20; 23; 25; 26; 28; 29; 30 [b]

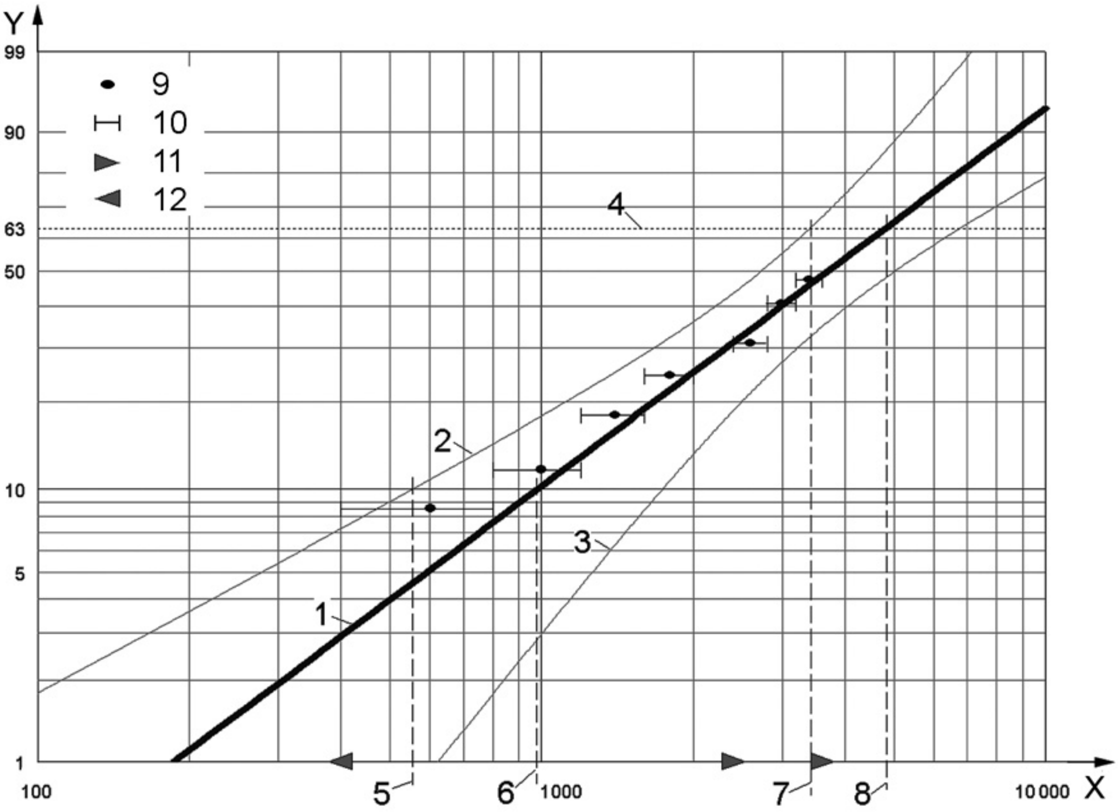
[a] Was mishandled.

[b] All these specimens were removed from testing.

Since the exact times to failure are not known, the mean of the intervals were used as the time to failure.

The modified Johnson formula for the plotting positions (Clause B.2), and Bernard's approximation for the median ranks (Clause B.4), could be used for developing a Weibull plot. However, commercial software was used to provide Figure B.3.

The two-parameter Weibull distribution was employed, using the MLE method for censored data.



Key

1 median rank for the three-parameter Weibull distribution
2 upper confidence bound 95%
3 lower confidence bound 5%
4 Eta
5 B_{10} life at 95% confidence level (555 h)
6 B_{10} life at the median level (982 h)
7 characteristic life at 95% confidence level (3 410 h)
8 characteristic life at the median level (4 809 h)
9 data point
10 interval
11 right censored data
12 left censored data

X time in hours
Y cumulative failure, expressed as a percentage

Figure B.3 — Weibull plot for interval data

From Figure B.3, results of the analysis are obtained. The shape parameter β is 1,416 9 and indicates a wear out of the components ($\beta > 1$). At the unreliability levels of 10% and 63,2%, the B_{10} life and the characteristic life, Eta, can be read off the traces.

The conclusion to be drawn from the test is that, at the 95% confidence level, the components have a B_{10} life of 555 h, and a characteristic life of 3 410 h.

Annex C
(informative)

Example calculation for collecting field data

C.1 Example of data surveyed in the field

The methods and equations of Annex B can be applied to data collected in the field.

Field data are usually right censored, since not all units have failed in service. To determine the reliability of a population of components statistically, information on the times to failure and suspensions are required. This example illustrates a method to calculate the reliability using data from sales and returns.

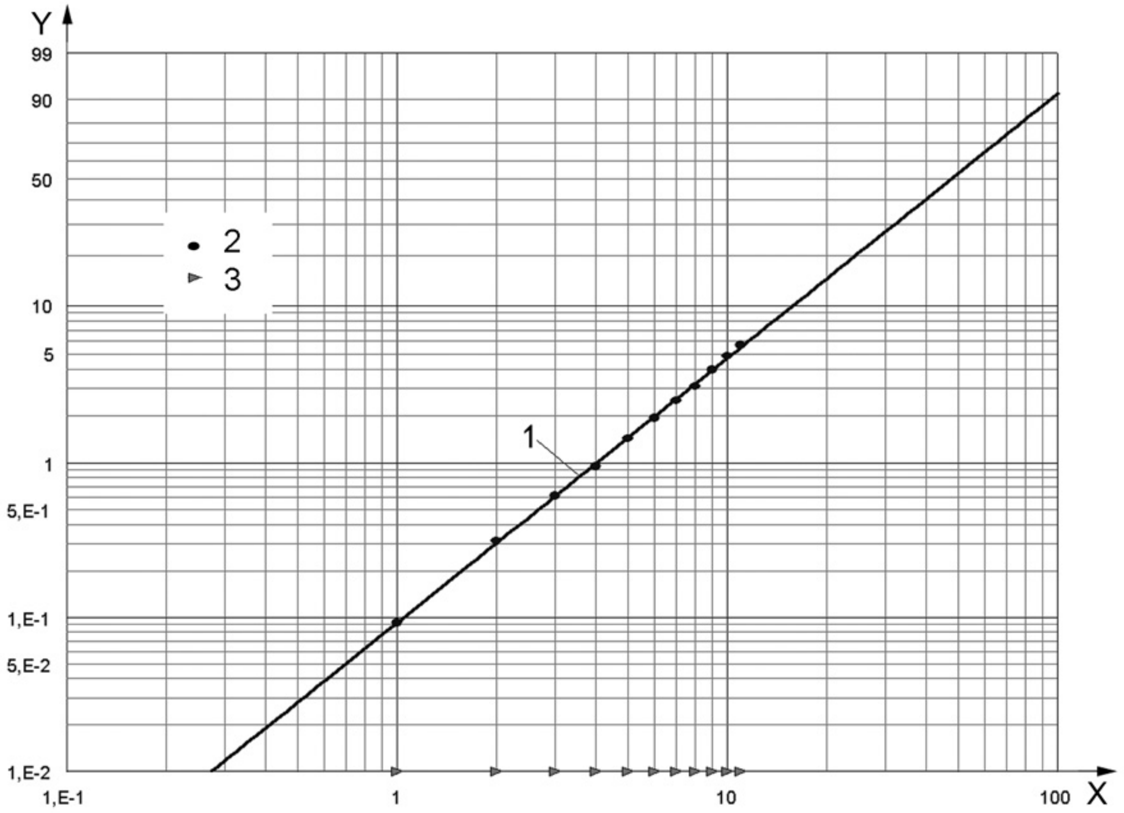
A Nevada chart is used to display sales and returns for a certain time period, as described in Table C.1. The horizontal rows describe the number of returns in succeeding months, from sales of the month in the left-hand column. The shaded diagonal cells indicate the number of returns in a common time interval from the month of sale. These are summed in the "Failed" column of the "Data for Weibull" category. (For example, there were 19 total returns after 2 months of service for all of the months of sales, i.e. the last shaded cell in the failed column.) Net returns from sales of a month in the left-hand column, are shown at the right-hand end. This number is subtracted from the sales to give the number of suspensions. The time is the number of months for the returns (failures) summed from the diagonal cells.

Table C.1 — Component field data set (Quantities of sales and returns)

		Returns											Data for Weibull				
Sales		Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Failed	Time	Susp.	Net returns	
Jan	815	1	1	2	2	3	0	2	5	8	7	7	7	11mo.	777	38	Jan
Feb	879	0	2	2	3	4	2	3	4	4	6	8	15	10	841	38	Feb
Mar	891	0	0	1	1	4	2	5	4	5	7	8	22	9	854	37	Mar
Apr	867	0	0	0	0	2	3	5	4	7	6	4	20	8	836	31	Apr
May	826	0	0	0	0	2	3	1	2	6	5	8	25	7	799	27	May
Jun	879	0	0	0	0	0	0	3	3	4	5	7	26	6	857	22	Jun
Jul	827	0	0	0	0	0	0	1	3	2	2	4	29	5	815	12	Jul
Aug	879	0	0	0	0	0	0	0	0	1	2	2	23	4	874	5	Aug
Sep	854	0	0	0	0	0	0	0	0	1	1	3	23	3	849	5	Sep
Oct	855	0	0	0	0	0	0	0	0	0	0	2	19	2	853	2	Oct
Nov	847	0	0	0	0	0	0	0	0	0	0	1	9	1	846	1	Nov
Dec	825	0	0	0	0	0	0	0	0	0	0	0	0	0	825	0	Dec

NOTE The above analysis is an approximation of the actual times that a product has been in service. If the actual dates of sales and returns are available, the true time to failure can be improved in the analysis. In that case, calculate the exact times to failure and suspension, and use a standard chart to analyse the data (see example B.2).

The modified Johnson formula for the plotting positions (Clause B.2), and Bernard's approximation for the median ranks (Clause B.4), could be used for developing a Weibull plot. However, commercial software was used to provide Figure C.1 using the data in the Nevada chart.



Key

X time in months

Y cumulative failure, expressed as a percentage

1 median rank for the two-parameter Weibull distribution

2 data points

3 censored data

NOTE Characteristic life = 58,75 months; Slope = 1,72

Figure C.1 — Weibull plot for component field data set

NOTE If the surveyed field data includes the whole population, confidence bounds are not meaningful. If only a part of the population is surveyed (sample) a lower confidence bound should be used to take random data into account. Then, the B_{10} life at the lower confidence bound should be used for declaration of reliability. An extrapolation beyond two times the failure or suspension time of the last data point is not recommended since further failures are uncertain.

Annex B equations can be applied to data collected in the field. The B_{10} life can be calculated using Equation (B.1). For a two-parameter Weibull, $x_0 = 0$ and Equation (B.1) reduces to Equation (C.1):

$$F(x) = 1 - e^{-\left(\frac{x}{\eta}\right)^{\beta}} \tag{C.1}$$

With a shape parameter $\beta = 1{,}72$ and a location parameter $\eta = 58{,}57$, the B_{10} life is calculated from Equation (C.2):

$$0{,}1 = 1 - e^{-\left(\frac{x}{58{,}57}\right)^{1{,}72}} \qquad \text{(C.2)}$$

and $x = 15{,}83$

The B_{10} life of the observed population is thus 15,83 months.

C.2 Reliability properties regarding interpretation of field data

C.2.1 General

Since reliability is a function influenced by several parameters and failure modes, caution is advised if results are generalized from a single data analysis. If a component can fail in several different failure modes, with consequently different shape parameters, the reliability will then depend on the failure mode. The application conditions (i.e. pressure, contamination, fluid, vibration and temperature) will also influence the location parameters. For these reasons, different reliability values of a component are possible. Thus, an unqualified general reliability statement for a component can be inaccurate. It is therefore recommended that if a single value of reliability is reported, that the most conservative value be used from either test assessment or field data.

C.2.2 Example with different failure modes

Consider a component used in several different applications with a different environmental condition for each application. The collected field data are statistically analysed and described in Table C.2 (only the results are shown and not the individual data values, for brevity in this example).

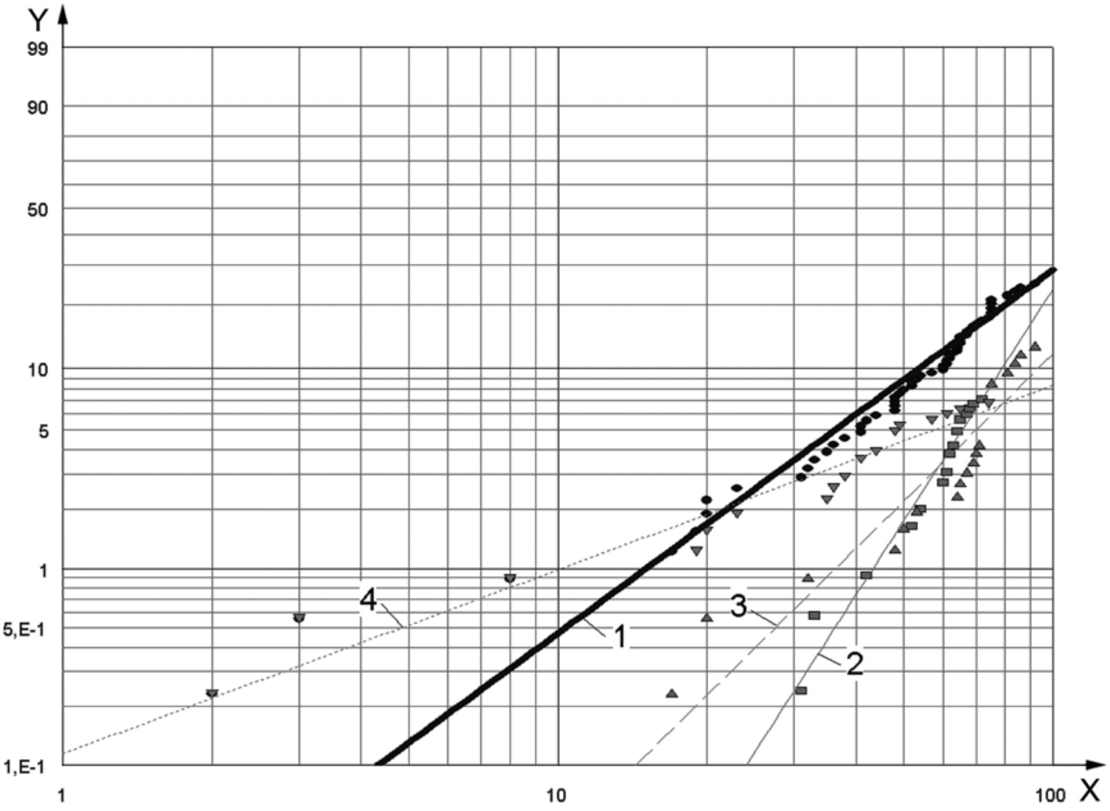
Under normal use conditions (application 1), the shape parameter of a distribution would remain constant while the location parameter would vary with the severity of a load. But, if more than one mode of failure can occur (with some modes not influenced by the load), then shape and location parameters will both change. All of these can change further, depending on the application conditions (applications 2 and 3).

In the following example with three failure modes of a directional control valve, different reliability values were calculated due to different conditions in the field.

Weibull plots for these three application conditions are shown in Figure C.2, Figure C.3 and Figure C.4.

Table C.2 — Component field data analysed with a two-parameter Weibull distribution

Application	Term	Failure mode			
		A: excessive leakage	**B: poor pressure gain**	**C: malfunction of electronic**	**D: Entire hydraulic component**
1: normal use	Beta	3,92	2,49	0,94	1,85
	Eta - months	140	230	1363	180
	B_{10} life - months	78,8	93,3	123,7	53,5
2: high pressure and contamination	Beta	3,94	2,07	1,35	1,74
	Eta - months	67	154	362	119
	B_{10} life - months	37,8	51,8	68,4	32,6
3: high temperature and vibration	Beta	4,65	2,28	1,00	1,17
	Eta - months	101	126	335	189
	B_{10} life - months	62,1	47,0	35,4	27,6



Key

X time in months

Y cumulative failure, expressed as a percentage

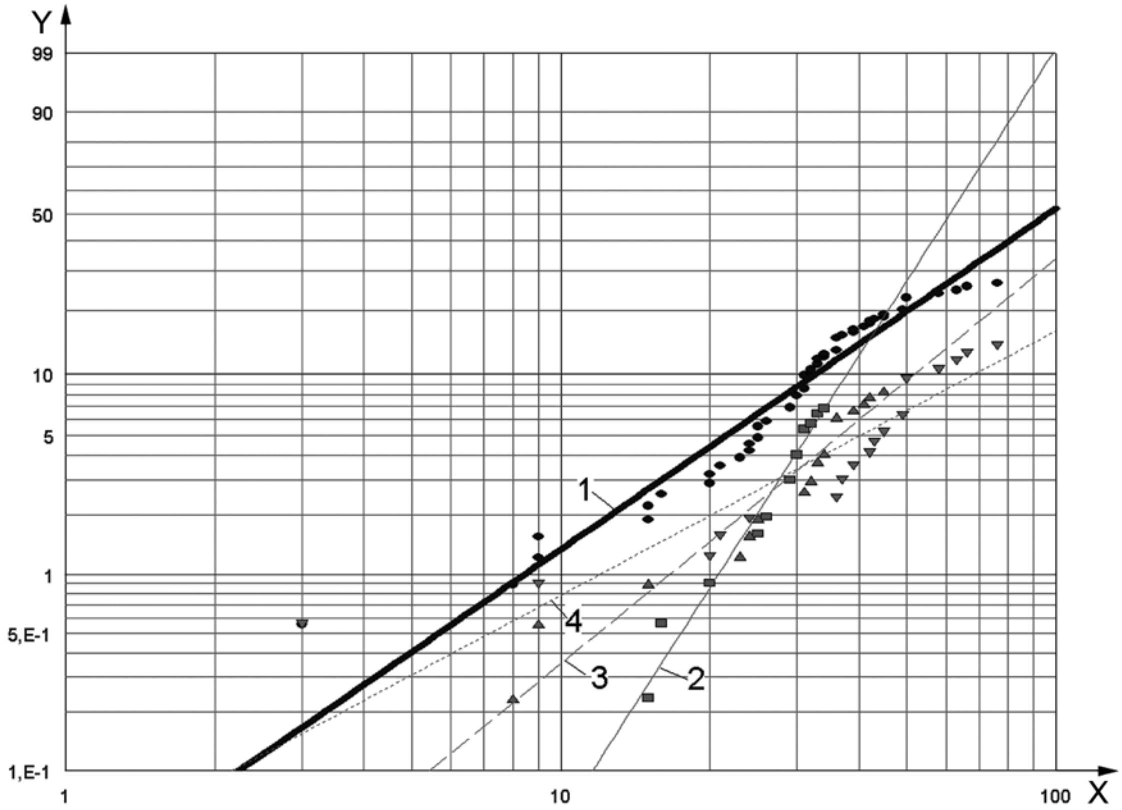
1 median rank probability for entire component: Eta = 180, $\beta = 1{,}85$

2 median rank probability for failure mode A: Eta = 140, $\beta = 3{,}92$

3 median rank probability for failure mode B: Eta = 230, $\beta = 2{,}49$

4 median rank probability for failure mode C: Eta = 1363, $\beta = 0{,}94$

Figure C.2 — Weibull plot for application 1 — Normal conditions



Key

X time in months

Y cumulative failure, expressed as a percentage

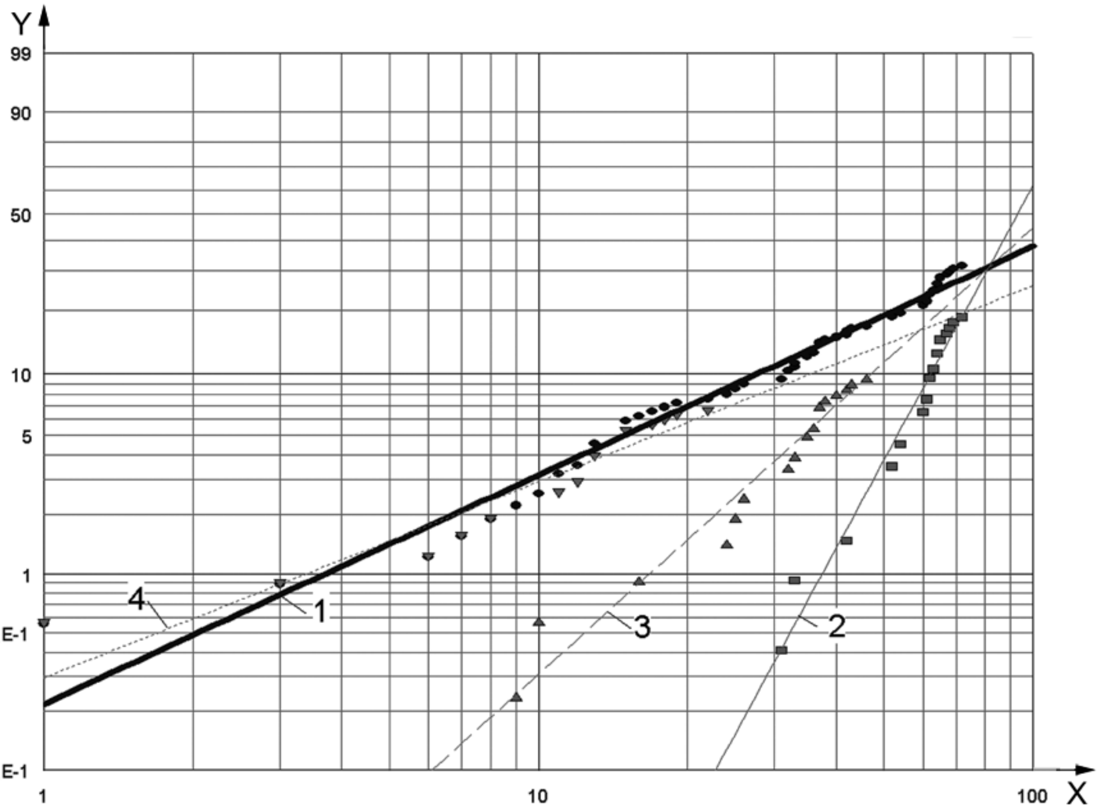
1 median rank probability for entire component: Eta = 119, $\beta = 1{,}74$

2 median rank probability for failure mode A: Eta = 67, $\beta = 3{,}94$

3 median rank probability for failure mode B: Eta = 154, $\beta = 2{,}07$

4 median rank probability for failure mode C: Eta = 362, $\beta = 1{,}35$

Figure C.3 — Weibull plot for application 2 — High pressure and contamination



Key

X time in months

Y cumulative failure, expressed as a percentage

1 median rank probability for entire component: Eta = 189, $\beta = 1{,}17$

2 median rank probability for failure mode A: Eta = 101, $\beta = 4{,}65$

3 median rank probability for failure mode B: Eta = 126, $\beta = 2{,}28$

4 median rank probability for failure mode C: Eta = 335, $\beta = 1{,}00$

Figure C.4 — Weibull plot for application 3 — High temperature and vibration

The median B_{10} life of the entire component is 53,3 months under normal use and is reduced for other applications with higher stresses due to individual failure modes of the elements.

Annex D
(informative)

Equation development and example calculations for substantiation testing

D.1 Development of the zero failure test duration equation

From the New Weibull Handbook [4], Equation (6-3):

$$R^n = (1 - \text{Confidence}) \qquad \text{(D.1)}$$

and from the cumulative distribution function for a 2-parameter Weibull from Equation (D.2):

$$R = e^{-\left(\frac{t}{\eta_0}\right)^{\beta}} \qquad \text{(D.2)}$$

and for a particular value along the distribution from Equation (D.3):

$$R_i = e^{-\left(\frac{t_i}{\eta_0}\right)^{\beta}} \qquad \text{(D.3)}$$

where:

t is the time at the corresponding value of R;

η_0 is the characteristic life for the zero distribution curve.

Let C = Confidence. By substituting expressions for R and for η_0, Equation (D.4) is obtained for t (test time); or Equation (D.5) is obtained for n (number of test specimens). These describe the requirements for a zero failure method to demonstrate that the test specimens represent a reliability equal to, or better than, the proposed distribution.

$$t = t_i \left(\frac{\ln(1-C)}{n \ln R_{\mathrm{i}}} \right)^{\frac{1}{\beta}} \qquad \text{(D.4)}$$

$$n = \left[\frac{\ln(1-C)}{\ln R_i} \right] \left(\frac{t_i}{t} \right)^{\beta} \qquad \text{(D.5)}$$

D.2 Zero failure test example

Consider that a population of hydraulic pumps has a Weibull slope of 2,0 and a characteristic life of 2 000 h (with a B_{10} life of 650 h). If the pump is redesigned using the same materials as the existing design, for how long do four new specimens have to be tested to demonstrate that they have a B_{10} life of at least 1 000 h at a confidence level of 70 % and what is the new characteristic life?

Alternatively, how many specimens are required if only 1 200 h of test time are available?

Since the redesigned pump uses the same materials as the original design, the Weibull slope β will be the same ($\beta = 2$).

From the description:

10 % for $B_i = B_{10}$; and

$R_\mathrm{i} = R_{10} = (1 - 0{,}10) = 0{,}90$; and

$t_i = 1\,000$ h; and $n = 4$ or $t_i = 1\,000$ h; and $t = 1\,200$ h for the alternative.

From Table 2 for B_{10} and $C = 70$ %, $A = 11{,}43$.

Then, from Equation (1) (see 10.2.1).

$$t = t_i \left(\frac{A}{n}\right)^{\frac{1}{\beta}} = 1\,000 \left(\frac{11{,}43}{4}\right)^{\frac{1}{2}} = 1\,690 \text{ h}$$

or

$$n = (11{,}43)\left(\frac{1\,000}{1\,200}\right)^2 = 7{,}9 \approx 8 \text{ samples.}$$

This is the test time required for zero failures, or the number of specimens for the reduced test time.

The new characteristic life is determined from the Weibull cumulative distribution function using known values at the B_{10} life using Equation (D.3), which can be solved as given in Equation (D.6):

$$\eta_0 = \frac{t_i}{(-\ln R_i)^{\frac{1}{\beta}}} = \frac{1\,000}{(-\ln 0{,}9)^{\frac{1}{2}}} = 3\,080{,}78 \text{ h} \tag{D.6}$$

In conclusion, the four specimens have each to survive 1 690 h of testing with no failures. In the alternative case, eight specimens have each to survive 1 200 h of testing with no failures. If either case is successful, the B_{10} life of the population will not be less than 1 000 h at a 70 % confidence level. The new characteristic life is 3 081 h.

In comparison, a standard test with four specimens tested to failure to determine a Weibull plot would require, [rearranging Equation (D.5) with the value of R_i at the fourth failure]:

$3\,081\ (-\ln 0{,}1591)^{1/2} = 4\,177$ h

of testing in order to determine the same reliability and confidence level. Thus, there is a saving of:

$(4\,177 - 1\,690) = 2\,487$ h

of test time over a standard failure test, if the Weibull distribution were not known. It is pointed out that this example assumes that the Weibull curve for the standard test is the same as that of the reduced test; and the fourth failure reliability value (of four specimens) is taken from the median curve, which is not exactly correct since the reduced test curve is a 70 % confidence curve. Nevertheless, this is just a comparison calculation.

D.3 Development of the zero/one failure duration equation

From the New Weibull Handbook [4], Equation (6-5):

$$(1 - \text{Confidence}) = R^n + nR^{n-1}(1 - R) \tag{D.7}$$

describes the binomial probability for no failures + 1 failure.

The value of $0 \leqslant R \leqslant 1$ that satisfies this equation has to be determined, and it begins by rearranging as follows:

$$X = R^n + nR^{n-1}(1 - R) - (1 - C)$$

where C is confidence.

For selected values of C and n, the roots of the equation will yield a value of $X = 0$. These roots can be found by organizing a spreadsheet for tables of C with columns of $2 \leqslant n \leqslant 10$ and rows of $0 \leqslant R \leqslant 1$. The cells of the table are values of X and a root value of R exists where the value of X becomes zero, corresponding to the value of n in the table for a C value. Other tables of C values yield similar results.

The root values of R are then used in the cumulative distribution equation for the 2-parameter Weibull, as given in Equation (D.8):

$$R_0 = e^{-\left(\frac{t_0}{\eta_{01}}\right)^{\beta}} \tag{D.8}$$

where

R_0 is the root value found in the Excel spreadsheet for particular C and n values;

η_{01} is the characteristic life for the zero/one distribution curve.

The value of t_0 corresponding to the value of R_0 is the test requirement.

Other values on the zero/one distribution curve can be found from Equation (D.9):

$$R_j = e^{-\left(\frac{t_j}{\eta_{01}}\right)^{\beta}} \tag{D.9}$$

Combining these last two equations results in Equation (D.10):

$$t_0 = t_{\mathrm{j}}\left(\frac{\ln R_0}{\ln R_j}\right)^{\frac{1}{\beta}} \tag{D.10}$$

which describes the test time t_0 required for a zero or one failure method to demonstrate that the specimens are equal to, or better than, the proposed new distribution.

D.4 Zero/one failure test example

Using the same example as in Clause D.2, consider that a population of hydraulic vane pumps has a Weibull slope of 2,0 and a characteristic life of 2 000 h (with a B_{10} life of 650 h). If the pump is redesigned using the same materials as the existing design, for how long do four new specimens have to be tested to demonstrate that they have a B_{10} life of 1 000 h at a confidence level of 70 % and what is the new characteristic life?

Since the redesigned pump uses the same materials as the old design, the Weibull slope β will be the same ($\beta = 2$). If for this case, the same B_{10} life is chosen as in the zero failure case, then $i = j$.

From the description:

10 % for $B_j = B_{10}$;

$R_j = R_{10} = (1 - 0{,}10) = 0{,}90$

$t_j = 1\ 000$ h

$n = 4$

From Table 3 at $C = 0{,}70$ and $n = 4$ then $R_0 = 0{,}491\ 6$.

Then, from Equation (D.10):

$$t_0 = t_j \left(\frac{\ln R_0}{\ln R_j} \right)^{\frac{1}{\beta}} = 1\,000 \left(\frac{\ln 0{,}4\ 916}{\ln 0{,}90} \right)^{\frac{1}{2}} = 2\ 596{,}4 \text{ h}$$

This is the test time for zero or one failure.

The new characteristic life is determined form the Weibull cumulative distribution function, using known values at the B_{10} life and Equation (D.9), which can be solved as given in Equation (D.11):

$$\eta_{01} = \frac{t_j}{\left(-\ln R_j \right)^{\frac{1}{\beta}}} = \frac{1\,000}{\left(-\ln 0{,}9 \right)^{\frac{1}{2}}} = 3\ 080{,}78 \text{ h} \qquad \text{(D.11)}$$

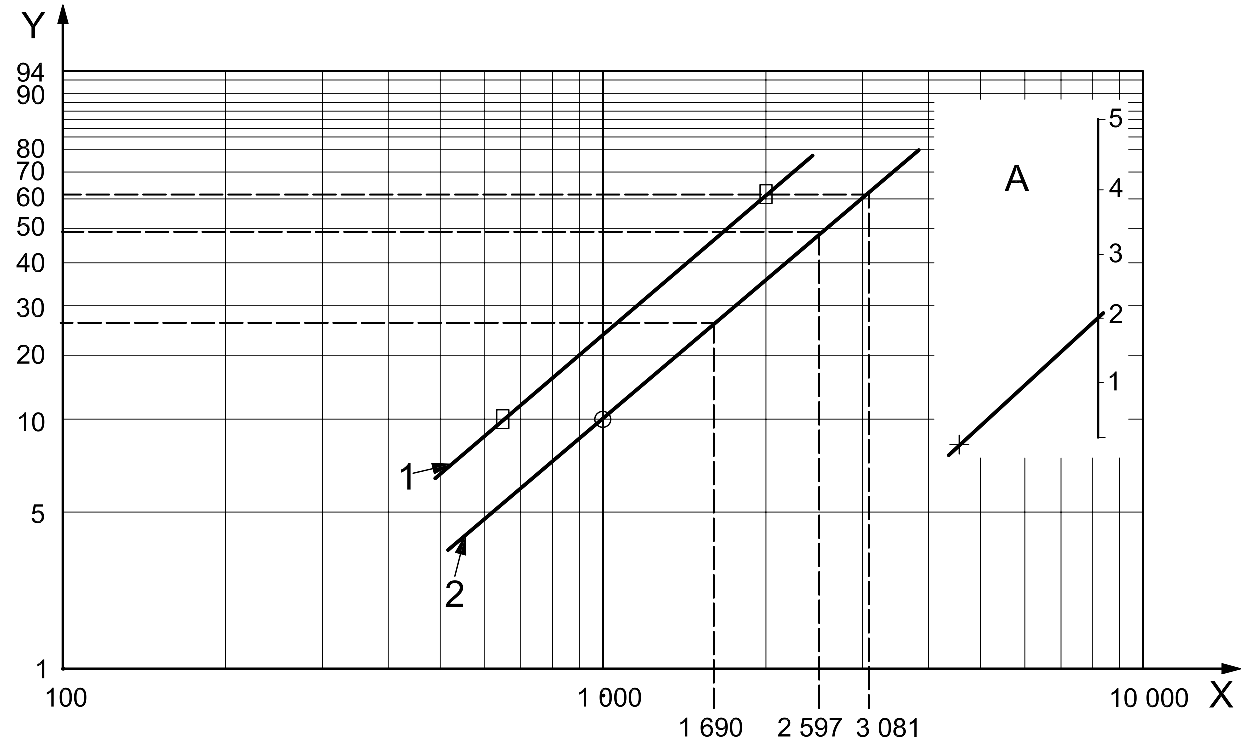
This is the same as for the zero failure method. This is to be expected if the same B_{10} life is used for both cases. However, the test time requirement is greater for the zero or one method since one failure is allowed. Nevertheless, the saving in test time is

(4 177 – 2 597) = 1 580 h

over a standard failure test, if the Weibull distribution were not known.

If all the specimen pumps could not be tested at one time (perhaps only one at a time), the last specimen need not be tested if all of the others survive their test runs. This is the meaning of zero or one failure.

The zero, and zero or one, methods are described in the Weibull plot shown in Figure D.1.



Key

X life, expressed in hours

Y cumulative failure, expressed as a percentage

A Weibull slope scale

1 existing pump

2 new pump with target reliability B_{10} life of 1 000 h

Figure D.1 — Zero and zero or one Weibull plots

Annex E
(informative)

Reference material

Table E.1 — Shape parameter, β, for hydraulic components from the Korea Institute of Machinery and Materials

Type	β	No.	Components	No.	Reliability assessment standards
Hydraulic components	1,1	1	Hydraulic valve	1	Hydraulic relief valve
				2	Hydraulic directional control valves
		2	Hydraulic valve	3	Steering valve for forklift
		3	Hydraulic filter	4	Filter for hydraulic circulation
		4	Agriculture machine filter	5	Spin-on type hydraulic filter for agriculture machines
	1,2	1	Oil cooler	6	Oil chillers for machine tool
				7	Shell and tube type oil coolers for industrial
		2	Multiple control valve	8	Multiple control valve for excavator
				9	Multiple control valve for forklift
		3	Heat exchanger	10	Plate type heat exchangers for marine engine
	1,3	1	Hydraulic motor	11	Swash plate type axial piston hydraulic motors for track drive unit of excavator
		2	High-pressure control valve	12	Industrial high-pressure relief valve
		3	Hydraulic valve	13	Speed-up valve for crusher
	1,4	1	Proportional valves	14	Electro-hydraulic proportional pressure relief valve for power steering
				15	Electro-hydraulic proportional pressure reducing valve
		2	Servo valve	16	Nozzle-flapper type electro-hydraulic servo valve, flow control
				17	Direct drive type electro-hydraulic servo valves, flow control
		3	Breaker	18	Hydraulic breaker
		4	Flexible hose and fitting	19	Hydraulic hose assemblies for construction machinery
		5	Accumulator	20	Oil hydraulic system – Bladder type accumulator
	1,5	1	Seal and packing	21	Reciprocating seal for hydraulic cylinder
				22	Rotary seal for hydraulic pump
		2	Servo actuator	23	Hydraulic servo actuator for simulation
	1,6	1	Transmission	24	Transmission for agriculture tractor use
	2,0	1	Hydraulic cylinder	25	Hydraulic cylinder for sluice gate
				26	Hydraulic cylinder for sluice gate of vessel
				27	Hydraulic cylinder for cargo crane
				28	Hydraulic actuator for aircraft landing gear
		3	Transmission	29	Manual transmission for small size diesel vehicle
				30	Manual transmission for high-powered motorcycle
				31	Power shift type auto transmission for forklift
		4	Track drive unit	32	Track drive unit for excavator
				33	Track drive unit for mini excavator
		5	Swing drive unit	34	Swing drive unit for excavator
		6	Hydraulic motor	35	Swing motor for inertia control
		7	Axle	36	Drive axle for medium size forklift
		8	Industrial lift	37	Fixed type single-stage table lift

Table E.1 (*continued*)

Type	β	No.	Components	No.	Reliability assessment standards
Hydraulic components	2,0	9	Ultra high-pressure 2-stage hydraulic actuator	38	Tension actuator for opening and shutting of nuclear reactor
		10	Mechanical spring	39	Helical spring for diesel engine valves
		11	Pressure transducer	40	Industrial semiconductor pressure sensor
		12	Gear box	41	Gearbox for roller
				42	Coupled 2-stage planetary gear box
				43	Reduced gear box for agitator
				44	Final drives for heavy equipment
	2,1	1	Mechanical spring	45	Door latch springs for vehicle
	2,5	1	Clutches	46	Hydrodynamic clutch for forklift truck
				47	High-capacity hydrodynamic clutch
	2,8	1	Hydrostatic transmission	48	Hydrostatic transmission for agriculture tractor transmission
				49	Hoist for steering function in armoured car
		2	Tandem pump	50	Tandem pump for excavator
	3,0	1	Oil pump	51	Power steering oil pumps for commercial vehicle
				52	Trochoid pump for lubrication
				53	Gear pumps for agricultural machinery
				54	Gear pump for forklift
				55	Power steering oil pump for passenger car
		2	High-pressure pump	56	Industrial high-pressure pump
Mechanical components	1,1	1	Ultrasonic component	1	Ultrasonic parts for cleaning
		2	Bearing	2	Ball bearings for manual transmission of a vehicle
				3	Thrust ball bearings of industry
		3	Rubber type anti-vibration mount	4	Air spring for railway vehicle
		4	Spindle shaft unit	5	Main spindle of CNC automatic lathe
		5	Mechanical seal	6	Mechanical seal for water pump
		6	Industrial solenoid	7	Solenoid for industrial sewing machine
		7	Industrial damper	8	Industrial multi-purpose shock absorber
		8	Ball valve	9	Multi-way half ball valve
		9	Flexible hose and fitting	10	Plastic hose assemblies
	1,2	1	Diesel engine	11	Diesel engine for agriculture tractor use
		2	Linear motor	12	Linear synchronous motor for position control
	1,4	1	Industrial brake	13	Drum brake for forklift truck
				14	Industrial gear coupling
	2,5	1	Vacuum pump	15	Water ring vacuum pump
	2,6	1	Coupling	16	Industrial gear coupling
	2,8	1	Centrifugal pump	17	Vertical type multi-stage centrifugal pump
	3,0	1	Industrial continuously variable speed changer	18	Industrial chain type continuously variable speed changer
		2	Industrial nozzle	19	Spray nozzle under pressure used in industry
		3	Industrial propeller shaft	20	Propeller shaft of paper machine
		4	Aerial ladder	21	Straight type aerial ladder for carrying freight
		5	Load cell	22	Shear beam type load cell
	6,5	1	Ball screw	23	Positioning ball screw

For additional reference material, see Barringer and Associates, Inc. [5].

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