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Pneumatic fluid power — Assessment of component reliability by testing —

Part 1:
General procedures

Transmissions pneumatiques — Évaluation par essais de la fiabilité des composants —

Partie 1: Procédures générales

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the WTO principles in the Technical Barriers to Trade (TBT) see the following URL: Foreword - Supplementary information

The committee responsible for this document is ISO/TC 131, *Fluid power systems*.

This second edition cancels and replaces the first edition (ISO 19973-1:2007) which has been technically revised.

ISO 19973 consists of the following parts, under the general title *Pneumatic fluid power — Assessment of component reliability by testing*:

- *Part 1: General procedures*
- *Part 2: Directional control valves*
- *Part 3: Cylinders with piston rod*
- *Part 4: Pressure regulators*
- *Part 5: Non-return valves, shuttle valves, dual pressure valves (AND function), one-way adjustable flow control valves, quick-exhaust valves*

Introduction

In pneumatic fluid power systems, power is transmitted and controlled through a gas under pressure within a circuit. Pneumatic 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.

It is necessary that machine producers know the reliability of the components that make up their machine's pneumatic fluid power system. Knowing the reliability characteristic of the component, which can be determined from laboratory testing, the producers can model the system and make decisions on service intervals, spare parts inventory and areas for future improvements.

There are three primary levels in the determination of component reliability:

a) preliminary design analysis: finite element analysis (FEA), failure mode and effect analysis (FMEA);

b) laboratory testing and reliability modelling: physics of failure, reliability prediction, pre-production evaluation;

c) collection of field data: maintenance reports, warranty analysis.

Each level has its application during the life of a component. A preliminary design analysis is useful to identify possible failure modes and eliminate them or reduce their effect on reliability. 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.

Specific component test procedures and exclusions are provided in ISO 19973-2, ISO 19973-3, ISO 19973-4 and ISO 19973-5.

Pneumatic fluid power — Assessment of component reliability by testing —

Part 1:
General procedures

1 Scope

This part of ISO 19973 provides general procedures, the calculation method for assessing the reliability of pneumatic fluid power components and the methods of reporting. These procedures are independent of the kinds of components and of their design.

This part of ISO 19973 also provides general test conditions and a method for data evaluation.

NOTE Because the service life of any component is subject to variations, a statistical evaluation assists the interpretation of the test results.

The methods specified in this part of ISO 19973 apply to the first failure without repairs (see IEC 60300-3-5), but exclude outliers; however, because outliers can be highly significant, information about how to deal with them is given in Annex F.

2 Normative references

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

ISO 3534-1, *Statistics — Vocabulary and symbols — Part 1: General statistical terms and terms used in probability*

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

ISO 6358 (all parts), *Pneumatic fluid power — Determination of flow-rate characteristics of components using compressible fluids*

ISO 10099, *Pneumatic fluid power — Cylinders — Final examination and acceptance criteria*

ISO 19973-3, *Pneumatic fluid power — Assessment of component reliability by testing — Part 3: Cylinders with piston*

ISO 80000-1, *Quantities and units — Part 1: General*

IEC 60050-191, *International Electrotechnical Vocabulary, chapter 191: Dependability and quality of service*

IEC 61649, *Goodness-of-fit tests, confidence intervals and lower confidence limits for Weibull distributed data*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 3534-1, ISO 5598 and IEC 60050-191 and the following apply.

3.1
catastrophic failure
failure of an item that results in its complete inability to perform all required functions

3.2
confidence coefficient
confidence level
value $(1 - \alpha)$ of the probability associated with a confidence interval or a statistical coverage interval

Note 1 to entry: See also 3.6.

Note 2 to entry: See ISO 3534-1 for notes related to this term and definition.

3.3
confidence limit
either of the limits, T_1 or T_2, of the two-sided confidence interval, or the limit, T, of the one-sided confidence interval

Note 1 to entry: See ISO 3534-1 for notes related to this term and definition.

3.4
failure
termination of the ability of an item to perform a required function

Note 1 to entry: In the ISO 19973 (all parts), the reaching of a threshold level for statistical calculation is also considered a statistical failure (see Annex A).

[SOURCE: IEC 60050-191]

3.5
one-sided confidence interval
T

interval estimator for a parameter, Θ, comprised of the interval from the smallest possible value of the parameter, Θ, up to T or the interval from T up to the largest possible value of Θ, where the probability $p(T \geq \Theta)$ or $p(T \leq \Theta)$ is at least equal to $(1 - \alpha)$, where $(1 - \alpha)$ is a fixed number, positive and less than 1

Note 1 to entry: See ISO 3534-1 for notes related to this term and definition.

3.6
relevant failure
failure that should be included in interpreting test or operational results or in calculating the value of a reliability performance measure

[SOURCE: IEC 60050-191]

3.7
reliability
probability that an item can perform a required function under given conditions for a given time interval

[SOURCE: IEC 60050-191]

3.8
sample
one or more test units taken from a population and intended to provide information on the population

Note 1 to entry: A sample can serve as a basis for a decision on the population or on the process that produced it.

3.9
sample size
number of test units in the sample

Note 1 to entry: In a multi-stage sample, the sample size is the total number of test units at the conclusion of the final stage of sampling.

3.10
three-point moving average
3PMA
arithmetic average of three consecutive measured component’s test data

3.11
threshold level
value of a performance characteristic (for example, leakage, shifting pressure, stroke time, etc.) against which the component’s test data is compared

Note 1 to entry: This is an arbitrary value defined by the experts as the critical value for performance comparisons, but is not necessarily indicative of a component failure.

4 Symbols and units of measurement

4.1 The symbols used in this part of ISO 19973 are given in Table 1.

Table 1 — Symbol list

Symbol[a]	Definition
B_{10}	Expected time at which 10 % of the population is predicted to fail (10 % of the lifetime distribution)
$(B_{10})_{95\,\%}$	B_{10} life at the one-sided 95 % confidence level
η	Scale parameter (characteristic life) of the Weibull distribution
$F(t)$	Probability of failure, expressed in percent
β	Shape parameter (slope) of the Weibull distribution
$R(t)$	Reliability of a component at time t ; $1-F(t)$
t	Life time expressed in time, cycles, or distance

[a] Other symbols can be used in other documents and software.

4.2 Units of measurement are in accordance with ISO 80000-1.

5 Concept of reliability

For the purposes of this part of ISO 19973, reliability is the probability that a component does not have a relevant failure for a specified interval of time, number of cycles or distance when it operates under stated conditions.

A relevant failure occurs when

— component data, determined using the three-points moving average (*3PMA*), exceeds a threshold level for the first time (see 10.2), or

— a component experiences a catastrophic failure (burst, fatigue or functional failure, etc.).

Threshold levels of the components covered by ISO 19973 (all parts) are specified in the component-specific parts of this International Standard.

This probability can be determined by analysing the results of a series of tests and describing the population failure by statistical methods. There are many different statistical distributions that describe the population of failures that result from testing.

It is also possible to verify the minimum life of a component by the one-sided confidence estimation at a specified reliability level. Examples are given in Annex E.

6 Strategies for conducting testing

6.1 Assumptions

The reliability of pneumatic components in an application depends on many environmental factors, including pressure, temperature, dew point and contamination level of the compressed air, externally imposed loads, duty cycle, etc. Any prediction of the reliability of an individual component, therefore, shall take all of these environmental factors into consideration.

This part of ISO 19973 is based on a prescribed level of stress, test conditions and duty cycle that reflects the best judgement of its developers to represent typical industrial conditions. It also includes conditions that provide consistency in the test method. Thus, the results can be used as a reference that a user can apply to judge against any other set of conditions.

In particular applications, the requirements of this part of ISO 19973 may be modified to suit a specific stress level, test condition or duty cycle. However, such testing shall follow all of the other requirements for test methods and data analysis specified in this part of ISO 19973.

6.2 Test stand and measurement of parameters

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

6.3 Test planning

Proper test planning is essential in order to produce results that accurately predict the component's reliability under specified conditions. The goals and objectives of the test program shall be clearly defined if a supplier and user agree to apply ISO 19973 (all parts).

7 Statistical analysis

The resulting test data shall be evaluated for assessing the reliability. One of the most commonly used methods is the Weibull analysis because of its versatility in modelling various statistical distributions. This method shall be used for the analysis of the test data to ensure comparability of the results. Examples of applying Weibull analysis are given in the Annex C and Annex D.

NOTE Commercial software can be helpful for this purpose.

8 Test conditions

8.1 Testing shall be carried out in accordance with the provisions defined in the part of ISO 19973 that relates to the component tested, including the test parameters that are measured and threshold levels specified for each test parameter.

8.2 No repairs are permitted on the test units during the reliability test.

8.3 Unless otherwise specified in the relevant part of ISO 19973 that relates to the component being tested, or when agreed between the user and supplier, all tests shall be carried out under the conditions specified in Table 2.

Table 2 — General test conditions

Parameter	Value
Test pressure	630 kPa ± 30 kPa (6,3 bar ± 0,3 bar)
Ambient temperature	23 °C ± 10 °C
Temperature of the medium	23 °C ± 10 °C
Filtration: nominal filtration rating	5 µm
Dryer: maximum inlet or test pressure dew point[a]	+7 °C
Lubrication	None

[a] Testing at dew points of less than −20 °C could result in shorter lifetimes.

8.4 Temperature changes due to thermodynamic processes while pressurizing and depressurizing test units should be considered during the setup and initial running period of the first day. If the temperature change of the test unit's body exceeds ±20 °C during the initial running period, the test frequency should be adjusted. Later adjustments of the test frequencies are not permitted.

8.5 During the endurance test, test units shall be operated continuously, and the measuring intervals for recording data shall be determined taking into account the experience and judgement of the people conducting the test. A measuring interval of one week is recommended.

8.6 Except for cylinders, the volume at outlet ports depends on the component's sonic conductance, C, as determined in accordance with ISO 6358 (all parts). The volumes shall meet or exceed the minimum values given in Table 3.

NOTE During testing, the volumes at the outlet ports can become hot. It is necessary to take care to protect personnel.

Table 3 — Minimum volume at the outlet ports, based on component's sonic conductance

Sonic conductance C dm^3/(s·kPa)(ANR)	**Minimum volume at the outlet ports** cm^3
$C \leq 0,004$	2
$0,004 < C \leq 0,04$	10
$0,04 < C \leq 0,12$	25
$0,12 < C \leq 0,2$	50
$0,2 < C \leq 0,4$	100
$C > 0,4$	200

9 Sample size and selection criteria

9.1 The samples shall be representative of the population and shall be selected randomly.

9.2 The minimum sample size shall be seven test units.

NOTE It is important that the sample has at least seven test units in order that the first data point on the Weibull graph is below the 10 % cumulative-failure point. This allows a more accurate projection of the lower confidence limit lines to intersect the 10 % cumulative-failure point and determine a B_{10} life.

9.3 For a product series with the same design principle, it is not necessary to test all types or sizes. However, the test program shall include the type with the most critical conditions, for example, highest stress caused by velocity or load.

10 End of test

10.1 Minimum number of failures required

The minimum number of test units that are required to fail (e.g. reach a threshold level) is described in Table 4. This number does not include suspensions, which are not considered failures.

NOTE It is desirable to achieve at least 10 failures in accordance with IEC 61649. Fewer failures result in a wider confidence interval and a shorter $(B_{10})_{95\,\%}$ life at the lower confidence limit.

Table 4 — Minimum number of failures for evaluation of the characteristic life

Sample size	7	8	9	10	>10
Minimum numbers of failures	5	6	7	7	70 % of the sample size

10.2 Termination time of a test unit

A test unit shall be terminated from testing when its life reaches the first failure, calculated as follows: First, determine a three-point moving average of the test data on a continuous basis (an example is shown in Annex A). When the three-point moving average exceeds the threshold value, the test unit shall have reached a first failure and shall be terminated from testing.

10.3 Termination life

The termination life shall be the last time at which the three-point moving average did not exceed the threshold, or the time preceding a catastrophic failure. If a more precise determination of the termination life is desired, performance of a test unit can be monitored with limit switches or other suitable means to detect failures.

10.4 Suspended test unit

Testing on an individual test unit may be stopped before a relevant failure occurs. This is known as a suspension. Some examples of suspensions include

— a unit which has been disassembled for inspection, or

— a unit which has been accidentally crushed.

Suspensions have an influence on the result of calculating the statistical parameters and should therefore be considered. See Annex D.

10.5 Censored test

If the test is stopped after the minimum number of failures specified in Table 4 is reached but the remaining test units are still operating, the test shall be considered censored. If the censored test does not include any suspensions, the method specified in Annex C should be used to calculate the statistical parameters. If the censored test includes one or more suspensions, the method specified in Annex D should be used to calculate the statistical parameters.

11 Evaluation of reliability characteristics from the test data

11.1 To improve the interpretation of the calculation results, the failure mode shall be specified and recorded.

11.2 The Maximum Likelihood Estimation or Median Rank Regression shall be used to determine the best fit of the Weibull curve to the test data, and the Fisher Matrix shall be used to determine the confidence bounds.

11.3 Calculations shall be made from the test data to determine the following:

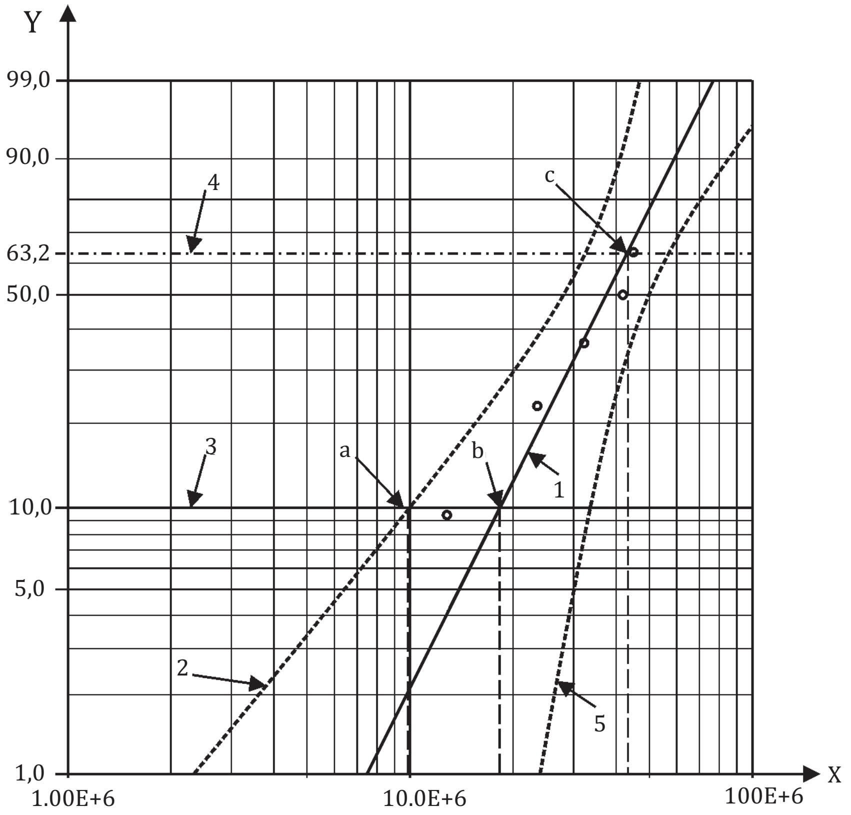
— characteristic life, η: relative location of the straight line in the Weibull plot relative to the x-axis (time or scale parameter);

— Weibull shape parameter, β: slope of the straight line in the Weibull plot.

11.4 Calculate the B_{10} life at the best fit line (see Figure 1, key b).

NOTE See Annex D for information on how to deal with censored data with suspensions.

11.5 Calculate the confidence limit of the $(B_{10})_{95\ \%}$ life at the lower 95 % confidence level (see Figure 1, key a).



Key

X	number of cycles to failure, *t*		a	$(B_{10})_{95\ \%}$ life at the lower, one-sided 95 % confidence level.
Y	probability of failure, expressed as a percentage		b	B_{10} life.
1	best fit line, determined by the Maximum Likelihood Estimation		c	Characteristic life, η.
2	lower confidence limit at 95 %, obtained by Fisher Matrix			
3	10 % failure probability line			
4	63,2 % failure probability line			
5	upper confidence limit at 5 %			

NOTE Commercial software can be useful in constructing the graphs.

Figure 1 — Example of how a B_{10} life value is determined from a Weibull curve

12 Test report

The test report shall include at least the following data:

a) number of the relevant part of ISO 19973, including the component-specific part number (for example, ISO 19973-2 for valves);

b) date of the test report;

c) component description (manufacturer, type designation, series number);

d) sample size;

e) test conditions (test pressure, temperature, air quality, frequency, load, etc.);

f) threshold levels;

g) type of failure for each test unit;

h) B_{10} life at the median rank, and confidence limit of $(B_{10})_{95\,\%}$ life at one-sided 95 % confidence level;

i) characteristic life, η, and shape parameter, β;

j) number of failures considered and test interval used;

k) method used to calculate the Weibull data (for example, maximum-likelihood, median rank regression, Fisher Matrix);

l) Weibull plot;

m) other remarks, as necessary.

13 Identification statement (reference to this part of ISO 19973)

It is recommended that manufacturers use the following statement in test reports, catalogues and sales literature when electing to comply with this part of ISO 19973:

"General procedures for assessing pneumatic component reliability by testing performed in accordance with ISO 19973-1, *Pneumatic fluid power — Assessment of component reliability by testing — Part 1: General procedures*."

Annex A
(normative)

Determination of the termination life

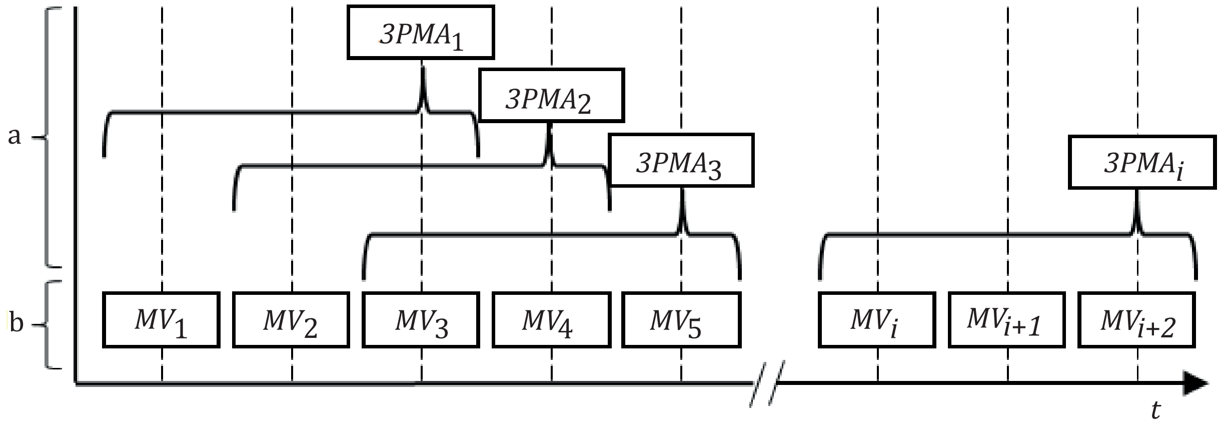
A.1 Characteristics of the failure process of pneumatic components

The failure process is extremely nonlinear. There are many observations where a failure threshold is exceeded, but continued testing often results in a test unit recovering from failure, its data goes back below the threshold. This phenomenon is a type of “self-repair” that is often explained from physical examinations. Then again, some failure modes hardly change; and at other times there is catastrophic failure where a unit is not functional. There is also a lot of noise in the measured values of the failure mode.

In order to accommodate these variations, the procedures described in this annex shall be used to determine the life at which a first failure occurs.

A.2 Three-point moving average

The three-point moving average (hereafter referred to as *3PMA*) is the mean of the values from three consecutive measuring intervals, as illustrated in Figure A.1 and calculated in accordance with Formula (A.1):



Key

a	three-points moving average
b	measured data
i	number of the measuring interval
t	life time expressed in time, cycles or distance
MV	measured value

Figure A.1 — Calculation rules for three-points moving average

$$3PMA_i = \frac{MV_i + MV_{i+1} + MV_{i+2}}{3} \qquad \text{(A.1)}$$

A.3 Termination life

Because interval data is recorded during a test, the three-point moving average is based on the data recorded corresponding to the cycle count at the time of inspection.

The termination time shall be the cycle count where the three-points moving average of the observed data exceeds the threshold level. The termination life shall be the last time at which the three-points moving average did not exceed the threshold level.

A.4 Examples

A.4.1 Shifting pressure of a valve

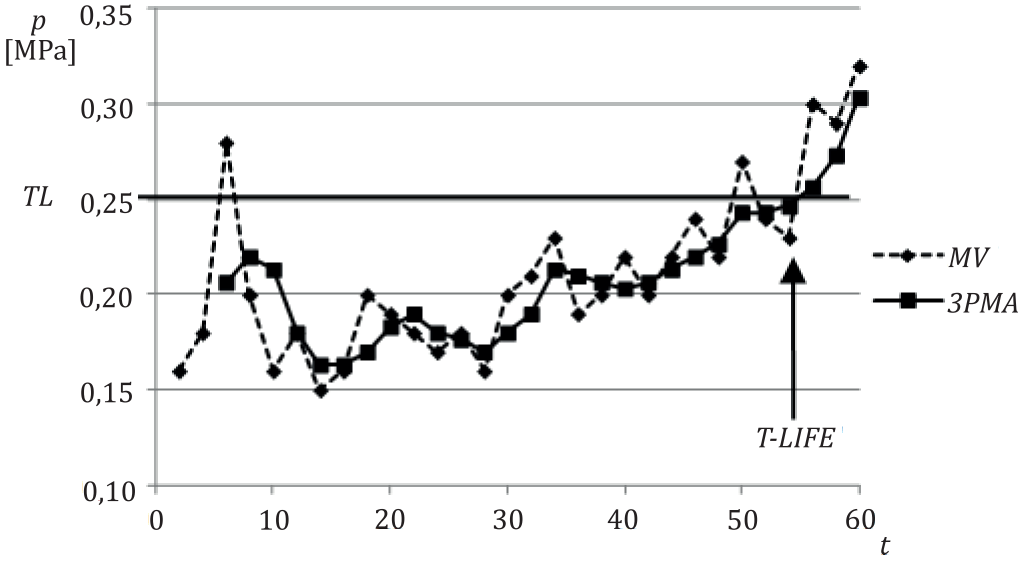
Table A.1 shows measured data from the immediate shifting pressure in a valve test. According to the manufacturer's catalogue, the minimum working pressure rating is 0,25 MPa. This value then, is the threshold level for immediate shifting. The light-shaded cells in the table indicate when the measurements, at a recorded cycle count, exceeded a threshold level. The termination time, using the three-points moving average, is indicated in the dark-shaded cell at 56 million cycles.

Thus, the termination life needed for plotting a Weibull curve is 54 million cycles (in accordance with 10.3).

Table A.1 — Recorded data of the immediate shifting pressure of a valve, and its calculated *3PMA*

t 10^6 cycles	*MV* [MPa]	*3PMA* [MPa]	*t* 10^6 cycles	*MV* [MPa]	*3PMA* [MPa]	*t* 10^6 cycles	*MV* [MPa]	*3PMA* [MPa]
2	0,16	-	22	0,18	0,19	42	0,20	0,21
4	0,18	-	24	0,17	0,18	44	0,22	0,21
6	0,28	0,21	26	0,18	0,18	46	0,24	0,22
8	0,20	0,22	28	0,16	0,17	48	0,22	0,23
10	0,16	0,21	30	0,20	0,18	50	0,27	0,24
12	0,18	0,18	32	0,21	0,19	52	0,24	0,24
14	0,15	0,16	34	0,23	0,21	54	0,23	0,25
16	0,16	0,16	36	0,19	0,21	56	0,30	0,26
18	0,20	0,17	38	0,20	0,21	58	0,29	0,27
20	0,19	0,18	40	0,22	0,20	60	0,32	0,30

Figure A.2 is a graph of the recorded data and the three-points moving average from Table A.1.



Key

3PMA	three-points moving average
p	immediate shifting pressure
MV	measured value
t	life time cycles by 10^6
T-LIFE	termination life
TL	threshold level

Figure A.2 — Immediate shifting pressure of a valve with comparison of measured data points and the *3PMA*

A.4.2 Leakage of a cylinder

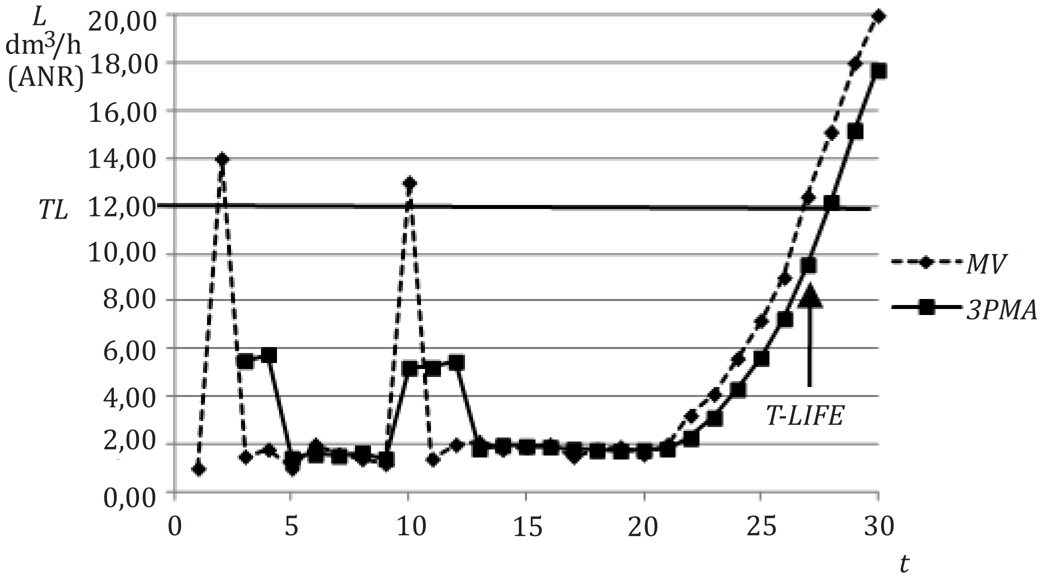
Table A.2 shows measured leakage data from a 40 mm bore cylinder test. According to ISO 19973-3 and ISO 10099, the threshold level for leakage of this bore size is 12 dm^3/h (ANR). The light-shaded cells in the table indicate when the measurements at a recorded cycle count, exceeded a threshold level. The termination time, using the three-points moving average, is indicated in the dark-shaded cell at 28 million cycles.

Thus, the termination life needed for in plotting a Weibull curve is 27 million cycles (in accordance with 10.3).

Table A.2 — Recorded data of the leakage of a cylinder, and its calculated *3PMA*

t 10^6 cycles	***MV*** [dm^3/h]	***3PMA*** [dm^3/h]	***t*** 10^6 cycles	***MV*** [dm^3/h]	***3PMA*** [dm^3/h]	***t*** 10^6 cycles	***MV*** [dm^3/h]	***3PMA*** [dm^3/h]
1	1,00	-	11	1,40	5,20	21	2,00	1,83
2	14,00	-	12	2,00	5,47	22	3,20	2,27
3	1,50	5,50	13	2,10	1,83	23	4,10	3,10
4	1,80	5,77	14	1,80	1,97	24	5,60	4,30
5	1,00	1,43	15	1,90	1,93	25	7,20	5,63
6	2,00	1,60	16	2,00	1,90	26	9,00	7,27
7	1,60	1,53	17	1,50	1,80	27	12,40	9,53
8	1,40	1,67	18	1,80	1,77	28	15,10	12,17
9	1,20	1,40	19	1,90	1,73	29	18,00	15,17
10	13,00	5,20	20	1,60	1,77	30	20,00	17,70

Figure A.3 is a graph of the recorded data and the three-points moving average from Table A.2.



Key

3PMA	three-points moving average
L	leakage rate
MV	measured value
t	life time cycles by 10^6
T-LIFE	termination life
TL	threshold level

Figure A.3 — Leakage from a cylinder — Comparison of measured data points and the *3PMA*

Annex B
(informative)

Determination of threshold values for leakage rates

B.1 General

The threshold values listed in the tables in ISO 19973-2 through ISO 19973-5 were determined according to the method described in this Annex. This method allows a systematic determination of threshold values for pneumatic components. The formulae in this Annex do not describe physical correlations or physical laws but are used only for the calculation of the threshold values.

B.2 Symbols

The symbols listed in Table B.1 are used in this Annex.

Table B.1 — Symbol list

Symbol[a]	Description	SI unit
AL	Cylinder bore size	mm
C	Sonic conductance	$\mathrm{dm^3/(s{\cdot}kPa)(ANR)}$
c	Subscript for critical values, e.g. for threshold or size	—
S	Component size Representative dimensions or performance data, such as piston diameter or nominal diameter.	millimetres raised to the nth power
K	Leakage level coefficient	$\frac{\mathrm{dm^3/h\ (ANR)}}{\mathrm{mm}^n}$
m	Threshold class (superscript) Groups of pneumatic components can be allocated to different threshold levels by using a threshold class factor. This can be necessary to concern different quality classes or design principles.	—
n	Slope index (superscript) The physical correlation between leakage and its cause is described by the slope index. The value of n is limited to $n = 1$ or $n = 2$. For linear correlations, such as diameter of a piston or length of a sealing device, the slope index is $n = 1$. For squared correlations, such as area of orifices or related energy, the slope index is $n = 2$.	—
p_{abs}	Absolute test pressure	MPa
q	Threshold value	$\mathrm{dm^3/h}$ (ANR)

[a] Other symbols can be used in other documents.

B.3 Principle of modelling threshold values for leakage rates

B.3.1 The threshold value, q, expressed in dm^3/h (ANR), can be calculated by using Formulae (B.1) and (B.2):

— if $S \geq S_\mathrm{c}$

$$q = K \cdot S^n \tag{B.1}$$

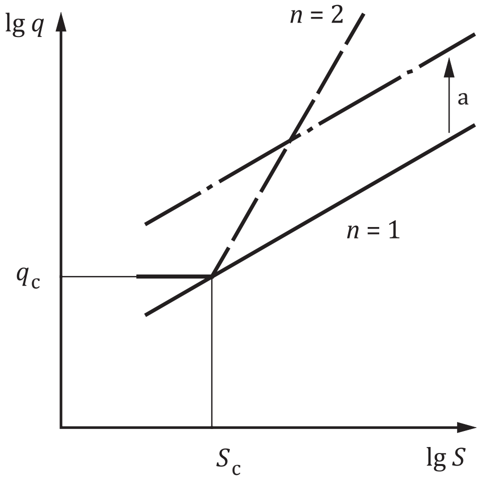
— if the threshold value for a small component (below a critical size) can be limited to a certain value, that is, if $S < S_\mathrm{c}$:

$$q = q_\mathrm{c} = K \cdot S_\mathrm{c}^n \tag{B.2}$$

In both cases, K is determined using Formula (B.3):

$$K = 0{,}06 \cdot p_\mathrm{abs} \cdot 10^m \tag{B.3}$$

B.3.2 Figure B.1 shows a graph that illustrates threshold values and the influences of different parameters.



Key

n slope index; examples for n = 1 and n = 2 are shown in the graph

S_c critical component size

q_c critical threshold value

[a] Influence of leakage level, K, and threshold class m [see also Formula (B.3)].

Figure B.1 — Graph illustrating threshold values and influences of parameters

B.4 Leakage-rate threshold values for valves

B.4.1 The leakage-rate threshold for values listed in ISO 19973-2 and ISO 19973-5 were calculated using the following conditions:

a) Component size, S, was related to the valve's sonic conductance using Formula (B.4):

$$S = 45{,}9 \cdot \sqrt{C} \tag{B.4}$$

NOTE The factor 45,9 was chosen to meet threshold values that are based on experiences of the experts of the Technical Committee ISO/TC 131, Working Group WG 4.

b) The critical component size, S_c, for all types of valves was set to:

$$S_c = 45{,}9 \cdot \sqrt{0{,}01} \tag{B.5}$$

c) The following threshold classes, m, were defined:

1) class 1.0, to be used for non-return valves and other components from ISO 19973-5;
2) class 1.5, to be used for valves with soft sealing (ISO 19973-2);
3) class 2.0, to be used for valves with metal-to-metal sealing (ISO 19973-2);

d) The slope index, n, was set to equal to 1, because the leakage of a valve is related to the length of the internal sealing devices;

e) An absolute test pressure, p_{abs}, of 0,73 MPa was used.

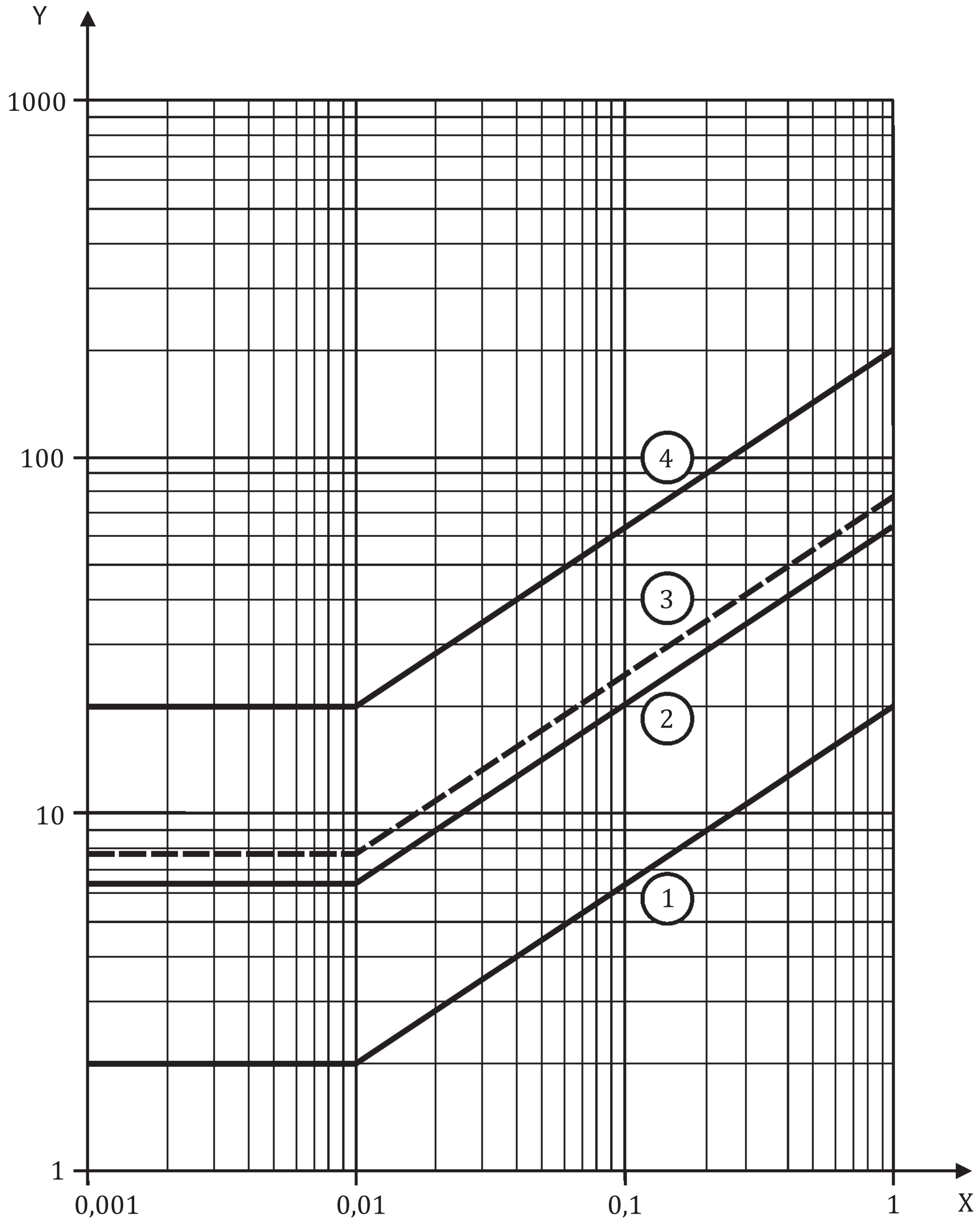
B.4.2 Using Formulae (B.1), (B.2), (B.3), (B.4) and (B.5), the threshold levels can be calculated according to Formulae (B.6) and (B.7).

$$q = 2{,}0 \cdot 10^m \cdot \sqrt{C} \tag{B.6}$$

$$q_c = 0{,}2 \cdot 10^m \tag{B.7}$$

The results are shown in Figure B.2.

B.4.3 The leakage rate threshold values in ISO 19973-2 and ISO 19973-5 are in accordance with Figure B.2 (rounded values). For easy application, the threshold values are subdivided into 11 ranges of the sonic conductance.



Key

X sonic conductance, *C*, expressed in dm^3/(s·kPa)(ANR)

Y leakage rate, *q*, expressed in dm^3/h (ANR)

1 threshold level for class 1.0 (non-return valves and other components, described in ISO 19973-5)

2 threshold level for class 1.5 (valves with soft sealing; ISO 19973-2)

3 threshold level for class 1.5 (regulators; ISO 19973-4; to be tested at absolute test pressure 0,9 MPa)

4 threshold level for class 2.0 (valves with metal-to-metal sealing; ISO 19973-2)

Figure B.2 — Leakage-rate threshold values for valves and regulators

B.5 Leakage-rate threshold values for cylinders

B.5.1 The leakage-rate threshold for values listed in ISO 19973-3, were calculated using the following conditions:

a) Component size, S, was related to the cylinder's bore size using Formula (B.4):

$$S = AL \tag{B.8}$$

b) The critical component size, S_c, for all types of cylinders was set to S_c = 16 mm;

c) One threshold class, m = 1,0, is defined for cylinders;

d) The slope index, n, was set to equal to 1, because the leakage of a cylinder is related to the length of the internal sealing devices;

e) An absolute test pressure, p_{abs}, of 0,73 MPa was used.

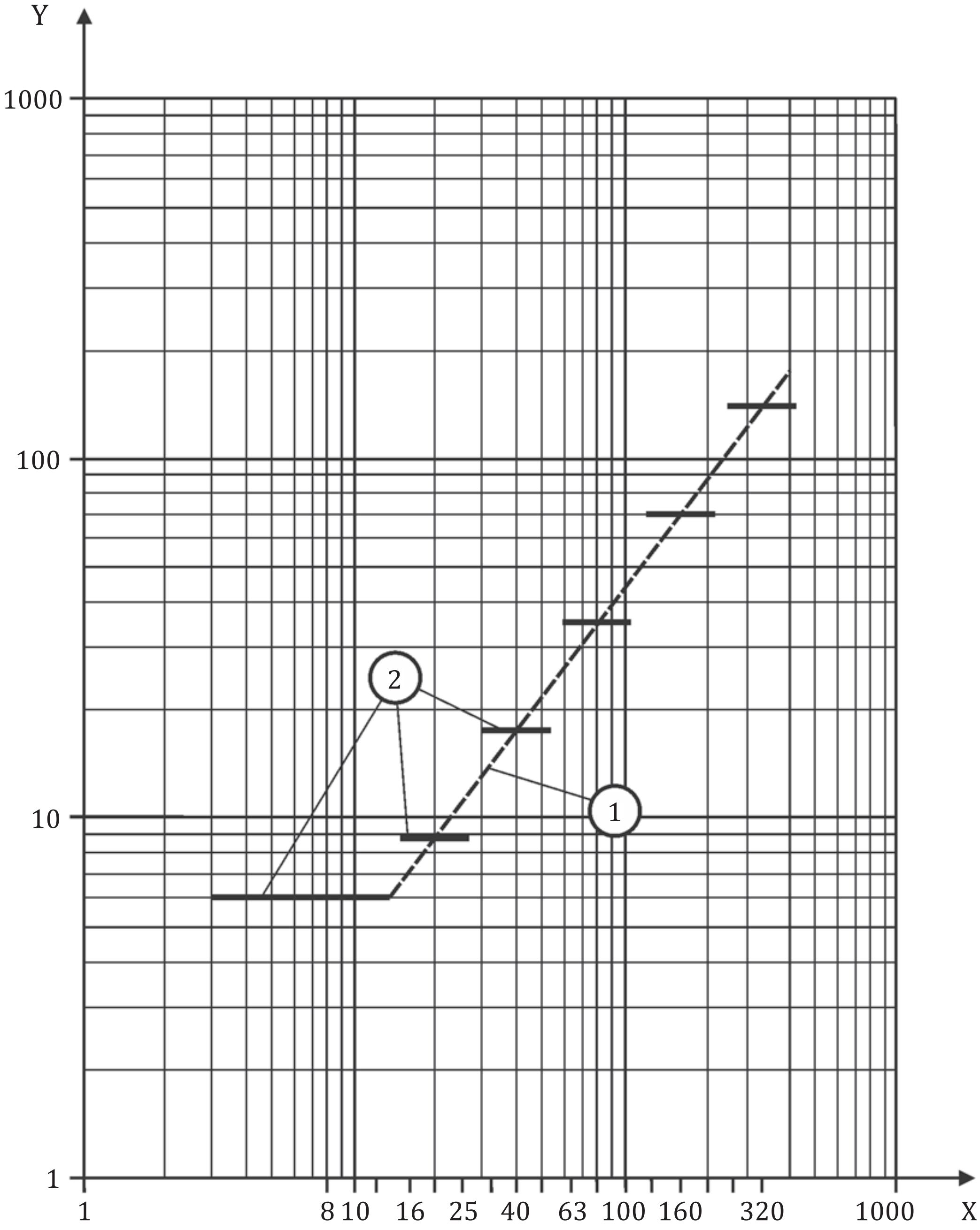
B.5.2 Using Formulae (B.1), (B.2), (B.3) and (B.8), the threshold level can be calculated according to Formulae (B.9) and (B.10):

$$q = 0{,}044 \cdot 10^m \cdot AL \tag{B.9}$$

$$q_c = 6{,}0\,\mathrm{dm}^3/\mathrm{h}\ (\mathrm{ANR}) \tag{B.10}$$

The results are shown in Figure B.3.

B.5.3 The leakage rate threshold values in ISO 19973-3 are in accordance with Figure B.3 (rounded values). For easy application, the threshold values are related to six intervals of cylinder bore sizes.



Key

X	cylinder bore size, *AL*, expressed in mm
Y	leakage rate, *q*, expressed in dm^3/h (ANR)
1	threshold level for class 1.0 (calculated values)
2	diameter clusters with a same threshold level

Figure B.3 — Leakage-rate threshold values for cylinders

B.6 Leakage-rate threshold values for regulators

B.6.1 The leakage-rate threshold for values listed in ISO 19973-4 were calculated using the following conditions:

a) component size, S, was related to the regulator's sonic conductance using Formula (B.4);

b) the critical component size, S_c, for all types of regulators was set to Formula (B.5);

c) one threshold class, $m = 1,5$, is defined for regulators;

d) the slope index, n, was set to equal to 1, because the leakage of a regulator is related to the length of the internal sealing devices;

e) an absolute test pressure, p_{abs}, of 0,90 MPa was used.

B.6.2 Using Formulae (B.1), (B.2), (B.3), (B.4) and (B.5), the threshold level can be calculated according to Formulae (B.11) and (B.12).

$$q = 2{,}48 \cdot 10^{m} \cdot \sqrt{C} \qquad \text{(B.11)}$$

$$q_{\text{c}} = 0{,}248 \cdot 10^{m} \qquad \text{(B.12)}$$

The results are shown in Figure B.2.

B.6.3 The leakage rate threshold values in ISO 19973-4 are in accordance with Figure B.2 (rounded values). For easy application, the threshold values are subdivided into 11 ranges of the sonic conductance.

Annex C

(informative)

Calculation procedures for censored data without suspensions

C.1 Example test setup and test results

Consider a test run on a sample of seven test units of a component, and parameters related to three failure modes (1, 2, 3) are measured during a reliability test. Raw data from each parameter is collected as the test progresses. When a failure has occurred (either by no longer being able to perform a required function, or by exceeding the threshold level in a *3PMA*), the cycle count at which the test unit was last observed in satisfactory condition is recorded as the termination life.

For the example shown in Table C.1, test unit number 5 experiences a mode 1 failure at the cycle count shown. The data for other test units are likewise determined from the observations when a test unit experiences any failure mode for the first time. These are shown as shaded cells in Table C.1. The test is concluded when the minimum number of test units specified in Table 3 fails, in this case, five test units.

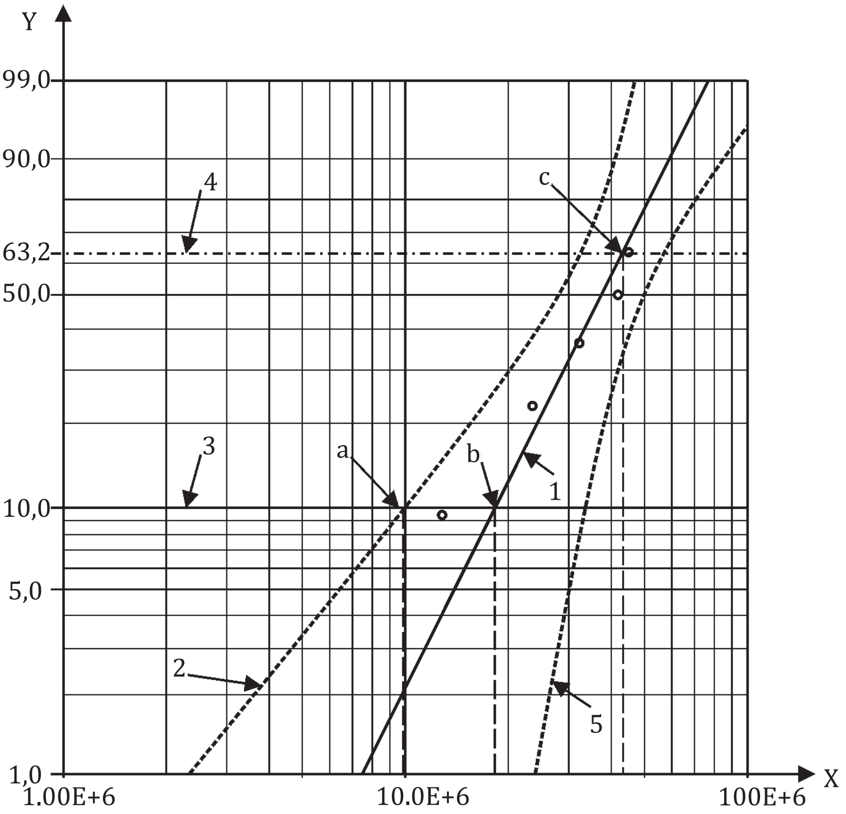
If the manufacturer desires to know more information about any test unit that has failed by reaching a threshold level, testing on that unit may continue. However, further data, such as observed at 36,6 × 10^6 for test unit 2 and 5 and 41,8 × 10^6 cycles for test unit 1, shall not be considered in the reliability analysis.

Table C.1 — Example of test unit cycle counts and failure modes

Termination life from *3PMA*	Failure mode 1 (leakage – seal A)	Failure mode 2 (leakage – seal B)	Failure mode 3 (shifting pressure)
12,8 x 10^6	Test unit number 5	—	—
23,5 x 10^6	—	Test unit number 1	—
32,2 x 10^6	—	Test unit number 2	—
33,6 x 10^6	Test unit number 2	Test unit number 5	—
41,8 x 10^6	Test unit number 3	—	Test unit number 1
43,9 x 10^6	—	—	—
44,9 x 10^6	—	—	Test unit number 6
44,9 x 10^6	Testing ended — test unit numbers 4 and 7 removed from test		
NOTE The example illustrates how test units can reach several threshold levels if they continue to be tested beyond their first failure mode. The shaded cells indicate which test units experienced a failure mode for the first time. Note also that one test unit did not experience a failure mode and was censored at the end of the test. This example shows termination-cycle counts for test units that were continuously monitored.			

C.2 Calculation procedures

C.2.1 In this example, the Weibull parameters are then determined from a Maximum Likelihood Estimation, using the termination life for each test unit (an example of the Median Rank Regression method is shown in D.3.1). Results are graphed on a Weibull plot, as shown in Figure C.1. The failure points use the cycle count data in Table C.1, and the plot line and Weibull parameters are based on the Maximum Likelihood Estimation. The confidence limit is based on a Fisher Matrix calculation.



Key

X number of cycles to failure, *t*

Y probability of failure, expressed as a percentage

1 best fit line, determined by Maximum Likelihood Estimation

2 lower confidence limit at 95 %, obtained by Fisher Matrix

3 10 % failure probability line

4 63,2 % failure probability line

5 upper confidence limit at 5 %

[a] $(B_{10})_{95\ \%}$ life at the lower, one-sided 95 % confidence level = 9,98 × 10^6 cycles.

[b] B_{10} life.

[c] Characteristic life = 43,0 × 10^6.

Figure C.1 — Weibull plot for Maximum Likelihood Estimation (data from Table C.1)

C.2.2 Results for the median conditions are:

a) characteristic life: η = 43,0 × 10^6 cycles;

b) slope: β = 2,63.

C.2.3 Calculate the B_{10} life at the best fit line from the two-parameter Weibull equation, with $F(B_{10}) = 0{,}1$, using Formula (C.1) as follows:

$$F(B_{10}) = 1 - e^{-(B_{10}/\eta)^{\beta}} \tag{C.1}$$

$$0{,}1 = 1 - e^{-\left(B_{10}/43{,}0\times 10^{6}\right)^{2{,}63}}$$

$$B_{10}\text{life}:\quad 18{,}3\times 10^{6}\,\text{cycles.}$$

C.2.4 From the Weibull plot, the $(B_{10})_{95\ \%}$ life at the 95 % confidence level is equal to $9{,}98 \times 10^{6}$ cycles.

Annex D
(informative)

Calculation procedures for censored data with suspensions

D.1 General

This example illustrates a case in which some test units are removed from testing prior to failure, while others continue to be tested. Reasons for such removal shall not be related to the objective of the test; acceptable reasons include equipment failures, external damage (e.g. fire, falling object, etc.), removal for inspection or any other reason. Any unit that is removed shall not be returned to the test program and shall be classified as a suspension. See C.1 for an explanation on how failed test units may yet be continued on test for supplementary manufacturers' information.

D.2 Example test setup and test results

Consider a test run on a sample of 12 test units and parameters related to three failure modes (1, 2 and 3) are measured during a reliability test. Raw data from each parameter are collected as the test progresses. When a failure has occurred (either by no longer being able to perform a required function, or by exceeding the threshold in a *3PMA*), the cycle count at which the test unit was last observed in satisfactory condition is recorded as the termination life.

See Table D.1 for an example of the data collected during such a test. The data for the test units are recorded from the observations when a unit fails by any failure mode for the first time; these data are shown in the shaded cells in Table D.1, along with data from suspended test units. For example, test unit number 5 reaches a threshold level for a mode 3 failure (shifting pressure) at the last cycle count shown. According to Table 4, it is necessary for at least 70 % of the sample size (that is, nine test units) to fail in order for the test to be considered complete.

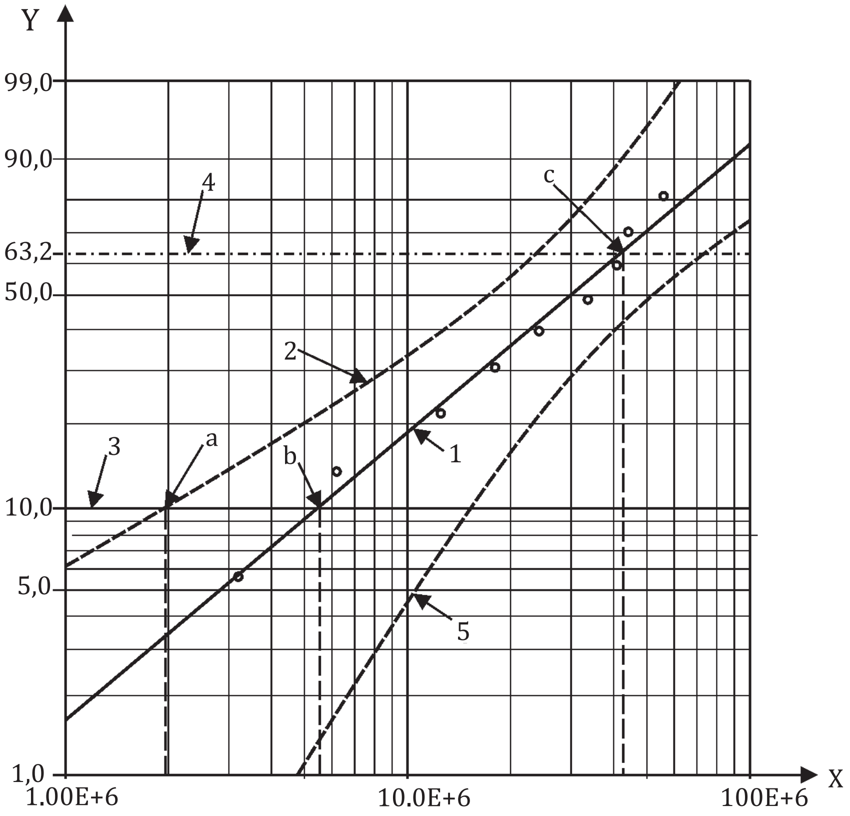
Table D.1 — Example of test-unit cycle counts and failure modes for a sample that contains suspended test units

Termination life from *3PMA*	Failure mode 1 (leakage – seal A)	Failure mode 2 (leakage – seal B)	Failure mode 3 (shifting pressure)
3,2 x 10^6	—	—	Test unit number 5
6,2 x 10^6	—	Test unit number 12	—
12,5 x 10^6	—	Test unit number 1	—
15,0 x 10^6	Test unit number 4 removed from test for detailed inspection		
18,0 x 10^6	Test unit number 9	—	—
24,2 x 10^6	—	—	Test unit number 2
33,6 x 10^6	Test unit number 2	Test unit number 8	
35,0 x 10^6	Test unit number 10 removed from test due to test equipment failure		
40,8 x 10^6	—	—	Test unit number 3
44,1 x 10^6	Test unit number 11	Test unit number 9	—
55,9 x 10^6	Test unit number 6	—	Test unit number 1
55,9 x 10^6	Testing ended — test unit number 7 still operating		

NOTE The example illustrates how test units can reach several threshold levels if they continue to be tested beyond their first failure mode. The shaded cells indicate which test units experienced a failure mode for the first time. Note also that one test unit did not experience a failure mode and was censored at the end of the test. This example shows termination-cycle counts for test units that were continuously monitored.

D.3 Calculation procedures

D.3.1 In this example, Weibull parameters are then determined from a Median Rank Regression, using the termination life for each test unit (an example of the Maximum Likelihood Estimation method is shown in C.2.1). Results are graphed on a Weibull plot as shown in Figure D.1. The failure points use the cycle count data in Table D.1, and the plot line and Weibull parameters are based on the median rank regression. The confidence limit is based on a Fisher Matrix calculation.



Key

X number of cycles to failure, *t*

Y probability of failure expressed as a percentage

1 best fit line, determined by Median Rank Regression

2 lower confidence limit at 95 %, obtained by Fisher Matrix

3 10 % failure probability line

4 63,2 % failure probability line

5 upper confidence limit at 5 %

[a] $(B_{10})_{95\ \%}$ life at the lower, one sided 95 % confidence level = 1,94 × 10^6 cycles.

[b] B_{10} life.

[c] Characteristic life = 41,7 × 10^6 cycles.

Figure D.1 — Weibull plot for Median Rank Regression that contains suspended test units (data from Table D.1)

D.3.2 Results for the median conditions are:

a) characteristic life: $\eta = 41{,}7 \times 10^6$ cycles;

b) slope: $\beta = 1{,}1$.

D.3.3 Calculate the B_{10} life at the best fit line from the two-parameter Weibull equation, with $F(B_{10}) = 0{,}1$, using Formula (C.1) as follows:

$$0{,}1 = 1 - e^{-\left(B_{10}/41{,}7\times10^6\right)^{1{,}1}}$$

B_{10} life $5{,}39\times10^6$ cycles.

D.3.4 From the Weibull plot, $(B_{10})_{95\ \%}$ life at the 95 % confidence level is equal to $1{,}94 \times 10^6$ cycles.

Annex E

(informative)

Verification of minimum life at a specified reliability and one-sided confidence level

E.1 Objective

It is desired to conduct a test to verify that a product has a certain minimum life at a specified reliability and one-sided confidence level. Such a test does not generate a failure distribution; it only proves that a distribution might exist that is greater than the one used for the verification. The advantage of this method is that the testing time is shorter than that specified in Clauses 9, 10 and 11.

E.2 Assumption

The reliability distribution is Weibull and its slope is known, either from historical data, engineering judgement or a combination of both. The life at a given reliability value and one-sided confidence level is declared and a test is conducted to verify that the declaration is true.

E.3 Procedure

The test is conducted in accordance with the relevant parts of ISO 19973, following the same procedures as for a standard reliability test. A test duration is calculated and none of the test units may fail during the conduct of the test. An alternate procedure is also available that allows one failure, but it requires longer testing time. If the test is successful, the product has at least the life at the reliability value and one-sided confidence level declared. It is also possible that the life can be longer.

E.4 Symbols

Table E.1 — Symbol list

Symbol	Definition
t	Test duration for testing without failures
t_p	Minimum life at the declared reliability value and confidence level
n	Number of test units tested
β	Shape parameter (slope) of the Weibull distribution
B_i	Expected time at which i % of the population fails
$R(t)$, also $1 - p$	Declared reliability of a component at the time t
p	Probability of an individual unit failing the test
T_d	Declared one-sided confidence interval

E.5 Problem

E.5.1 Definition of problem and development of equations

E.5.1.1 Develop an equation to calculate the duration of a test that verifies the minimum life of a component at a declared reliability value and one-sided confidence level, using a given Weibull slope.

E.5.1.2 There are only two possibilities for the test to verify the declaration statement: either it succeeds or it fails. Thus, a binomial equation can characterize the test outcome, where the probability of test success, $p(y)$, is as given in Formula (E.1):

$$p(y) = C_y^n p^y q^{(n-y)} \tag{E.1}$$

where

$$C_y^n = \frac{n!}{y!(n-y)!} \tag{E.2}$$

E.5.1.3 In this case, $p(y)$ is the probability that from a group of n test units, y test units fail before the end of the test. Because the objective is for all test units to pass, y is set equal to 0 and the terms in Formula (E.1) reduce to those given in Formulae (E.3) to (E.6):

$$C_0^n = 1 \tag{E.3}$$

$$p^0 = 1 \tag{E.4}$$

$$q = 1 - p \tag{E.5}$$

$$p(0) = (1-p)^n \tag{E.6}$$

E.5.1.4 The probability, p, of an individual unit failing before the end of the test is as given in Formula (E.7):

$$p = 1 - R(t) \tag{E.7}$$

where $R(t)$ is the reliability of the test units.

E.5.1.5 The overall probability, $p(0)$, of the test succeeding is as given in Formula (E.8):

$$p(0) = \left(1 - T_\mathrm{d}\right) \tag{E.8}$$

Formulae (E.9) and (E.10) can be derived by substitution into Formula (E.8):

$$\left(1 - T_\mathrm{d}\right) = (1-p)^n = \left\{1 - \left[1 - R(t)\right]\right\}^n = R(t)^n \tag{E.9}$$

$$\ln R(t) = \frac{1}{n} \ln\left(1 - T_\mathrm{d}\right) \tag{E.10}$$

E.5.1.6 The cumulative reliability, $R(t)$, can be expressed in terms of the Weibull equation, as given in Formulae (E.11) to (E.13):

$$R(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}} \tag{E.11}$$

$$\ln R(t) = -\left(\frac{t}{\eta}\right)^{\beta} \tag{E.12}$$

$$\left[-\ln R(t)\right]^{\frac{1}{\beta}}=\frac{t}{\eta} \tag{E.13}$$

For a particular value at t_{p}, Formulae (E.11) to (E.13) take on the form of Formulae (E.14) to (E.16), respectively:

$$R(t_{\mathrm{p}})=e^{-\left(\frac{t_{\mathrm{p}}}{\eta}\right)^{\beta}} \tag{E.14}$$

$$\ln R(t_{\mathrm{p}})=-\left(\frac{t_{\mathrm{p}}}{\eta}\right)^{\beta} \tag{E.15}$$

$$\left[-\ln R(t_{\mathrm{p}})\right]^{\frac{1}{\beta}}=\frac{t_{\mathrm{p}}}{\eta} \tag{E.16}$$

E.5.1.7 Taking the ratio of Formulae (E.13) and (E.16) results in Formula (E.17):

$$\frac{t}{t_{\mathrm{p}}}=\left[\frac{\ln R(t)}{\ln R(t_{\mathrm{p}})}\right]^{\frac{1}{\beta}} \tag{E.17}$$

Substituting Formula (E.10) yields Formula (E.18):

$$t=t_{\mathrm{p}}\left\{\frac{\frac{1}{n}\ln\left[1-T_{\mathrm{d}}\right]}{\ln R(t_{\mathrm{p}})}\right\}^{\frac{1}{\beta}} \tag{E.18}$$

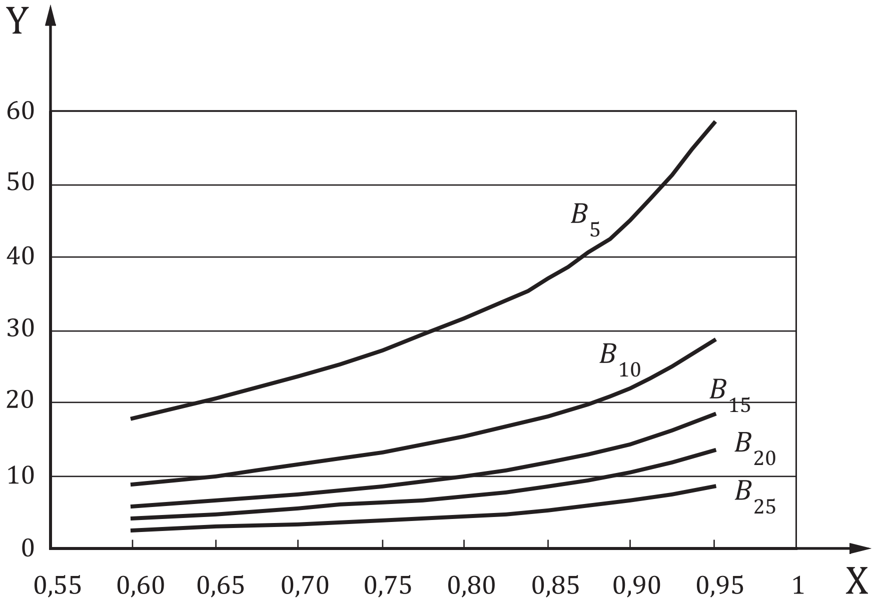
$$t=t_{\mathrm{p}}\left[\frac{\ln(1-T_{\mathrm{d}})}{n\ln R(t_{\mathrm{p}})}\right]^{\frac{1}{\beta}} \tag{E.19}$$

$$t=t_{\mathrm{p}}\left(\frac{A}{n}\right)^{\frac{1}{\beta}} \tag{E.20}$$

where

$$A=\left[\frac{\ln(1-T_{\mathrm{d}})}{\ln R(t_{\mathrm{p}})}\right] \tag{E.21}$$

E.5.1.8 If $R(t_{\mathrm{p}}) = 1 - p_i$, where p_i is the proportion of test units failing at level i (for example, B_{10} is the number of cycles (time) that it takes for 10 % of the sample to fail), then the A values in Figure E.1 can apply to many circumstances.



Key

X confidence level

Y *A* values

Figure E.1 — A values for various B_i at various declared one-sided confidence levels, T_d

E.5.2 Example problem

For how long is it necessary to test 10 pneumatic cylinders to demonstrate that they represent a population with a $(B_{10})_{95\,\%}$ life of 10 000 km at a one-sided 95 % confidence level, if a similar design has a Weibull slope of 2,0?

Using Formula (E.20):

$$t = t_p \left(\frac{A}{n} \right)^{\frac{1}{\beta}} = 10^4 \,\text{km} \left(\frac{28{,}43}{10} \right)^{\frac{1}{2}} = 16\,860 \,\text{km}$$

E.6 Specific application

E.6.1 Definition of problem and development of equations

Consider the case for $(B_{10})_{95\,\%}$ life at a one-sided 95 % confidence level. Rearrange Formula (E.20) and designate the resulting ratio as the test life ratio, *L*, as given in Formula (E.22):

$$\frac{t}{t_p} = \left(\frac{A}{n} \right)^{\frac{1}{\beta}} = L \tag{E.22}$$

where $t = t_p \cdot L$.

For this application, $A = 28{,}43$, from which the life ratios in Table E.2 can be determined.

Table E.2 — Values of life ratios for various Weibull slopes and number of test units tested

Number of units tested *n*	Life ratios *L* Weibull slope *β* 1,0	 1,5	 2,0	 3,0
2	14,2	5,87	3,77	2,42
3	9,48	4,48	3,08	2,12
4	7,11	3,70	2,67	1,92
5	5,69	3,19	2,38	1,78
6	4,74	2,82	2,18	1,68
7	4,06	2,55	2,02	1,60
8	3,55	2,33	1,89	1,53
9	3,16	2,15	1,78	1,47
10	2,84	2,01	1,69	1,42

E.6.2 Example problem

How long is it necessary to test seven pneumatic cylinders in order to demonstrate that they represent a population with a $(B_{10})_{95\ \%}$ life of 10 000 km at a 95 % one-sided confidence level, if a similar design has a Weibull slope of 2,0?

Using Formula (E.22) and the values for L from Table E.2:

$t = t_p \cdot L = 10\ 000\ (2{,}02) = 20\ 200$ km

Annex F
(informative)

Dealing with outliers in test data

F.1 General

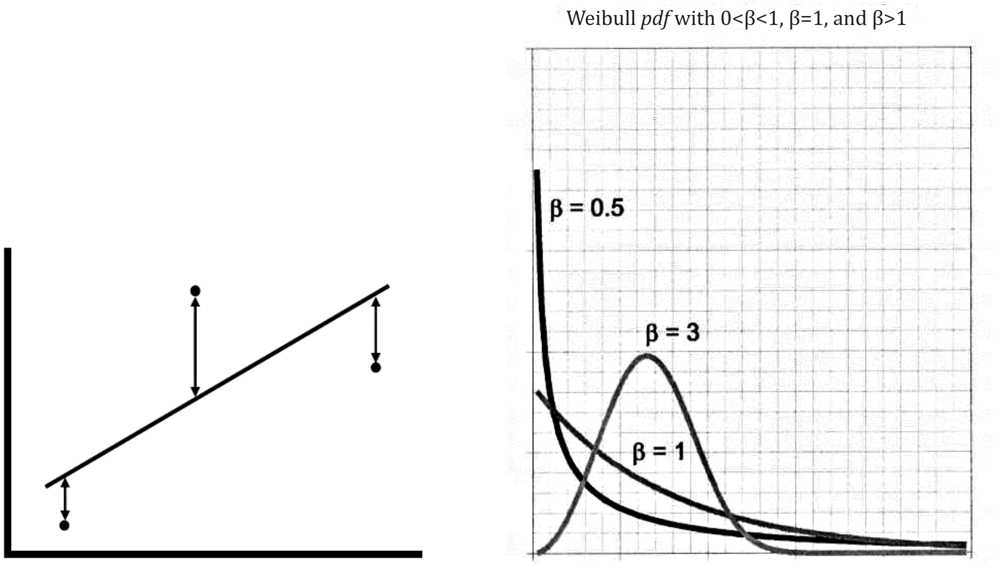
Sometimes a data point is suspect of being an outlier, not belonging to the population collected in the test. Reasons for the suspicion can include doubt about the accuracy of its collection, temporarily inappropriate conditions during the test, human error, or some other anomaly that is not repeated.

There are literally hundreds of methods developed to analyse outliers and many of these are described in ISO 16269-4. The user is encouraged to review these and apply them because they are a collection of methods developed by the experts in this field.

Before claiming that a data point is an outlier, examination for reasons should be made as to why such an unusual value has been recorded. This often leads to corrective actions, which are always beneficial. At the least, a reason for obtaining the unusual value may be justification for declaring it an outlier without any analytical exercise.

F.2 Principle of the method used in this Annex

F.2.1 The method described in this annex may be used as an alternative to any other method. It is based on the principle that a data point is declared an outlier if its squared residual, plotted in a separate Weibull distribution, is located in the 5 % tail of the probability density function (pdf) of that Weibull. This is illustrated in Figure F.1.



a) Residuals measured in y-axis **b) Squared residuals plotted as a Weibull**

Figure F.1 — Illustration of the principle described in this annex

F.2.2 The distribution of the squared residual Weibull can vary, depending on the data.

F.2.3 Those data points located in the 5 % tail may be excluded from a revised analysis of the raw test data but should be reported as outliers.

F.3 Description of the calculation method

F.3.1 Organize the raw failure life test data into a table sorted by ascending life, as shown in the first three columns of Table F.1. Include the suspected outliers but do not include any suspension. Enter values of the median ranks in the median rank plot position column. Values of X and Y are the locus of data points in the Weibull plot of the basic test data as shown in Figure F.1, a).

Table F.1 — Raw failure life test data to be used to calculate outliers

Test unit number	Order number	Cycles at failure x	Median rank plot position y	MLE value y'	Residual r	Residual Squared r^2	Tail %
	1						
	2						
	3						

F.3.2 Calculate the unreliability value (y') of the Weibull curve at each failure life of the test data as shown in Figure F.1, a), as described in Formula (F.1) and enter them in the MLE value column of Table F.1.

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

where

x is the failure life;

η is the characteristic life;

β is the Weibull slope;

δ is the minimum life (for a three-parameter type).

The values of η, β and δ are obtained from the Weibull plot of the raw data using the Maximum Likelihood Estimate (MLE) method for obtaining the Weibull regression line.

NOTE Depending on the software used, values of η may have to be adjusted if the Weibull plot is a three-parameter type.

F.3.3 Determine the residual, r, for each entry as shown in Figure F.1, a) and described by Formula (F.2):

$$r = y - y' \tag{F.2}$$

where

y is the median rank plot position;

y' is the MLE value.

Enter the values in the residual column of Table F.1, then square these values and enter the results in the r^2 column of the same table.

F.3.4 Using the squared residual values as an independent variable, plot a Weibull curve using the MLE method, and determine the parameters $(\eta, \beta, \delta)_{\mathrm{sr}}$. This establishes the distribution of the squared residuals.

F.3.5 Using these Weibull parameters, calculate the probability tail value remaining for each squared residual using Formula (F.3), and list the result in the tail column in Table F.1 as a percentage:

$$\text{Probability tail value (Tail)} = 1 - F\left(x_{sr}\right) = e^{-\left(\frac{x-\delta}{\eta}\right)_{sr}^{\beta}} \tag{F.3}$$

where the subscript *sr* refers to data from the squared residual distribution.

F.3.6 Any test unit whose tail value that is 5 % or less may be considered to be an outlier. Its failure life may be discounted in the raw data and the Weibull replotted without the outlier. However, the final report should describe any discounted outlier.

F.4 Example problem

F.4.1 Consider the example data in the first three columns of Table F.2:

Table F.2 — Data considered in example problem

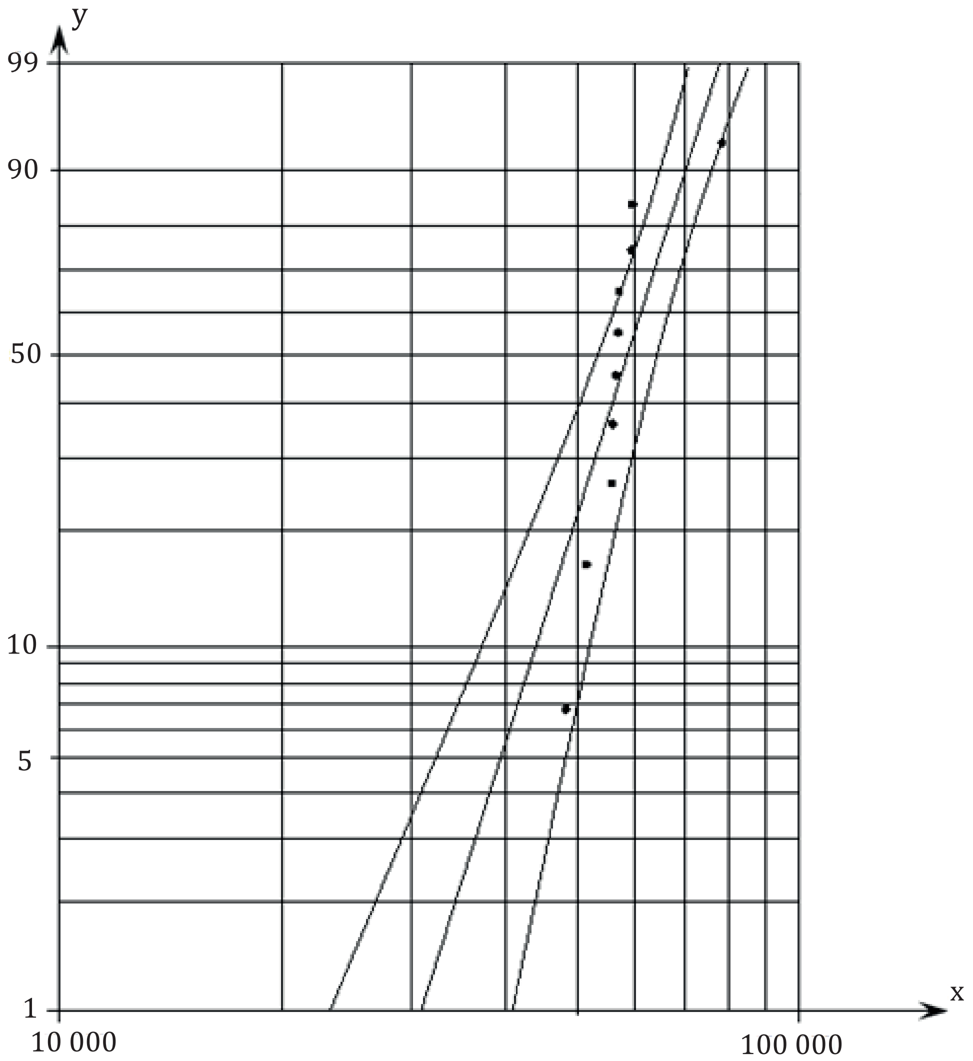
1	2	3	4	5	6	7	8
Test unit number	**Order number**	**Cycles at failure** x	**Median Rank plot position** y	**MLE value** y'	**Residual** r	**Squared residual** r^2	**Tail** %
5	1	48 658	0,067	0,185	−0,118	0,01390	48,8
9	2	51 841	0,162	0,267	−0,105	0,01106	55,4
3	3	56 120	0,259	0,409	−0,150	0,02237	34,0
1	4	56 241	0,355	0,413	−0,058	0,00336	80,8
7	5	56 864	0,452	0,436	+0,016	0,00025	97,7
2	6	57 177	0,548	0,448	+0,100	0,01000	58,2
4	7	57 361	0,645	0,455	+0.190	0,03611	19,8
6	8	59 688	0,741	0,546	+0,195	0,03805	18,3
8	9	59 800	0,838	0,550	+0,288	0,08273	3,7
10	10	79 057	0,933	0,994	−0,061	0,00368	79,4

F.4.2 A Weibull plot of the data in the third column using the Maximum Likelihood Estimation method for the regression analysis is shown in Figure F.2. This is a two-parameter Weibull curve that gives the following results:

— η (characteristic life) = 61 860 cycles;

— β (slope) = 6,61;

— δ (minimum life) = 0 cycles.



Key

x cycles

y cumulative failure probability

Figure F.2 — Weibull plot of raw failure data from Table F.2

F.4.3 Using a table of Median Ranks from any statistical reference, list the values corresponding to each order number in the fourth column of Table F.1 for a sample size of 10 test units. This corresponds with the data points shown in Figure F.2.

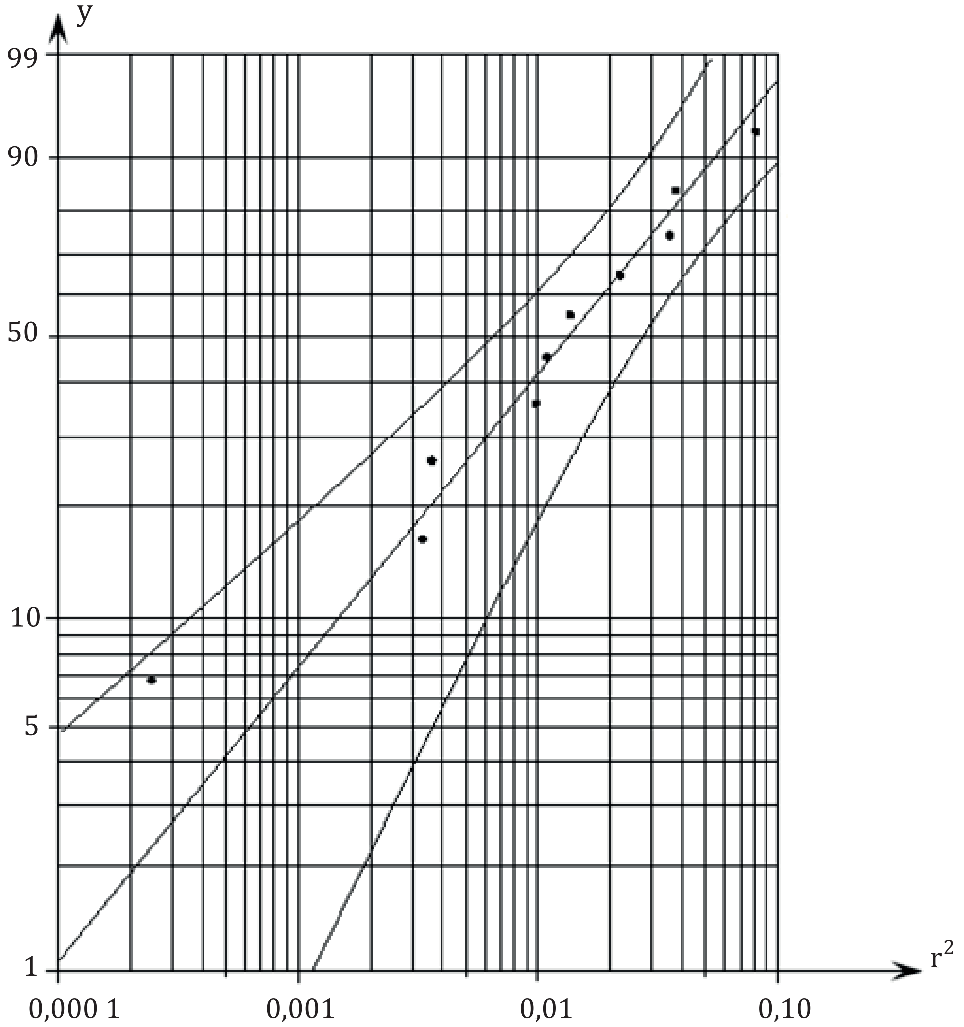
F.4.4 Using Formula (F.1), calculate the values of the y' intercept of the MLE curve at each value of the failure lives. The calculation for the first data point is shown in Formula (F.4):

$$y' = 1 - e^{-\left(\frac{48658-0}{61860}\right)^{6,61}} = 0,185 \tag{F.4}$$

F.4.5 Calculate the difference between the fourth and fifth columns of Table F.1 as the residual, using Formula (F.2), and enter the result in the sixth column. Square the residual valve and enter the result in the seventh column.

F.4.6 Plot a Weibull curve of the squared residuals from the seventh column of Table F.1 as shown in Figure F.3. This data probably needs to be sorted in ascending order for use in the Weibull software. Use the Maximum Likelihood Estimation method for the regression analysis. This is a two-parameter Weibull curve that gives the following results:

- η (characteristic life) = 0,02 cycles;
- β (slope) = 0,85;
- δ (minimum life) = 0 cycles.



Key

r^2 square of the residuals

y cumulative failure probability

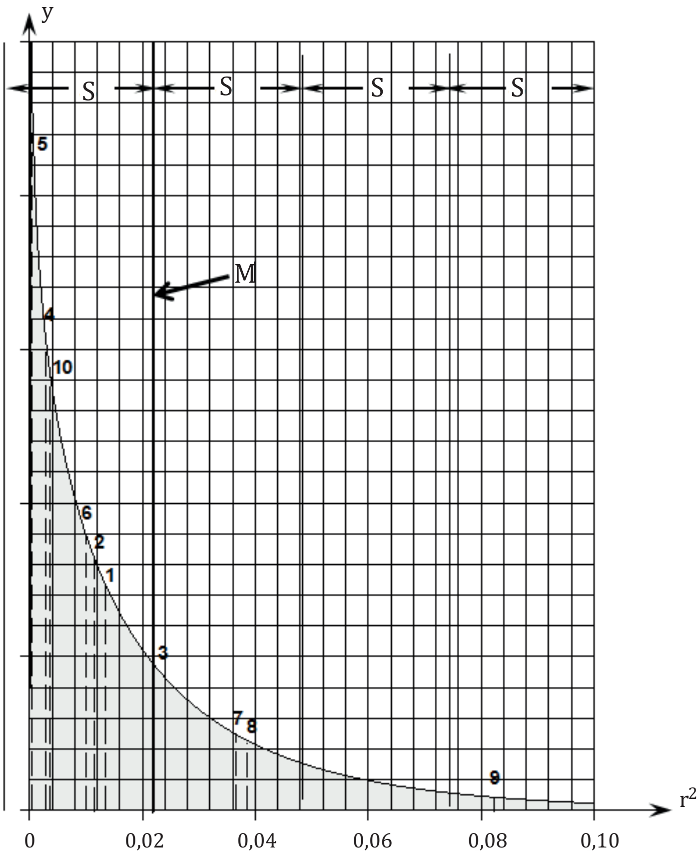
Figure F.3 — Weibull curve of squared residuals

F.4.7 Calculate the probability tail value of each data point using Formula (F.3). The calculation of the first data point is shown in Formula (F.5):

$$\text{Tail} = e^{-\left(\frac{0,01390-0}{0,02}\right)^{0,85}} = 0,488 = 48,8\% \qquad \text{(F.5)}$$

In this case, the tail area of the squared residual is 48,8 %, which is larger than the 5 % and therefore not an outlier. Results of the rest of the calculations show that test unit number 8, order number 9, is an outlier, as its tail are is 3,7 %, which is less than 5 %.

F.4.8 A plot of the probability density function (pdf), as shown in Figure F.4, is also informative. Plotting the mean and standard deviations for this curve requires the use of Gamma functions and other equations not described in this annex.



Key

r^2	square of the residuals
y	pdf (product density function)
M	mean value of the squared residuals
S	standard deviation of the squared residuals
1-10	order No. from Table F.2

Figure F.4 — Probability density function (pdf) plot of the squared residuals, showing mean and standard deviations

Annex G
(informative)

Examples of test results

G.1 Test conditions

The test conditions for this example are given in Tables G.1 and G.2.

Table G.1 — Test conditions for valves

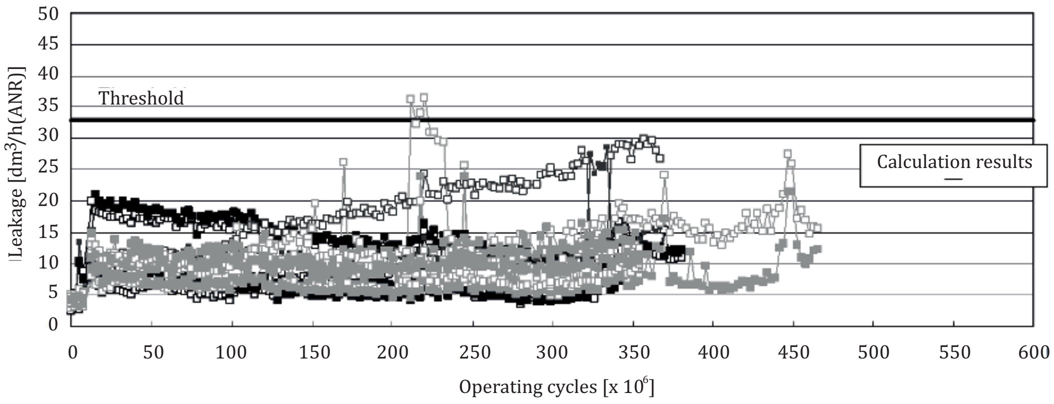
	Valve-1	Valve-2
	Electro-pneumatic 5/2 monostable directional control valve, Rc 1/4 with metal-to-metal sealing	Electro-pneumatic 5/2 monostable directional control valve, G 1/8 with rubber sealing
Sample size	8 test units	8 test units
Test pressure	630 kPa	800 kPa
Volume at outlet port	12 cm^3	10 cm^3
Cycling frequency	4 Hz	1 Hz for 3,47 × 10^6 cycles 2 Hz for 15,6 × 10^6 cycles 4 Hz for 72 × 10^6 cycles
Measuring interval	One week	One week

Table G.2 — Test conditions for cylinders

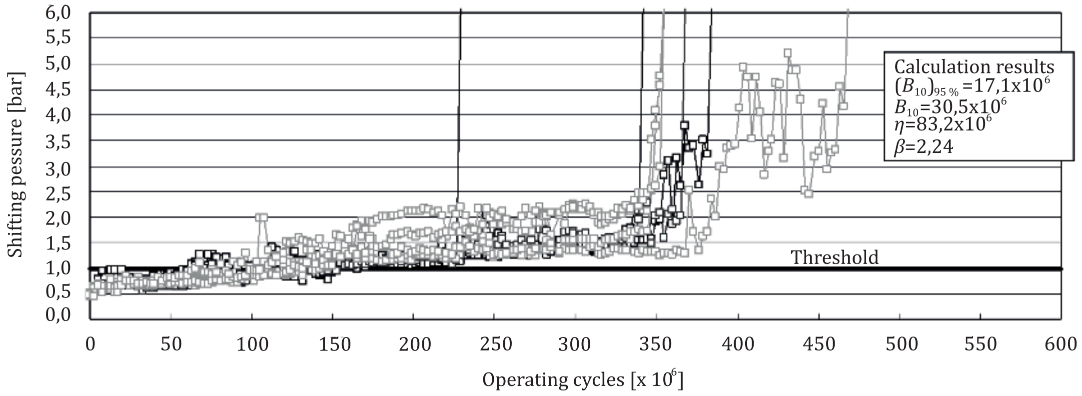
	Cylinder-1	Cylinder-2
	Double-acting cylinder Bore size 25, stroke 50 mm, class 2	Double-acting cylinder Bore size 50, stroke 160 mm, class 3
Sample size	8 test units	8 test units
Test pressure	630 kPa	630 kPa
Load mass	0,3 kg	4 kg
Cycling frequency	1,25 Hz	1 Hz
Measuring interval	One week	One week

G.2 Results of testing Valve-1

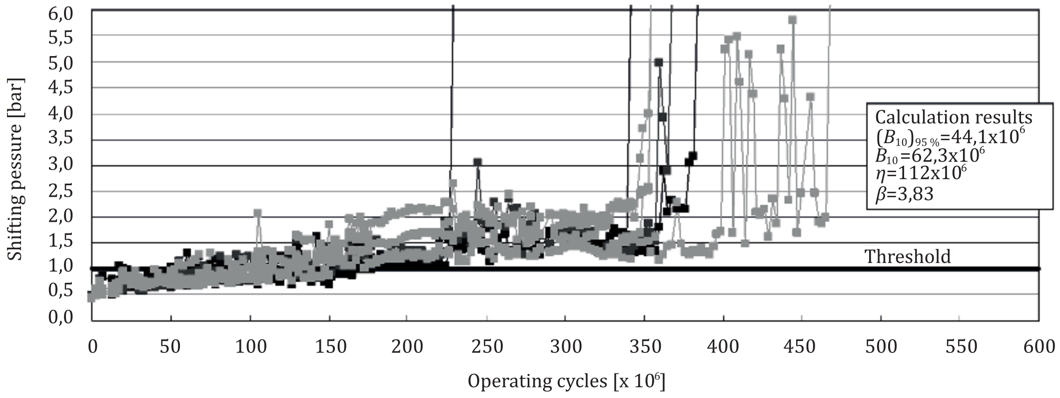
All 8 test units have reached catastrophic failure and the testing has been completed at 468 × 10^6 cycles. The measurement results are shown in Figure G.1. The leakage rapidly increased and reached a peak at around 10 × 10^6 cycles. After that, the leakage slowly decreased and maintained an almost constant value. After 150 × 10^6 cycles were reached, the leakage of some test units started to increase, but it was below the threshold level. The shifting pressure after 24 h rest and immediate shifting pressure gradually increased while repeating a small amplitude and rapidly increased at around 350 × 10^6 cycles. All 8 test units stopped shifting one after another until 468 × 10^6 cycles.



(a) Leakage



(b) Shifting pressure after 24 h rest

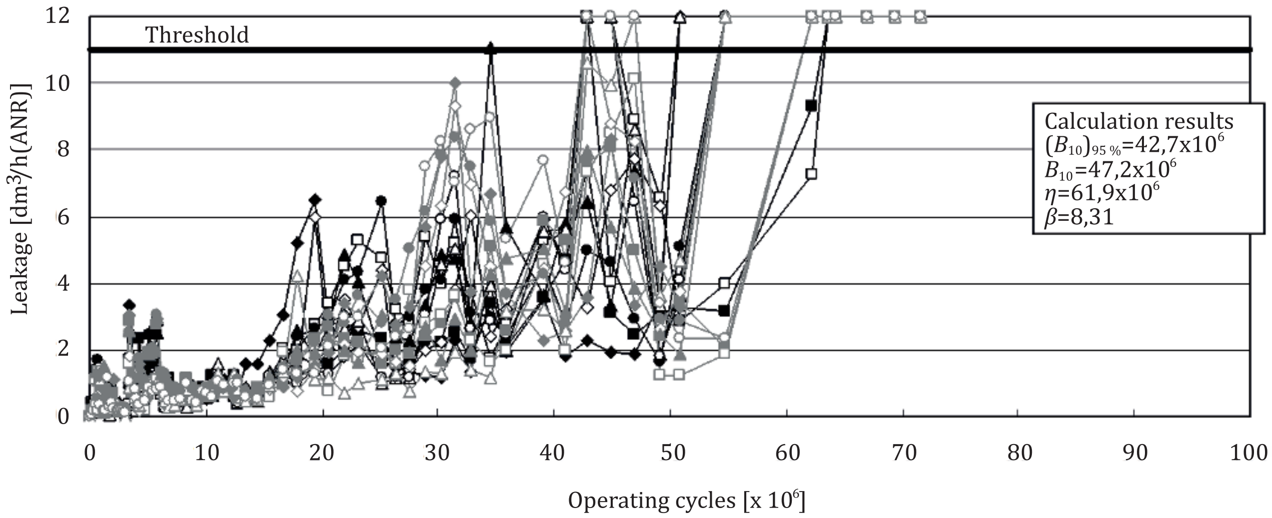


(c) Immediate shifting pressure

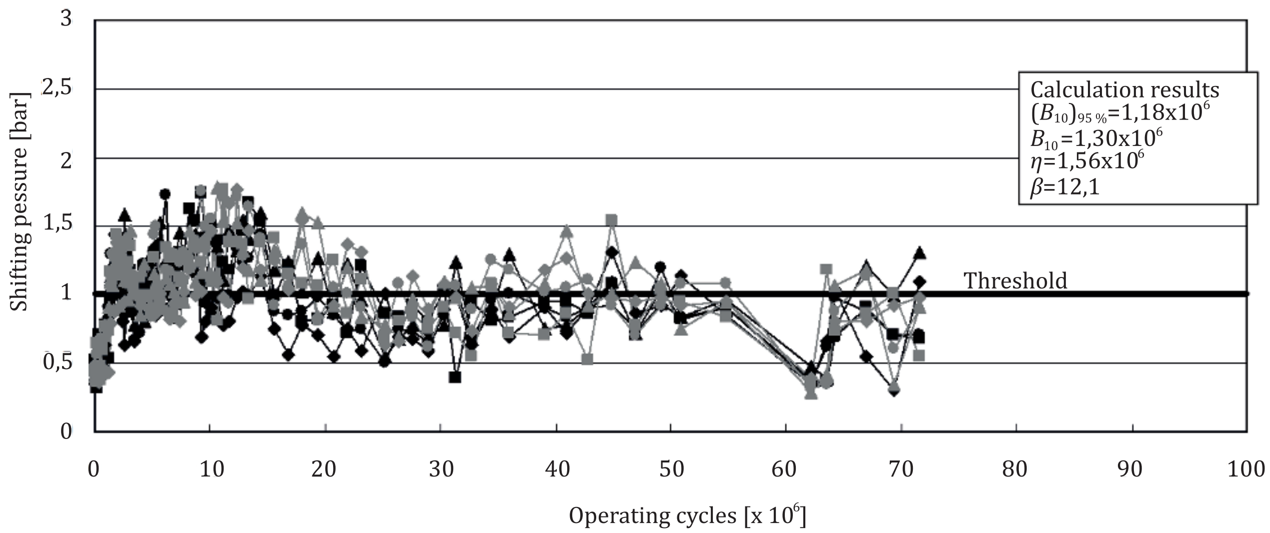
Figure G.1 — Results of measurement and calculation for Valve-1

G.3 Results of testing Valve-2

The test was suspended after 72 × 10⁶ cycles (about 61 weeks), and the measurement results are shown in Figure G.2. The immediate shifting pressure rapidly increased, and all the test units exceeded the threshold level and reached a peak at around 10 × 10⁶ cycles. After that, the immediate shifting pressure gradually decreased while repeating small amplitude and finally stayed below the threshold level after repeated rising and falling. The leakage gradually increased while repeatedly rising and falling and eventually exceeded the threshold level around 40 × 10⁶ cycles (about 41 weeks).



(a) Leakage

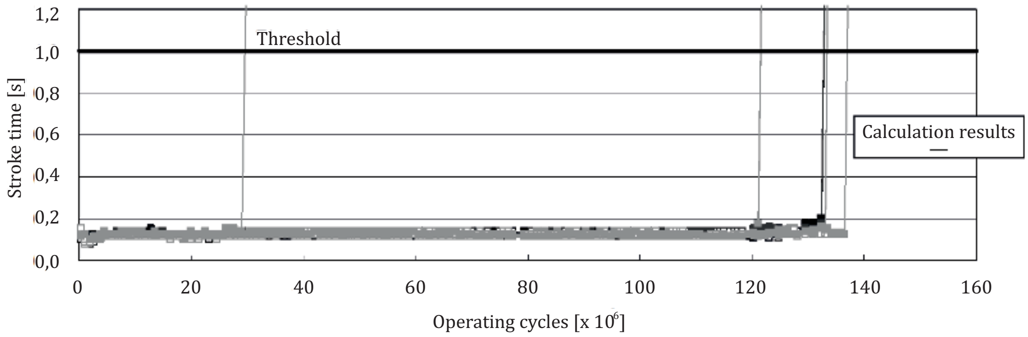


(b) Immediate shifting pressure

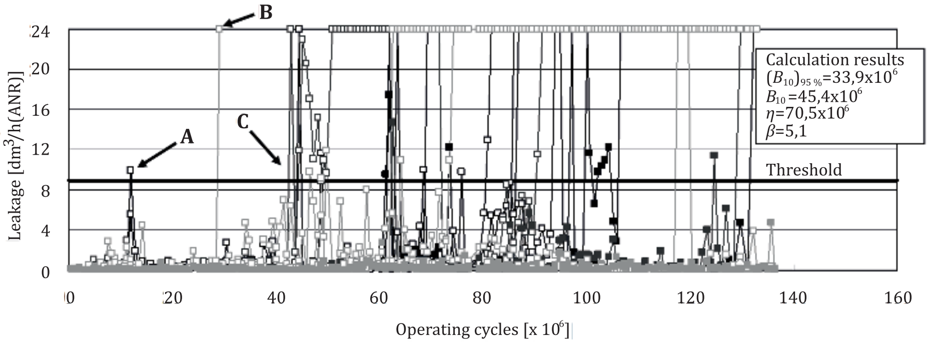
Figure G.2 — Results of measurement and calculation for Valve-2

G.4 Results of testing Cylinder-1

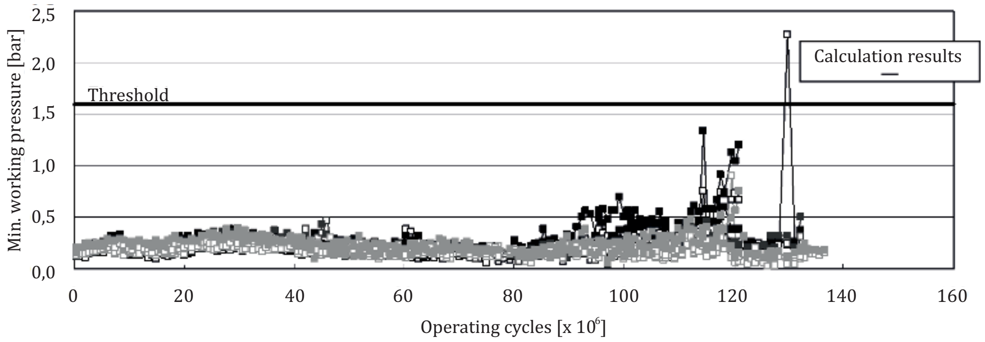
All 8 test units have reached catastrophic failure and the testing has been completed at 136 × 10⁶ cycles. The measurement results are shown in Figure G.3. The stroke time and minimum working pressure are almost the same as the initial values and significantly below the threshold level. The leakage of one test unit exceeded the threshold level once slightly after passing 10 × 10⁶ cycles (= 14 weeks = 1000 km) (see point A), but it subsided after that. One of the test units stopped due to a large amount of leakage around 30 × 10^6 cycles (see point B), and several test units exceeded the threshold level after 40 × 10^6 cycles (see point C).



(a) Stroke time



(b) Leakage

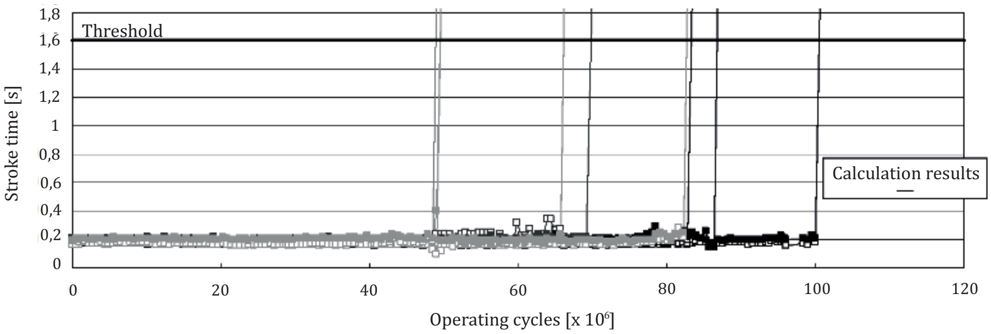


(c) Minimum working pressure

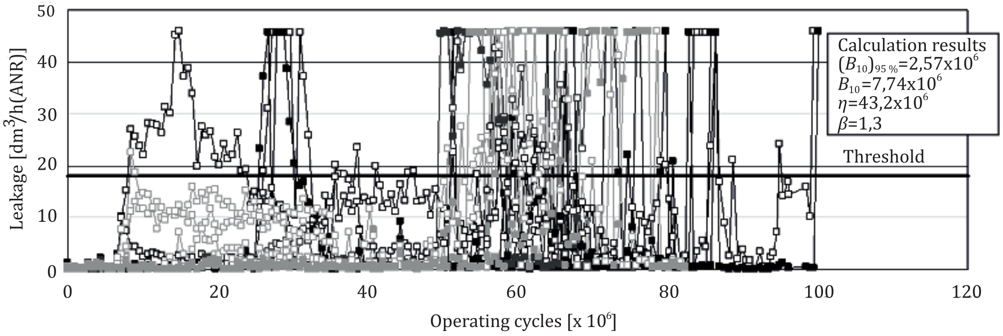
Figure G.3 — Results of measurement and calculation for Cylinder-1

G.5 Results of testing Cylinder-2

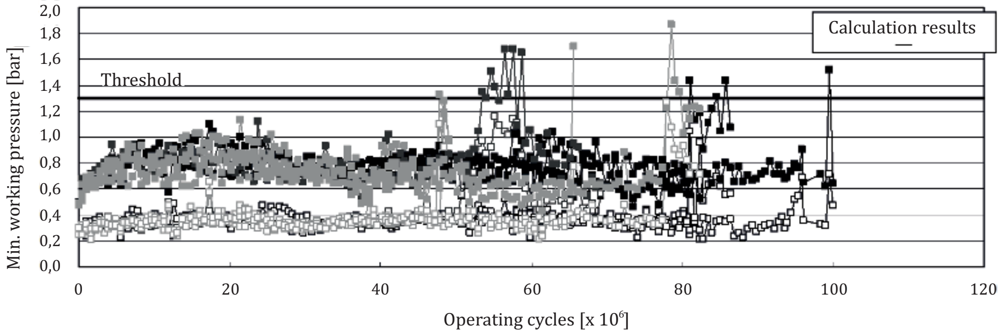
All 8 test units have reached catastrophic failure and the testing has been completed at 100 × 10^6 cycles. The measurement results are shown in Figure G.4. The stroke time is almost the same as the initial value and is significantly below the threshold level. The leakage started to exceed the threshold level after passing 10 × 10^6 cycles (= 18 weeks = 3200 km), and a large amount of leakage started to be generated after passing 50 × 10^6 cycles. The minimum working pressure started to exceed the threshold level after 40 × 10^6 cycles.



(a) Stroke time



(b) Leakage



(c) Minimum working pressure

Figure G.4 — Results of measurement and calculation for Cylinder-2

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