Standard ECMA-396

2nd Edition / June 2014

Test Method for the Estimation of Lifetime of Optical Disks for Long-term Data Storage

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Introduction

Markets and industry have developed a common understanding that the property referred to as the lifetime of data recorded to optical disks plays an increasingly important role in many applications. Disparate standardized test methodologies exist for Magneto-Optical disks vs recordable compact disks and DVD systems. The first edition of this International Standard provided a common methodology, applicable for various purposes, that included lifetime testing of then-available writable CD and DVD optical disks.

ISO/IEC JTC 1/SC 23/JWG 1, which is a Joint working group comprising ISO/TC 42, ISO/TC 171/SC 1 and ISO/IEC JTC 1/SC 23, initiated work on this subject and developed initial drafts with assistance from Ecma International TC31.

After the issuance of the first edition of this International Standard, ISO/IEC standards for the physical formats of BD Recordable and Rewritable disks were published. Accordingly, ISO/IEC JTC 1/SC 23/JWG 1 started work again to include testing of writable BD optical disks in this Second edition of the International Standard. Additional details for lifetime estimation are also incorporated.

This Ecma Standard has been adopted by the General Assembly of June 2014.

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Test Method for the Estimation of Lifetime of Optical Disks for Long-term Data Storage

1 Scope

This Ecma Standard specifies an accelerated-aging test method for estimating the lifetime of the retrievability of information stored on recordable or rewritable optical disks.

The method is based on the theoretical assumption that the lifetime of data recorded on an optical disk has a lognormal distribution.

Detailed testing is specified for the following formats: DVD-R/RW/RAM disks, +R/+RW disks, CD-R/RW disks and BD Recordable / Rewritable disks. The testing may be applied to additional optical-disk formats, with substitution of the appropriate specifications, and may also be updated by committee in the future as required.

This Ecma Standard includes:

- stress conditions
  - Basic and Rigorous stress-conditions for testing and subsequent analysis using both the Eyring and Arrhenius methods.
- ambient storage conditions in which the lifetime of data stored on optical disk is estimated
  - A Controlled storage-condition, 25 °C and 50 % RH, representing full-time air conditioning. The Eyring method is used to estimate the lifetime under this storage condition.
  - A Harsh storage-condition, 30 °C and 80 % RH, representing the most severe conditions in which users handle and store optical disks. The Arrhenius method is used to estimate the lifetime under this storage condition.
- a description of the evaluation system
- procedures for specimen preparation and data acquisition
- definitions and methods used in testing specific disk types
- analysis of test results to determine the lifetime of stored data
- a format for reporting the estimated lifetime of stored data

The methodology includes only the effects of temperature and relative humidity. It does not attempt to model degradation due to complex failure-mechanism kinetics, nor does it test for exposure to light, corrosive gases, contaminants, handling, or variations in playback subsystems. Disks exposed to these additional sources of stress or higher levels of temperature and relative humidity are expected to experience shorter usable lifetimes.

2 Conformance

A disk tested by this methodology shall conform to all normative references specific to that disk format.

3 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.

ECMA-130 Data Interchange on Read-only 120 mm Optical Data Disks (CD-ROM) (ISO/IEC 10149:1995)

ECMA-267 120 mm DVD – Read-Only Disk, 3rd edition (ISO/IEC 16448:2002)

ECMA-268 80 mm DVD – Read-Only Disk, 3rd edition (ISO/IEC 16449:2002)

ECMA-330 120 mm (4,7 Gbytes per side) and 80 mm (1,46 Gbytes per side) DVD Rewritable Disk (DVD-RAM), 3rd edition (ISO/IEC 17592:2004)

ECMA-337 120 mm and 80 mm – Optical Disk using +RW Format – Capacity: 4,7 and 1,46 Gbytes per side (Recording speed up to 4X), 4th edition (ISO/IEC 17341:2009)

ECMA-338 80 mm (1,46 Gbytes per side) and 120 mm (4,70 Gbytes per side) DVD Re-recordable Disk (DVD-RW) (ISO/IEC 17342:2004)

ECMA-349 120 mm and 80 mm Optical Disk using +R Format – Capacity: 4,7 and 1,46 Gbytes per Side (Recording speed up to 16X), 4th edition (ISO/IEC 17344:2009)

ECMA-359 80 mm (1,46 Gbytes per side) and 120 mm (4,70 Gbytes per side) DVD Recordable Disk (DVD-R) (ISO/IEC 23912:2005)

ECMA-364 120 mm and 80 mm Optical Disk using +R DL Format – Capacity: 8,55 and 2,66 Gbytes per Side (Recording speed up to 16X), 3rd edition (ISO/IEC 25434:2008)

ECMA-371 120 mm and 80 mm Optical Disk using +RW HS Format – Capacity: 4,7 and 1,46 Gbytes per Side (Recording speed 8X) 2nd edition (ISO/IEC 26925:2009)

ECMA-374 120 mm and 80 mm Optical Disk using +RW DL Format – Capacity: 8,55 and 2,66 Gbytes per Side (Recording speed 2,4x) 2nd edition (ISO/IEC 29642:2009)

ECMA-382 120 mm (8,54 Gbytes per side) and 80 mm (2,66 Gbytes per side) DVD Recordable Disk for Dual Layer (DVD-R for DL) (ISO/IEC 12862:2009)

ECMA-384 120 mm (8,54 Gbytes per side) and 80 mm (2,66 Gbytes per side) DVD re-recordable disk for dual layer (DVD-RW for DL) (ISO/IEC 13170: 2009)

ECMA-394 Recordable Compact Disc Systems CD-R Multi-Speed

ECMA-395 Recordable Compact Disc Systems CD-RW Ultra-Speed

ISO/IEC 30190 Information technology – Digitally recorded media for information interchange and storage – 120 mm Single Layer (25,0 Gbytes per disk) and Dual Layer (50,0 Gbytes per disk) BD Recordable disk

ISO/IEC 30191 Information technology – Digitally recorded media for information interchange and storage – 120 mm Triple Layer (100,0 Gbytes per disk) and Quadruple Layer (128,0 Gbytes per disk) BD Recordable disk

ISO/IEC 30192 Information technology – Digitally recorded media for information interchange and storage – 120 mm Single Layer (25,0 Gbytes per disk) and Dual Layer (50,0 Gbytes per disk) BD Rewritable disk

ISO/IEC 30193 Information technology – Digitally recorded media for information interchange and storage – 120 mm Triple Layer (100,0 Gbytes per disk) BD Rewritable disk

4 Terms and definitions

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

4.1
Arrhenius method
accelerated aging model based on the effects of temperature only

4.2
baseline
analysis of an initial test (e.g., initial data errors) after recording and before exposure to any stress condition, i.e. measurement at stress time t = 0 hours

4.3
basic stress-condition
accelerated-aging conditions for estimating the lifetime of data stored on optical disks with a reasonable amount of time and labour

4.4
B_5 Life
5 percentile of the lifetime distribution (i.e. 5 % failure time) or 95 % survival lifetime

4.5
(B_5 Life)$_L$
95 % lower confidence bound of B_5 Life

4.6
B_{50} Life
50 percentile of the lifetime distribution (i.e. 50 % failure time) or 50 % survival lifetime

4.7
controlled storage condition
well-controlled storage conditions with full-time air conditioning (25 °C and 50 % RH), which may extend the lifetime of data stored on optical disks

4.8
Eyring method
accelerated-aging model based on the combined effects of temperature and relative humidity

4.9
data error
data error measured on a sample disk before error correction is applied

4.10
harsh storage condition
most-severe conditions in which users handle and store the optical disks (30 °C and 80 % RH) under which the lifetime of data stored on optical disks may be reduced

4.11
incubation
process of enclosing and maintaining controlled test-sample environments

4.12
LDC Block
ECC Block of BDs using Long-Distance Code

[SOURCE: ISO/IEC 30190:2013, 13.6]

4.13
maximum data error
maximum data error measured anywhere in one of the relevant areas on the disk:

NOTE For BD Recordable SL/DL disks, BD Recordable TL/QL disks, BD Rewritable SL/DL disks and BD Rewritable TL disks, this is the Maximum RSER; for DVD-R/RW disks and +R/+RW disks, this is the Maximum PI Sum 8; for DVD-RAM disks, this is the Maximum BER and for CD-R/RW disks, this is the Maximum C1 Ave 10.

4.14
retrievability
ability to recover physically-recorded information as recorded

4.15
rigorous stress-condition
accelerated-aging conditions for estimating the lifetime of data stored on optical disks with higher confidence

4.16
shelf life
maximum time an unrecorded disk can be stored under specific conditions and still meet the performance requirements specified

4.17
shelf time
time spent on the shelf

4.18
stress
temperature and relative humidity variables to which the sample is exposed during the incubation sub-intervals

4.19
system
combination of hardware, software, storage medium and documentation used to record, retrieve and reproduce information

5 Conventions and notations

5.1 Representation of numbers

A measured value is rounded off to the least significant digit of the corresponding specified value. For instance, it follows that a specified value of 1,26 with a positive tolerance of + 0,01 and a negative tolerance of - 0,02 allows a range of measured values from 1,235 to 1,275.

5.2 Variables

A variable with "^" above the character denotes that its value is obtained by estimation.

5.3 Names

The names of entities having explicitly-defined meanings for the purpose of this document are capitalized.

6 List of acronyms

BER	Byte Error Rate
BLER	BLock Error Rate

DL	Dual Layer
ECC	Error-Correction Code
LDC	Long-Distance Code
PI	Parity (of the) Inner (code)
QL	Quadruple Layer
RH	Relative Humidity
NOTE	The same meaning as "relative humidity" and used for the unit with %.
RSER	Random Symbol Error Rate
SER	Symbol Error Rate
SL	Single Layer
TL	Triple Layer

7 Measurements

7.1 Summary

7.1.1 Stress incubation and measuring

A group of disks shall be measured at four stress conditions for Basic stress-condition testing, or five stress conditions for Rigorous stress-condition testing, for analysis by the Eyring method. For analysis by the Arrhenius method, three stress conditions shall be used for Basic stress-condition testing and four stress conditions shall be used for the Rigorous stress-condition testing.

Each total incubation time is divided into several incubation sub-interval time periods. The purpose of the sub-intervals is to provide sufficient data points to enable proper fitting of the data to an exponential curve during analysis. Each disk in each group of disks has its initial data errors measured before exposure to a stress condition. After each incubation sub-interval, each disk shall be measured for its data errors again.

A control disk used for monitoring the measurement equipment may also be measured after each incubation sub-interval.

7.1.2 Assumptions

This Ecma Standard is based on the following assumptions for applicability to the optical disks to be tested:

- the life-distribution of the disks is appropriately modeled by a statistical distribution,

- the Eyring method can be used to model aging with both stresses involved (temperature and relative humidity),

- the dominant failure mechanism acting when disks are in use under normal conditions will be the same as that acting under the stress conditions,

- compatibility of a disk and drive combination can assure the initial recording quality, and will not otherwise affect the resulting lifetime estimation,

- a hardware and software system needed to read the disk will be available at the time retrieval of the information is attempted,

- the recorded format will be recognizable and interpretable by the reading software.

7.1.3 Data error

7.1.3.1 General

Data errors shall be measured at disk locations defined in 7.5. For each format, the Maximum Data Error used to estimate the time-to-failure shall be determined as follows:

BD Recordable SL/DL disks, BD Recordable TL/QL disks, BD Rewritable SL/DL disks and BD Rewritable TL disks defined in ISO/IEC 30190, ISO/IEC 30191, ISO/IEC 30192 and ISO/IEC 30193, respectively :
Maximum Random SER (Max RSER),

DVD-R disks defined in ECMA-359 and ECMA-382 (ISO/IEC 23912 and ISO/IEC 12862), DVD-RW disks defined in ECMA-338 and ECMA-384 (ISO/IEC 17342 and ISO/IEC 13170), +R disks defined in ECMA-364 and ECMA-349 (ISO/IEC 25434 and ISO/IEC 17344), and +RW disks defined in ECMA-337, ECMA-371 and ECMA-374 (ISO/IEC 17341, ISO/IEC 26925 and ISO/IEC 29642) :
Maximum PI Sum 8 (Max PI Sum 8),

DVD-RAM disks defined in ECMA-330: Maximum Byte Error Rate (Max BER),

CD-R/RW disks defined in ECMA-394 and ECMA-395 respectively:
Maximum C1 Ave 10 (Max C1 Ave 10).

7.1.3.2 RSER

Per ISO/IEC 30190, ISO/IEC 30191, ISO/IEC 30192 and ISO/IEC 30193, a Random Symbol Error Rate (RSER) is defined as the SER where all erroneous bytes contained in burst errors of length ≥ 40 bytes are not counted, neither in the numerator nor in the denominator of the SER calculation:

$$\frac{\sum_{i=1}^{N}\left(E_{\mathrm{a}_i} - E_{\mathrm{b}_i}\right)}{N \times 75392 - \sum_{i=1}^{N} E_{\mathrm{b}_i}}$$

where, E_{a_i} = number of all erroneous bytes in LDC Block *i*,
E_{b_i} = number of all erroneous bytes ≥ 40 bytes in LDC Block *i*,
N = number of LDC Blocks.

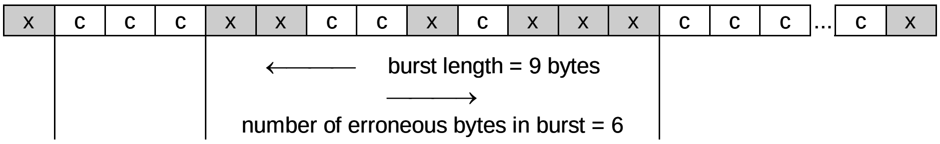
RSER shall be averaged over any 10 000 consecutive LDC Blocks with the condition that all Blocks are recorded either in a continuously-written sequence, or in a discontinuously-written sequence excluding disk defects.

A burst error is defined as a sequence of bytes where there are not more than two correct bytes between any two erroneous bytes.

For determining burst errors, the bytes shall be ordered in the same sequence as they were recorded on the disk. The length of a burst error is defined as the total number of bytes counting from the first erroneous byte that is preceded by at least three correct bytes to the last erroneous byte that is followed by at least three correct bytes.

The number of erroneous bytes in a burst is defined as the actual number of bytes in that burst that are not correct (see example in Figure 1).

The maximum value of the RSER measured over the area specified in 7.5 (Max RSER) shall not exceed 10^{-3}.



c = correct byte, x = erroneous byte

Figure 1 — Example of burst error

7.1.3.3 PI Sum 8

Per ISO/IEC 16448 or ISO/IEC 16449, a row in an ECC block that has at least 1 byte in error constitutes a PI error. PI Sum 8 is measured over any 8 consecutive ECC blocks. The maximum number of PI errors, also called Max PI Sum 8, before error correction, measured over the area specified in 7.5 shall not exceed 280.

7.1.3.4 BER

The number of erroneous symbols shall be measured in any consecutive 32 ECC blocks in the first pass of the decoder before correction. The BER is the number of erroneous symbols divided by the total number of symbols included in the 32 consecutive ECC blocks. The maximum value of the BER measured over the area specified in 7.5 (Max BER) shall not exceed 10^{-3}.

7.1.3.5 C1 Ave 10

ISO/IEC 10149 specifies that the BLER averaged over any 10 seconds shall be less than 3×10^{-2}. At the standard (1X) data transfer rate, the total number of blocks per second entering the C1-decoder is 7 350.

Thus, the number of C1 errors per second before error correction which is averaged over any 10 seconds is called C1 Ave 10. The maximum value measured over the area specified in 7.5 (Max C1 Ave 10) shall not exceed 220.

7.1.4 Data quality

Data quality is checked by plotting the median rank of the estimated time to failure values with a best-fit line for each stress condition. The lines are then checked for reasonable parallelism.

7.1.5 Regression

The log predicted time-to-failure values shall be calculated using linear regression.

Multiple linear-regression is used for the Eyring method and linear regression is used for the Arrhenius method.

7.2 Test specimen

The sample disks shall represent the construction, materials, manufacturing process, quality and variation of the final process output.

Consideration shall be made for shelf life. Longer shelf time of optical disks before recording and testing may impact test results. Shelf time shall be representative of normal usage.

NOTE In case the support of disk manufacturer is available, it is recommended to use the disks gathered from as many production lots as possible.

7.3 Recording conditions

7.3.1 General

Before disks are entered into accelerated-aging tests, they shall be recorded as optimally as is practicable according to the descriptions given in the related standard. OPC (Optimum Power Control) during the writing process shall serve as the method to achieve minimum data errors. It is generally assumed that optimally-recorded disks will yield the longest estimated-lifetime. Disks are deemed acceptable for entry into the aging tests when their data errors and all other disk parameters are found to be within their respective standard's specification limits.

The choice of recording hardware is at the discretion of the recording party. It may be based either on a commercial drive or a specialty recording tester. It shall be capable of producing recordings that meet all specifications.

The recording speed used for testing shall be reported.

NOTE It is expected that the lifetime of data on a disk may be affected by recording conditions including recording speed.

7.3.2 Recording test environment

When performing recordings, the air immediately surrounding the disk shall have the following properties:

temperature:	23 °C to 35 °C
relative humidity:	45 % to 55 %
atmospheric pressure:	60 kPa to 106 kPa

No condensation on the disk shall occur. Before testing, the disk shall be conditioned in this environment for 48 hrs minimum. It is recommended that, before testing, the entrance surface be cleaned according to the instructions of the manufacturer of the disk.

7.4 Playback conditions

7.4.1 Playback tester

Specimen disks shall be read as described in the relevant format standards identified in Clause 3.

7.4.2 Playback test environment

When measuring the data errors, the air immediately surrounding the disk shall have the following properties:

temperature:	23 °C to 35 °C,
relative humidity:	45 % to 55 %,
atmospheric pressure:	60 kPa to 106 kPa.

Unless otherwise stated, all tests and measurements shall be made in this test environment.

7.4.3 Calibration

The test equipment should be calibrated as needed or prescribed by its manufacturer using calibration disks approved by said manufacturer before disk testing. A control disk should be maintained at ambient conditions, and its data error should be measured at the same time the stressed disks are measured, both initially and after each stress sub-interval.

The mean and standard deviation of the control disk shall be established by collecting at least five measurements. Should any individual data error differ from the mean by more than three times the standard deviation, the problem shall be corrected and all data collected since the last valid control point shall be re-measured.

7.5 Disk testing locations

7.5.1 Rigorous stress-condition testing

All data areas on a disk shall be tested.

7.5.2 Basic stress-condition testing

Testing locations shall be a minimum of three bands spaced evenly across the inner, middle and outer radius regions on the disk as indicated in Table 1. The total testing area shall represent a minimum of 5 % of the disk capacity. For BD disks, each of the three test bands in each layer shall have more than 10 000 LDC Blocks. For DVD disks and +R / +RW disks, each of the three test bands in each layer shall have more than 750 ECC blocks for 80 mm disks, or 2 400 ECC blocks for 120 mm disks. For CD disks, each of the three test bands shall have more than 5 900 sectors.

Table 1 — Nominal radii of three test bands (Unit; mm)

	BD Recordable disk / BD Rewritable disk (SL / DL / TL / QL) (inner radius)	DVD-R / DVD-RW / +R / +RW disk (SL /DL) (Inner radius)		DVD-RAM disk		CD-R / RW disk (inner radius)
	120 mm	80 mm	120 mm	80 mm	120 mm	120 mm
Band 1	25,0	25,0	25,0	24,1 to 25,0	24,1 to 25,0	25,0
Band 2	40,0	30,0	40,0	29,8 to 38,8	39,4 to 40,4	40,0
Band 3	55,0	35,0	55,0	34,6 to 35,6	54,9 to 55,8	55,0

8 Accelerated stress test

8.1 General

Accelerated stress testing is used in order to estimate the lifetime of the optical disk. All information needed for this testing is provided in this document.

8.2 Stress conditions

8.2.1 General

Stress conditions for this test method are increases in temperature and/or relative humidity. The stress conditions are intended to accelerate the chemical reaction rate from what would occur normally at ambient storage or usage conditions. The chemical reaction is expected to cause degradation in some desired material property that eventually leads to disk failure.

Regarding use of the Eyring method, five stress conditions shall be used for Rigorous stress-condition testing and the minimum number of specimens that shall be used for those stress conditions are shown in Table 2. The four stress conditions that shall be used for Basic stress-condition testing and the minimum numbers of specimens are shown in Table 3. Additional specimens and conditions may be used, if desired for improved precision.

The total incubation time for each stress condition shall be greater than or equal to the minimum total incubation time. The minimum total incubation-time for the Rigorous stress-condition is defined in Table 2. The minimum total incubation-time for the Basic stress-condition is defined in Table 3. If all the data errors of specimens for a certain stress condition far exceed the Maximum Data Error before the minimum total incubation-time and the continuation of testing is judged as irrelevant then the testing for that stress condition may be stopped.

The incubation sub-interval time shall be smaller than or equal to the maximum incubation sub-interval time. The maximum incubation sub-interval time for the Rigorous stress-condition is defined in Table 2. The maximum incubation sub-interval time for the Basic stress-condition is defined in Table 3.

The number of incubation sub-intervals depends on the total incubation time and the incubation sub-interval time. For example the total time for each stress condition given in Table 2 and Table 3 is divided into five and four equal incubation sub-intervals respectively in the case of a combination of the maximum incubation sub-interval time and the minimum total incubation-time. It is recommended to set the number of incubation sub-intervals to greater than or equal to 4, considering the case that a specimen reaches the Maximum Data Error before the minimum total incubation-time.

Regarding use of the Arrhenius method, stress conditions are given in Table C.1 and Table C.2 in Annex C.

The temperature and relative humidity during each incubation sub-interval shall be controlled as given in Table 4 and shown in Figure 2.

Table 2 — Rigorous stress-condition for use with Eyring method

Test specimen group	Test stress condition (incubation)		Number of specimens	Maximum incubation sub-interval time	Minimum total incubation-time	Intermediate relative humidity	Minimum equilibration duration time
	Temp (°C)	% *RH*		hours	hours	% *RH*	hours
A	85	80	20	300	1 500	30	7
B	85	70	20	400	2 000	30	6
C	85	60	20	600	3 000	30	5
D	75	80	20	600	3 000	32	8
E	65	80	30	800	4 000	35	9

Table 3 — Basic stress-condition for use with Eyring method

Test specimen group	Test stress condition (incubation)		Number of specimens	Maximum incubation sub-interval time	Minimum total incubation-time	Intermediate relative humidity	Minimum equilibration duration time
	Temp (°C)	% *RH*		hours	hours	% *RH*	hours
A	85	80	20	250	1 000	30	7
B	85	70	20	250	1 000	30	6
C	65	80	20	500	2 000	35	9
D	70	75	30	625	2 500	33	11

NOTE Total incubation time and incubation sub-interval time should be determined from the aging characteristic of the disks under test.

8.2.2 Temperature

The temperature levels chosen for this test plan are based on the following:

There shall be no change of phase of moisture within the test system over the test-temperature range. This restricts the temperature to greater than 0 °C and less than 100 °C.

The temperature shall not be so high that plastic deformation occurs anywhere within the disk structure. In case a stress condition would be destructive for a disk to be tested see Annex D for alternative stress conditions.

The typical substrate material used for optical disks is polycarbonate (glass-transition temperature is around 150 °C). The glass-transition temperature of other layers may be lower. Experience with high-temperature testing of BD disks, DVD disks, +R/+RW disks, and CD disks indicates that an upper limit of 85 °C is practical for most applications.

8.2.3 Relative humidity

Experience indicates that 80 % RH is the generally-accepted upper limit for control within most accelerated test cells.

8.2.4 Incubation and ramp profiles

The relative-humidity transition (ramp) profile is intended to avoid moisture condensation on the substrate, minimize substantial moisture gradients in the substrate and end at ramp-down completion with the substrate equilibrated at the ambient condition. This is accomplished by varying the moisture content of the chamber only at the stress-incubation temperature, and allowing sufficient time for equilibration during the ramp down based on the diffusion coefficient of water in polycarbonate.

Table 4 —Temperature and relative humidity transition (ramp) profiles for each incubation sub-interval

Process step	Temperature °C	Relative humidity %	Duration hours
Start	at T_{amb}	at RH_{amb}	—
Temperature, relative-humidity ramp	to T_{inc}	to RH_{int}	1,5 ± 0,5
relative-humidity ramp	at T_{inc}	to RH_{inc}	1,5 ± 0,5
Incubation	at T_{inc}	at RH_{inc}	See Table 2 or Table 3
relative humidity ramp	at T_{inc}	to RH_{int}	1,5 ± 0,5
Equilibration	at T_{inc}	at RH_{int}	See Table 2 or Table 3
Temperature, relative- humidity ramp	to T_{amb}	to RH_{amb}	1,5 ± 0,5
end	at T_{amb}	at RH_{amb}	—

amb = room-ambient temperature or relative humidity (T_{amb} or RH_{amb})
inc = stress-incubation temperature or relative humidity (T_{inc} or RH_{inc})
int = intermediate relative-humidity (RH_{int}) that at T_{inc} supports the same equilibrium moisture absorption in polycarbonate as that supported at T_{amb} and RH_{amb}

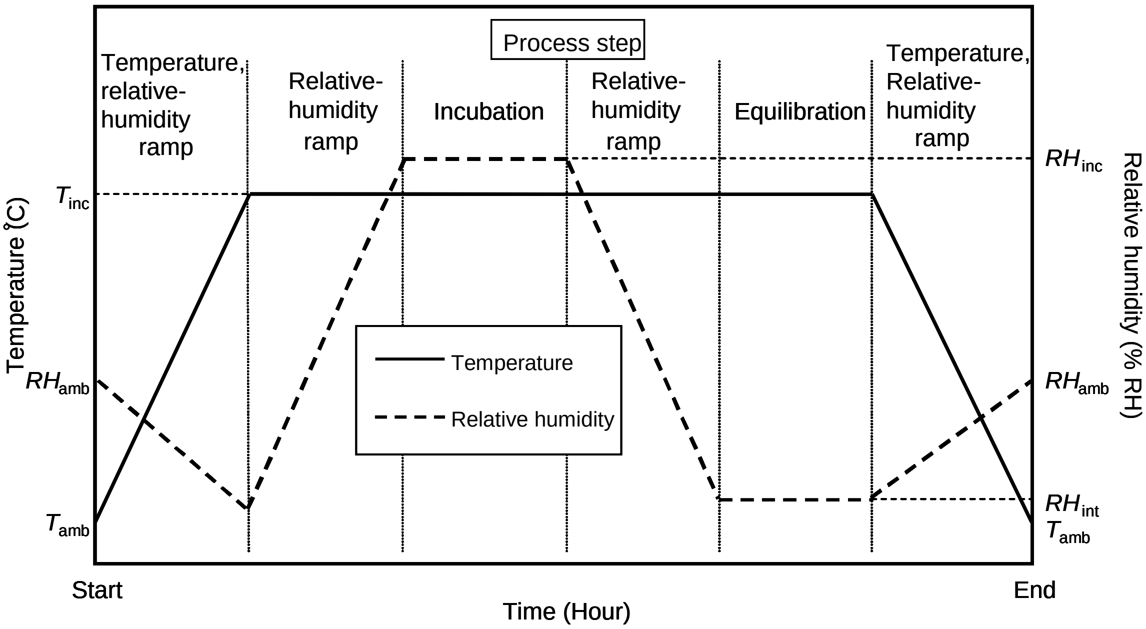


Figure 2 — Graph of typical transition (ramp) profile for each incubation sub-interval

8.3 Measuring-time intervals

For data collection, RSER (BD Recordable SL/DL disk, BD Recordable TL/QL disk, BD Rewritable SL/DL disk, BD Rewritable TL disk), PI Sum 8 (DVD-R, DVD-RW, +R, +RW disk), BER (DVD-RAM disk), or C1 Ave 10 (CD-R, CD-RW disk) shall be measured on each disk : 1) before disk exposure to any stress condition to determine its baseline measurement and 2) after each incubation sub-interval. The length of time for intervals is dependent on the severity of the stress conditions.

In case all the data errors of specimens do not reach the Maximum Data Error within the minimum total incubation time, testing at a particular stress condition may have to be stopped. (see 0 for guidance).

8.4 Design of stress conditions

A separate group of specimens shall be used for each stress condition.

Table 2, for the Rigorous stress-condition, and Table 3, for the Basic stress-condition, specify the temperatures, relative-humidity values, maximum Incubation sub-intervals, minimum total incubation time, and minimum number of specimens for each stress condition. All temperatures shall be maintained within ± 2 °C of the target temperature; all relative-humidity values shall be maintained within ± 3 % RH of the target relative humidity.

The intermediate relative-humidity values in Table 2 and Table 3 are calculated assuming 25 °C and 50 % RH ambient conditions. If the ambient is different, the intermediate relative humidity to be used is calculated using the equation:

$$RH_{\mathrm{int}} = \frac{0{,}24 + 0{,}0037 \times T_{\mathrm{amb}}}{0{,}24 + 0{,}0037 \times T_{\mathrm{inc}}} \times RH_{\mathrm{amb}}$$

where,

$T_{\mathbf{amb}}$ and $T_{\mathbf{inc}}$ are the ambient and incubation temperature in units of °C,

$RH_{\mathbf{amb}}$ is the ambient relative humidity,

RH_{int}	is the intermediate relative humidity.

The stress conditions in Table 2, Table 3 and Table 4 offer sufficient combinations of temperature and relative humidity to satisfy the mathematical requirements of the Eyring method.

8.5 Disk orientation

The disks subjected to this test method shall be maintained during incubation in a vertical position with a minimum of 2 mm separation between disks to allow air flow between disks and to minimize deposition of debris, which could negatively influence the data-error measurements, on the disk surface.

9 Lifetime estimation

9.1 Time-to-failure

Ideally, all disks subjected to stress conditions should have their times-to-failure calculated at the stress conditions they have been subjected to. In case any times-to-failures are not available for a stress condition, however, see 0.

Failure criteria are: Max RSER exceeding 10^{-3} for BD Recordable SL/DL disks, BD Recordable TL/QL disks, BD Rewritable SL/DL disks and BD Rewritable TL disks (see Annex F), Max PI Sum 8 exceeding 280 for DVD-R/RW disks and +R/+RW disks, Max BER exceeding 10^{-3} for DVD-RAM disks and Max C1 Ave 10 exceeding 220 for CD-R/-RW disks.

It is assumed that the data errors on a disk are the result of material degradation. The chemical changes are generally expected to cause test data to have a distribution that follows an exponential function over time. Therefore, test values of: PI Sum 8, BER, C1 Ave 10 or RSER as functions of time are expected to exhibit an exponential distribution.

The best function fitting an error trend can be found by regression of the test data against time, for example, with a least-squares fit. The time-to-failure per disk type can be calculated using the error-trend function and the failure criteria. But if a determination of time-to-failure is judged not to be effective then that case should be treated as a missing time-to-failure (see 0).

9.2 Accelerated-aging test methods

9.2.1 Eyring acceleration model (Eyring method)

Using the Eyring model, the following equation is derived from the laws of thermodynamics and can be used to handle the two critical stresses of temperature and relative humidity.

$$t = AT^{a}e^{\Delta H/kT}e^{(B+C/T)\times RH}$$

where

t	is the time to failure,
A	is the pre-exponential time constant,
T^{a}	is the pre-exponential temperature factor,
ΔH	is the activation energy per molecule,
k	is the Boltzmann's constant (1,380 7 × 10^{-23} J/molecule degree K),
T	is the temperature (in Kelvin),
B, C	are the *RH* exponential constants,
RH	is the relative humidity.

In this Ecma Standard T (in Kelvin) is set as T = 273,15+*Temp* (°C).

For the temperature range used in this test method, “*a*” and “*C*” shall be set to zero. The Eyring-model equation then reduces to the following equation:

$$t = Ae^{\Delta H / kT} e^{B \times RH}$$

or, $\ln(t) = \ln(A) + \frac{\Delta H}{kT} + B \times RH$.

9.2.2 Arrhenius-accelerated model (Arrhenius method)

The Arrhenius method uses only temperature stress for accelerated aging.

The time-to-failure is assumed to be governed by the following Arrhenius-model equation:

$$t = Ae^{\Delta H / kT} ,$$

$$\ln(t) = \ln(A) + \frac{\Delta H}{kT} .$$

9.3 Data analysis and judgment of effectiveness

Data analysis and a method for judging the effectiveness of the data are contained in the following Annexes:

Annex A: Outline of Disk-life estimation method and data-analysis steps,

Annex B: Disk-life estimation for the Controlled storage-condition (Eyring method),

Annex C: Disk-life estimation for the Harsh storage-condition (Arrhenius method),

Annex E: Interval estimation for B_5 Life using maximum likelihood.

9.4 Result of estimated disk life

An estimated lifetime based on the data analysis shall be reported as follows.

(1) Number and title of this standard.

(2) Ambient storage condition for the lifetime estimation:

25 °C / 50 % RH (Controlled storage-condition) or 30 °C / 80 % RH (Harsh storage-condition).

(3) Stress and testing condition:

Rigorous stress-condition testing or Basic stress-condition testing and whether or not the alternative condition was used.

(4) The recording speed used for testing shall be reported (see 7.3).

(5) Time-to-failure data

Complete data or data with the substitutes of missing times-to-failure.

(6) Sample information

Number of samples tested under each stress condition.

(7) Estimation method and the estimated data

Maximum-likelihood method with the least squares method / acceleration-factor method and the estimated log standard deviation

(8) B_{50} Life, B_5 Life and 95 % lower confidence bound of B_5 Life (= (B_5 Life)$_L$) for the maximum-likelihood method with least squares method.

B_{50} Life, B_5 Life and the point estimates of the 5 percentile with variation (= B_{5V} Life) for the acceleration-factor method.

Annex A
(normative)

Outline of Disk-life estimation method and data-analysis steps

A.1 Data analysis for disk-life estimation

A.1.1 General

Data analysis for lifetime estimation is based on the following assumptions.

- The lifetime of data recorded on an optical disk has a lognormal distribution.
- The Eyring method is used for the Controlled storage condition (25 °C, 50 % RH) (see Annex B).
- The Arrhenius method is used for the Harsh storage condition (30 °C, 80 % RH) (see Annex C).

The maximum-likelihood method (see Annex E) is applied for a precise analysis and a precise interval estimation. Thus the lifetime estimation in this Ecma Standard is specified based on the maximum-likelihood method estimation.

The calculation for the maximum-likelihood method is complicated and it is not so easy to adopt. If the lifetime data is complete and its distribution is lognormal, then the estimated lifetime can also be calculated using the least-squares method and the calculated results will be the same as that of the maximum-likelihood method. Thus for the complete data case the least-squares method, which is relatively easy to calculate, is adopted as the practical calculation method for estimating the population.

For the case that the lifetime data is not complete and there are missing times-to-failure, the estimation method is shown in A.2.4 as an informative sub clause.

The acceleration-factor method has been widely used for the life time estimation of DVD disks. Those who need the evaluation with relation to the past data can refer to the acceleration method, explained in A.2.6 and B.2.

A.1.2 Lognormal model and point estimation of $\ln\hat{B}_5$ and $\ln\hat{B}_{50}$

As time-to-failure t is distributed with lognormal distribution $LN(\mu, \sigma^2)$, log lifetime ($y = \ln t$) follows a normal distribution $N(\mu, \sigma^2)$, where μ and σ^2 are the expected values of y and variance, respectively. μ can be expressed as a function of $\boldsymbol{x}$ as follows,

$$y = \mu(\boldsymbol{x}) + \sigma \cdot z$$

$$= \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \sigma \cdot z$$

NOTE $\boldsymbol{x}$ is a vector with two dimensions (x_1, x_2).

where z denotes a percentile of $N(0,1)$, $\beta_0 = \ln A$, $\beta_1 = \Delta H / k$, $\beta_2 = B$ (for the definition of A and B see 9.2.1), x_1 represents the variable related to the temperature as $x_1 = 1/T$ and x_2 represents the variable related to the relative humidity as $x_2 = RH$.

The p percentile of the lifetime distribution, or B_P Life, is widely used in reliability engineering. The point estimation of $\ln B_p$ is described as

$$\mathrm{In}\hat{B}_\mathrm{p} = \hat{\beta}_0 + \hat{\beta}_1 x_1 + \hat{\beta}_2 x_2 + z_{\mathrm{p}/100}\hat{\sigma} \ .$$

Then the point estimates of the 5 percentile and 50 percentile of the lifetime distribution are given by：

$$\mathrm{In}\hat{B}_5 = \hat{\beta}_0 + \hat{\beta}_1 x_{10} + \hat{\beta}_2 x_{20} - 1{,}64\hat{\sigma} \ ,$$

$$\mathrm{In}\hat{B}_{50} = \hat{\beta}_0 + \hat{\beta}_1 x_{10} + \hat{\beta}_2 x_{20} \, .$$

where, x_{10}, x_{20} denotes the Controlled storage-condition (25 °C and 50 % RH).

（x_{10} = 1/(273,15 + 25) , x_{20} = 50 ）

NOTE The purpose of the lifetime estimation is to estimate the lifetime of the population. Thus $(\sigma)^2$ is the unbiased variance.

A.1.3 Interval estimation for optical disks

For interval estimation of $\mathrm{In}\hat{B}_p$ for an optical disk, one may consider only the lower bound. $(100-\alpha)$ % lower confidence bound of log lifetime $\mathrm{In}\hat{B}_p$ is given by the following equation:

$$(\mathrm{In}\hat{B}_p)_\mathrm{L} = \mathrm{In}\hat{B}_p + z_{\alpha/100}\sqrt{\mathrm{var}(\mathrm{In}\hat{B}_p)} \ ,$$

where, $\mathrm{var}(\mathrm{In}\hat{B}_p)$ denotes the variance of $\mathrm{In}\hat{B}_p$ (see Annex E).

A.1.4 Estimation of β and σ using least-squares method

The multiple linear-regression model for the ij **th** specimen is described as follows.

$$y_{ij} = \beta_0 + \beta_1 x_{1j} + \beta_2 x_{2j} + \varepsilon_{ij} \quad (i = 1 \text{ to } n_j)\ (j = 1 \text{ to } J)\, ,$$

where, ε_{ij} denotes errors, n_j denotes the number of specimens in each group and J denotes the total number of groups.

The estimate $\hat{y}_j$ is given as

$$\hat{y}_j = \hat{\beta}_0 + \hat{\beta}_1 x_{1j} + \hat{\beta}_2 x_{2j} \, ,$$

where, x_{1j} = 1/(273,15 + T_j (in °C) $x_{2j} = RH_j$.

Also, the sum of squared residual errors S_e is computed as

$$S_e = \sum_{j=1}^{J} \sum_{i=1}^{n_j} (y_{ij} - \hat{y}_j)^2 \, .$$

If the lifetime data is complete and the distribution is lognormal then the estimated regression coefficients obtained by the least-squares method are the same as that of the maximum-likelihood method and they can be used for the estimation. The following shows the way to utilize the calculation results obtained by the least-squares method.

The estimated regression coefficients of $\hat{y}_j$ can be obtained by applying the least-squares method to S_e. The estimates $\hat{\beta}_0$, $\hat{\beta}_1$ and $\hat{\beta}_2$ are obtained by solving 110 linear-regression equations of group A, B, C, D and E.

Let $(\hat{\sigma}_{lsm})^2$ be the unbiased variance obtained by the least-squares method, then

the estimate $(\hat{\sigma}_{lsm})^2$ is given by

$$(\hat{\sigma}_{lsm})^2 = \frac{S_e}{(n-3)} = \frac{\sum_{j=1}^{J}\sum_{i=1}^{n_j}(y_{ij}-\hat{y}_j)^2}{(n-3)}$$

where, $n = \sum_{j=1}^{J} n_j$ and it denotes the total number of specimens.

$n-3 = n-2-1$. -1 is for the limited number of the sampling and -2 is for the number of degrees of freedom (temperature and humidity).

NOTE This clause shows the case for the Eyring method. In case of the Arrhenius method the degree of freedom is 1 (temperature only) and $n - 3$ becomes $n - 2$.

The estimated regression-coefficients $\hat{\beta}_0$, $\hat{\beta}_1$ and $\hat{\beta}_2$ and estimated variance of residual errors $(\hat{\sigma}_{lsm})^2$ are obtained using regression analysis statistics software tools.

B_{50} Life, B_5 Life and the 95 % lower confidence bound of B_5 Life are described as follows.

$$B_{50}\ \text{Life} = \exp(\ln \hat{B}_{50})$$

$$= \exp(\hat{\beta}_0 + \hat{\beta}_1 x_{10} + \hat{\beta}_2 x_{20}),$$

$$B_5\ \text{Life} = \exp(\ln \hat{B}_5)$$

$$= \exp(\hat{\beta}_0 + \hat{\beta}_1 x_{10} + \hat{\beta}_2 x_{20} - 1{,}64\hat{\sigma}),$$

$$= \exp(\hat{\beta}_0 + \hat{\beta}_1 x_{10} + \hat{\beta}_2 x_{20} - 1{,}64\hat{\sigma}_{lsm}),$$

where, x_{10}, x_{20} denotes the Controlled storage-condition (25 °C and 50 % RH).

By substituting $\hat{\sigma}_{lsm}$ for $\hat{\sigma}$, $\operatorname{var}(\ln \hat{B}_{50})$ and $\operatorname{var}(\ln \hat{B}_5)$ are obtained as follows (see E.3).

$$\operatorname{var}(\ln \hat{B}_{50}) = \begin{bmatrix} 1 & x_{10} & x_{20} \end{bmatrix} \begin{bmatrix} \frac{n}{\hat{\sigma}^2_{lsm}} & \frac{1}{\hat{\sigma}^2_{lsm}}\sum_{j=1}^{J} n_j x_{1j} & \frac{1}{\hat{\sigma}^2_{lsm}}\sum_{j=1}^{J} n_j x_{2j} \\ \frac{1}{\hat{\sigma}^2_{lsm}}\sum_{j=1}^{J} n_j x_{1j} & \frac{1}{\hat{\sigma}^2_{lsm}}\sum_{j=1}^{J} n_j x_{1j}^2 & \frac{1}{\hat{\sigma}^2_{lsm}}\sum_{j=1}^{J} n_j x_{1j} x_{2j} \\ \frac{1}{\hat{\sigma}^2_{lsm}}\sum_{j=1}^{J} n_j x_{2j} & \frac{1}{\hat{\sigma}^2_{lsm}}\sum_{j=1}^{J} n_j x_{1j} x_{2j} & \frac{1}{\hat{\sigma}^2_{lsm}}\sum_{j=1}^{J} n_j x_{2j}^2 \end{bmatrix}^{-1} \begin{bmatrix} 1 \\ x_{10} \\ x_{20} \end{bmatrix}$$

$$\mathrm{var}(\ln\hat{B}_5) = \left[1\ \ x_{10}\ \ x_{20}\ \ -1{,}64\right] \begin{bmatrix} \frac{n}{\hat{\sigma}^2_{lsm}} & \frac{1}{\hat{\sigma}^2_{lsm}}\sum_{j=1}^{J} n_j x_{1j} & \frac{1}{\hat{\sigma}^2_{lsm}}\sum_{j=1}^{J} n_j x_{2j} & 0 \\ \frac{1}{\hat{\sigma}^2_{lsm}}\sum_{j=1}^{J} n_j x_{1j} & \frac{1}{\hat{\sigma}^2_{lsm}}\sum_{j=1}^{J} n_j x_{1j}^2 & \frac{1}{\hat{\sigma}^2_{lsm}}\sum_{j=1}^{J} n_j x_{1j} x_{2j} & 0 \\ \frac{1}{\hat{\sigma}^2_{lsm}}\sum_{j=1}^{J} n_j x_{2j} & \frac{1}{\hat{\sigma}^2_{lsm}}\sum_{j=1}^{J} n_j x_{1j} x_{2j} & \frac{1}{\hat{\sigma}^2_{lsm}}\sum_{j=1}^{J} n_j x_{2j}^2 & 0 \\ 0 & 0 & 0 & \frac{2n}{\hat{\sigma}^2_{lsm}} \end{bmatrix}^{-1} \begin{bmatrix} 1 \\ x_{10} \\ x_{20} \\ -1{,}64 \end{bmatrix}$$

where, $n = \sum_{j=1}^{J} n_j$ and it denotes the total number of specimens.

Using the result of the above equation, the lower confidence bound of log lifetime $\ln\hat{B}_5$ = $(B_5\,\mathrm{Life})_{\mathrm{L}}$ is given by the following equation.

$$(B_5\,\mathrm{Life})_{\mathrm{L}} = \exp((\ln\hat{B}_5)_{\mathrm{L}}) = \exp(\ln\hat{B}_5 - 1{,}64\sqrt{\mathrm{var}(\ln\hat{B}_5)}\ )$$

A.2 Data analysis steps for lifetime estimation

A.2.1 Judgment of effectiveness of test data and time-to-failure determination

Before the lifetime-estimation calculation, the effectiveness of the test data shall be checked, following the procedure listed below.

Step 1:

Calculate the linear regression of the logarithm of test-data error rate (Error_t) = $\ln(\mathrm{Error}_t)$ against incubation time and plot $\ln(\mathrm{Error}_t)$ versus the incubation time and their best-fit straight line on the linear-scale graph for each test-condition specimen.

Step 2:

Check the following three conditions:

a) The best-fit line is almost linear.

b) All $\ln(\mathrm{Error}_t)$ are almost on the best-fit straight line.

c) The best-fit straight line has reasonable increase and is not flat nor having a negative slope.

If all three conditions are satisfied, then go to Step 3.

If the three conditions are not satisfied, then that time-to-failure shall not be determined.

There are two cases where the above three conditions are not satisfied.

- The first case is that there is a sample that shows unexpected deterioration during the first sub-interval time of the accelerated-aging test while other samples satisfy the three conditions. In this case the deterioration mechanism of the abnormal sample may be different from that of other samples. The sample whose error rate can not be obtained after the first sub-interval time shall be treated as having the missing time-to-failure. Then go to Step 4 in A.2.2. In this case keep the number of specimens as it is.

- The second case is that there is a sample in a group which does not deteriorate within the minimum total incubation-time and its best-fit straight line does not show reasonable increase while other samples in that group satisfy the three conditions. The case when the time-to-failure of a sample that does not satisfy the three conditions shall be treated as the missing time-to-failure and the procedure shall continue at Step 4 in 0. In this case keep the number of specimens as it is.

Step 3:

For each test-condition specimen, determine the time-to-failure where the best-fit straight line crosses the Maximum Data Error.

For a test-condition specimen for which the measured error rate did not reach the Maximum Data Error within the minimum total incubation-time, the time-to-failure may be determined using the extrapolation of the best-fit straight-line of $\ln(\mathrm{Error}_t)$ as a predicted time-to-failure.

After Step 3, go to the procedure in 0.

A.2.2 Judgment of complete data

Follow the procedure listed below.

Step 4:

For each specimen of a stress group, order the time-to-failure values by increasing incubation time. Calculate the median rank of each specimen for each time-to-failure (see B.1 Step 2).

If there is a sample that shows unexpected deterioration during the first sub-interval time of the accelerated-aging then its missing time-to-failure shall be given the median rank smaller than that of the shortest time-to-failure when sorting times-to-failure for the determination of the median rank.

If there is a sample that does not deteriorate within the minimum total incubation-time then its missing time-to-failure shall be given the median rank larger than that of the longest time-to-failure when sorting times-to-failure for the determination of the median rank.

Step 5:

Plot the median rank versus the time-to-failure on a lognormal graph, with time-to-failure on the abscissa and median rank on the ordinate, for each specimen of the stress group.

Plot the best-fit straight line for each specimen of the stress group.

Step 6:

Check the following conditions.

a) All the times-to-failure corresponding to each median rank are almost on the best-fit straight-line of each stress group.

b) The best-fit straight lines of all stress groups are reasonably parallel with each other.

If both conditions listed above are satisfied, then the data is deemed complete. Proceed to the procedure in 0 (Maximum-likelihood method with least-squares method) or in A.2.6 (acceleration-factor method). For the precise analysis or the precise interval estimation, go to the procedure in A.2.5.

If a time-to-failure is away from the best-fit straight line, then that time-to-failure shall not be used for the lifetime estimation. That time-to-failure is treated as a missing time-to-failure.

If at least one condition listed above is not satisfied, then go to the procedure in 0.

A.2.3 Condition for lifetime-estimation effectiveness

Follow the procedure listed below.

Step 7:

Check the following three conditions and judge the effectiveness of the time-to-failure.

a) The lognormal data plots of each stress group are almost on the best-fit straight-line.

b) Exclude the missing times-to-failure, then check the specimens of each stress group have effective times-to-failure that span over one-half of a median rank point.

c) The best-fit straight lines of all stress groups are reasonably parallel with one another.

If these three conditions are satisfied, we can assume that the lifetime distribution is lognormal. In case there are missing times-to-failure the calculation based on the maximum-likelihood method may be possible, but the method is complicated and is not easy to apply. It may not be as precise as the maximum-likelihood method but the other method in which the missing times-to-failure are substituted is shown in A.2.4.

In A.1, it was assumed that the lifetime data has a lognormal distribution. If the three conditions are not satisfied, it is proven that the assumption is not effective and a reliable lifetime estimation can not be obtained.

A.2.4 Life-time estimation when there are missing times-to-failure (Informative)

As shown in Step 7 in A.2.3 there are cases that lifetime distribution is lognormal but missing times-to-failure exist. The method to substitute those missing times-to-failure is shown in this clause. Be aware that this method uses substituted data in the best-fit straight lines and the estimated lifetime may be longer.

1. Substitution of times-to-failure

   For each missing time-to-failure, check the corresponding median rank and substitute the missing time-to-failure value with the value where the best-fit straight line crosses the corresponding median rank on the lognormal graph.

2. Maximum-likelihood method with least-squares method application

   Substitute all the missing times-to-failure and prepare the complete data set. Then follow the steps in A.2.5.

3. Acceleration-factor method application

   Substitute all the missing times-to-failure and prepare the complete data set. Then follow the steps in A.2.6. For the precise analysis or the precise interval estimation, go to the steps in A.2.5.

A.2.5 Lifetime-estimation calculation method (Maximum-likelihood method with least-squares method)

Calculation of the maximum likelihood method with the least-squares method can be done as listed below.

1) Calculate the multiple regression coefficients and standard error using the least-squares method across all times-to-failure. This calculation can be performed by multiple regression analysis using statistics software tools.

2) B_{50} Life, B_5 Life and 95 % lower confidence bound of B_5 Life at the Controlled storage condition are calculated using the multiple regression-coefficients and standard error obtained by the least-squares method and the equations of maximum-likelihood method (see B.2 and E.4).

A.2.6 Lifetime-estimation calculation method (acceleration-factor method)

Calculation of the conventional acceleration-factor method can be done as follows.

1) Calculate regression coefficients using the log-mean failure time.

2) Calculate acceleration factors from the difference between the estimated log-mean at each stress condition.

3) Calculate the normalized time-to-failure at the ambient condition for each specimen group using the acceleration factors, and plot these data on a lognormal graph.

4) Assuming that the normal distribution of the population varies according to the 95% lower confidence bound of the normal distribution, B_{50} Life, B_5 Life and the point estimates of the percentile with variation (= B_{5V} Life) at the Controlled storage-condition are calculated using $\hat{\mu}$ and $\hat{\sigma}$ obtained from the fitting line (see B.2).

NOTE The data-analysis steps using the Arrhenius method are almost the same as with the Eyring method. A single regression at the Harsh storage temperature can be used with the Arrhenius method.

Annex B
(normative)

Disk-life estimation for Controlled storage-condition (Eyring method)

B.1 General

In this annex, the analysis of the complete data case using the results of a least-squares method and a conventional acceleration-factor method for the Rigorous stress-condition testing are shown.

Data analysis and lifetime estimation using least-squares method

Step 1

Determine the time-to-failure for each specimen at the stress applied following the procedure described below. The data error to be measured is defined in 7.1.3:

BD Recordable disks and BD Rewritable disks:	Max RSER,
DVD-R/-RW, +R/+RW disks:	Max PI Sum 8,
DVD-RAM disks:	Max BER,
CD-R/-RW disks:	Max C1 Ave 10.

Use the initial data-errors measured prior to accelerated aging plus the data errors measured after each specified accelerated-aging incubation sub-interval.

For each specimen, a linear regression is performed with the natural logarithm of measured data-errors as the dependent variable and time as the independent variable. The time-to-failure of the specimen is calculated from the slope and intercept of the regression as the time at which the specimen would have a Max RSER of 10^{-3}, Max PI Sum 8 of 280, Max BER of 10^{-3} or Max C1 Ave 10 of 220.

Table B.1 shows calculations leading to an estimated time-to-failure from a hypothetical data set. The data for five stress conditions (Group A, Group B, Group C, Group D and Group E) are offered solely as an example of the mathematical methodology used in this test procedure.

Step 2

For each stress condition, the specimens are ordered by increasing log time-to-failure values.

The median rank of each specimen is calculated using the estimate $(i-0{,}3)/(n+0{,}4)$, where i is the time-to-failure order and n is the total number of specimens at the stress condition.

Table B.2 shows the ordered log time-to-failure and the median rank for the example data.

Table B.1 — Ordered estimated time-to-failure for example data (Rigorous stress-condition)

Order number	Group A	Group B	Group C	Group D	Group E
	85 °C / 80 % RH	85 °C / 70 % RH	85 °C / 60 % RH	75 °C / 80 % RH	65 °C / 80 % RH
1	429	613	864	1 728	5 455
2	451	640	913	1 882	5 730
3	476	649	915	1 907	5 908
4	484	675	945	1 989	6 114
5	493	679	951	2 020	6 326
6	495	696	993	2 076	6 431
7	501	703	994	2 129	6 544
8	512	709	998	2 151	6 632
9	521	719	1 009	2 180	6 711
10	526	732	1 014	2 227	6 779
11	534	739	1 027	2 277	6 860
12	540	743	1 030	2 318	6 935
13	542	747	1 037	2 352	7 038
14	548	751	1 049	2 404	7 108
15	557	766	1 069	2 443	7 202
16	576	778	1 080	2 512	7 285
17	579	785	1 098	2 589	7 362
18	586	804	1 125	2 590	7 454
19	618	856	1 222	2 776	7 562
20	645	896	1 249	2 891	7 569
21					7 710
22					7 827
23					7 955
24					8 067
25					8 250
26					8 405
27					8 546
28					8 700
29					8 953
30					9 452

Table B.2 — Log time-to-failure and median rank for example data

Group A	85 °C / 80 % RH		
Order number	Time-to-failure H (hours)	ln(H)	Median rank
1	429	6,061 1	0,034
2	451	6,111 5	0,083
3	476	6,165 4	0,131
4	484	6,182 2	0,181
5	493	6,200 5	0,230
6	495	6,204 6	0,279
7	501	6,216 6	0,328
8	512	6,238 3	0,377
9	521	6,255 8	0,426
10	526	6,265 3	0,475
11	534	6,280 4	0,525
12	540	6,291 3	0,574
13	542	6,295 3	0,623
14	548	6,306 3	0,672
15	557	6,322 6	0,721
16	576	6,356 1	0,770
17	579	6,361 3	0,819
18	586	6,373 3	0,869
19	618	6,426 5	0,917
20	645	6,469 3	0,966
Mean	531	6,269 2	

Group B	85 °C / 70 % RH		
Order number	Time-to-failure H (hours)	ln(H)	Median rank
1	613	6,418 4	0,034
2	640	6,461 5	0,083
3	649	6,475 4	0,131
4	675	6,514 7	0,181
5	679	6,520 6	0,230
6	696	6,545 3	0,279
7	703	6,555 4	0,328
8	709	6,563 9	0,377
9	719	6,577 9	0,426
10	732	6,595 8	0,475
11	739	6,605 3	0,525
12	743	6,610 7	0,574
13	747	6,616 1	0,623
14	751	6,621 4	0,672
15	766	6,641 2	0,721
16	778	6,656 7	0,770
17	785	6,665 7	0,819
18	804	6,689 6	0,869
19	856	6,752 3	0,917
20	896	6,797 9	0,966
Mean	734	6,594 3	

Group C	85 °C / 60 % RH		
Order number	Time-to-failure H (hours)	ln(H)	Median rank
1	864	6,761 6	0,034
2	913	6,816 7	0,083
3	915	6,818 9	0,131
4	945	6,851 2	0,181
5	951	6,857 5	0,230
6	993	6,900 7	0,279
7	994	6,901 7	0,328
8	998	6,905 8	0,377
9	1 009	6,916 7	0,426
10	1 014	6,921 7	0,475
11	1 027	6,934 4	0,525
12	1 030	6,937 3	0,574
13	1 037	6,944 1	0,623
14	1 049	6,955 6	0,672
15	1 069	6,974 5	0,721
16	1 080	6,984 7	0,770
17	1 098	7,001 2	0,819
18	1 125	7,025 5	0,869
19	1 222	7,108 2	0,917
20	1 249	7,130 1	0,966
Mean	1 029	6,932 4	

Group D	75 °C / 80 % RH		
Order number	Time-to-failure H (hours)	ln(H)	Median rank
1	1 728	7,454 9	0,034
2	1 882	7,540 3	0,083
3	1 907	7,553 4	0,131
4	1 989	7,595 3	0,181
5	2 020	7,610 6	0,230
6	2 076	7,638 1	0,279
7	2 129	7,663 2	0,328
8	2 151	7,673 9	0,377
9	2 180	7,687 1	0,426
10	2 227	7,708 5	0,475
11	2 277	7,730 8	0,525
12	2 318	7,748 4	0,574
13	2 352	7,763 2	0,623
14	2 404	7,785 0	0,672
15	2 443	7,800 8	0,721
16	2 512	7,828 7	0,770
17	2 589	7,859 2	0,819
18	2 590	7,859 4	0,869
19	2 776	7,928 6	0,917
20	2 891	7,969 5	0,966
Mean	2 272	7,719 9	

Group E	65 °C / 80 % RH		
Order number	Time-to-failure H (hours)	ln(H)	Median rank
1	5 455	8,604 3	0,023
2	5 730	8,653 5	0,056
3	5 908	8,684 1	0,089
4	6 114	8,718 3	0,122
5	6 326	8,752 5	0,155
6	6 431	8,768 9	0,188
7	6 544	8,786 4	0,220
8	6 632	8,799 7	0,253
9	6 711	8,811 5	0,286
10	6 779	8,821 6	0,319
11	6 860	8,833 5	0,352
12	6 935	8,844 3	0,385
13	7 038	8,859 1	0,418
14	7 108	8,869 0	0,451
15	7 202	8,882 2	0,484
16	7 285	8,893 6	0,516
17	7 362	8,904 1	0,549
18	7 454	8,916 5	0,582
19	7 562	8,930 9	0,615
20	7 569	8,931 9	0,648
21	7 710	8,950 3	0,681
22	7 827	8,965 3	0,714
23	7 955	8,981 6	0,747
24	8 067	8,995 5	0,780
25	8 250	9,018 0	0,813
26	8 405	9,036 6	0,845
27	8 546	9,053 2	0,878
28	8 700	9,071 1	0,911
29	8 953	9,099 7	0,944
30	9 452	9,154 0	0,977
Mean	7 296	8,886 4	

NOTE Some tables in this document show values with many digits. Those digits are retained during the calculation in order to estimate the lifetime without introducing excessive round-off errors. However the resulting estimated lifetime is not intended to be quoted or relied on to the same high level of precision.

Step 3

The data can be plotted in different ways. If lognormal-graph paper is employed, the data is plotted with time-to-failure on the abscissa and median rank on the ordinate.

NOTE On most lognormal-graph paper, the actual ordinate scale is the probability of failure, and the median rank is converted to the probability of failure by multiplying by 100.

Figure B.1 shows lognormal plots of specimen groups A, B, C, D and E from Table B.2. The ordinate scale is the probability of failure. Each best-fit straight line is drawn through the plotted data. If the lines are judged to be reasonably parallel, the assumption of equivalent log standard deviation applicable to the individual data sets is verified.

An estimate of the log standard deviation can be obtained from the graphical treatment of the failure data. First, for each stress condition, estimate the times corresponding to 15,9 % and 84,1 % failure based on the best-fit straight line through the time-to-failure data. The estimated log standard deviation $\hat{\sigma}$ is then calculated as follows.

$$\hat{\sigma} = (\ln t_{0,841} - \ln t_{0,159})/2$$

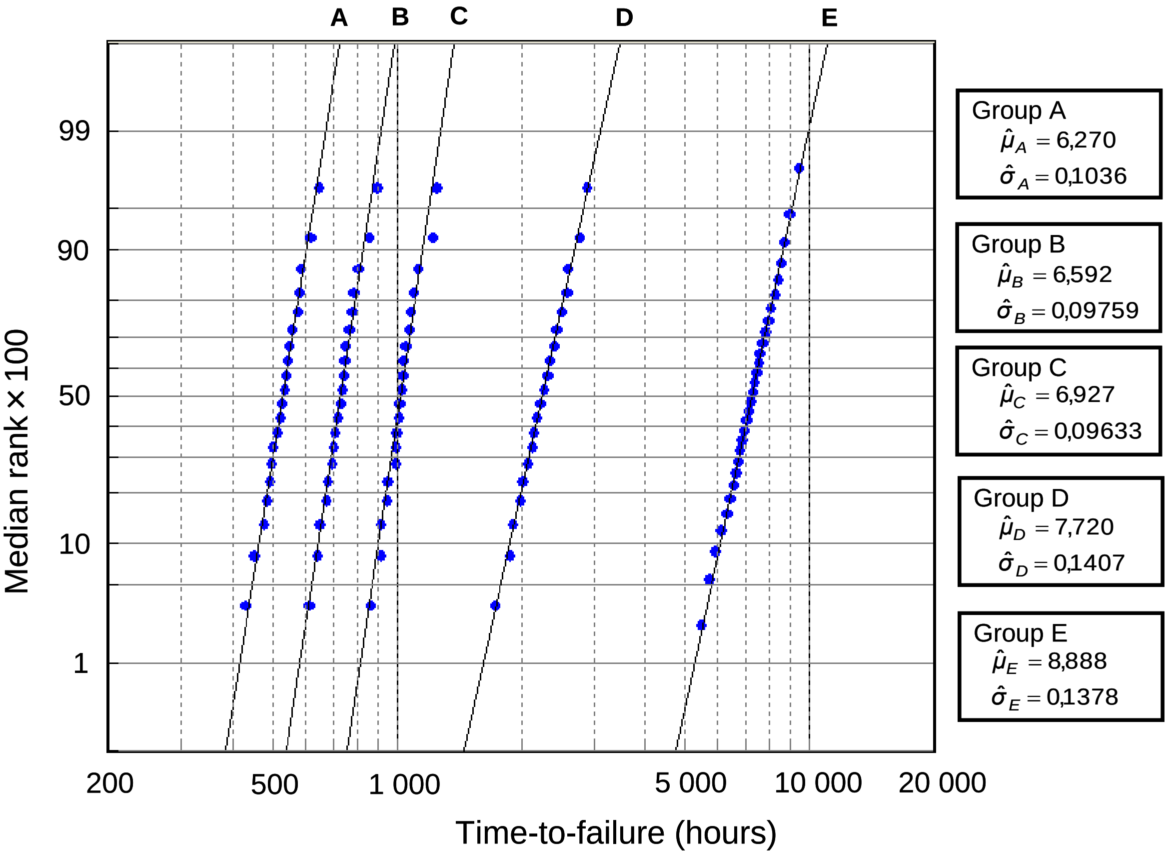


Figure B.1 — Best-fit lines of specimen groups A, B, C, D and E on lognormal paper (Verify that the fitting lines for all stress conditions are reasonably parallel to one another)

The averaged log standard deviation estimate $\hat{\sigma}_m$ of the five groups is then calculated as

$$\hat{\sigma}_m = (\hat{\sigma}_A + \hat{\sigma}_B + \hat{\sigma}_C + \hat{\sigma}_D + \hat{\sigma}_E)/5$$
$$= (0{,}1036 + 0{,}09759 + 0{,}09633 + 0{,}1407 + 0{,}1378)/5 = 0{,}1152.$$

Step 4

Table B.3 shows all 110 sample data points belonging to specimen groups A, B, C, D and E for regression analysis. The regression coefficients and error variance are calculated by applying the least-squares method. Table B.4 shows the result of regression analysis performed by the statistics software tool. Estimated variance of residual errors $(\hat{\sigma}_{lsm})^2$, estimated log standard deviation $\hat{\sigma}_{lsm}$ and estimated regression coefficients $\hat{\beta}_0$, $\hat{\beta}_1$ and $\hat{\beta}_2$ are quickly obtained. Other statistics tools can also be used for regression analysis.

NOTE The estimated log standard deviation $\hat{\sigma}_{lsm}$ (=0,132 35) at the Controlled storage condition is fairly large in comparison with the averaged log standard deviation estimate $\hat{\sigma}_m$ of the five specimen groups. Variation in the best-fit lines among the five groups and the lognormal distributions of each group are among the anomalies that may affect the estimated log standard deviation.

Table B.3 — 110 sample data for regression analysis

Number	ln *t*	x_1	x_2	
1	6,061 055	0,002 792	80	Group A
2	6,111 467	0,002 792	80	
3	6,165 418	0,002 792	80	
4	6,182 176	0,002 792	80	
5	6,200 509	0,002 792	80	
6	6,204 558	0,002 792	80	
7	6,216 606	0,002 792	80	
8	6,238 325	0,002 792	80	
9	6,255 750	0,002 792	80	
10	6,265 301	0,002 792	80	
11	6,280 396	0,002 792	80	
12	6,291 310	0,002 792	80	
13	6,295 266	0,002 792	80	
14	6,306 275	0,002 792	80	
15	6,322 565	0,002 792	80	
16	6,356 108	0,002 792	80	
17	6,361 302	0,002 792	80	
18	6,373 320	0,002 792	80	
19	6,426 488	0,002 792	80	
20	6,469 250	0,002 792	80	
1	6,418 365	0,002 792	70	Group B
2	6,461 468	0,002 792	70	
3	6,475 433	0,002 792	70	
4	6,514 713	0,002 792	70	
5	6,520 621	0,002 792	70	
6	6,545 350	0,002 792	70	
7	6,555 357	0,002 792	70	
8	6,563 856	0,002 792	70	
9	6,577 861	0,002 792	70	
10	6,595 781	0,002 792	70	
11	6,605 298	0,002 792	70	
12	6,610 696	0,002 792	70	
13	6,616 065	0,002 792	70	
14	6,621 406	0,002 792	70	
15	6,641 182	0,002 792	70	
16	6,656 727	0,002 792	70	
17	6,665 684	0,002 792	70	
18	6,689 599	0,002 792	70	
19	6,752 270	0,002 792	70	
20	6,797 940	0,002 792	70	
1	6,761 573	0,002 792	60	Group C
2	6,816 736	0,002 792	60	
3	6,818 924	0,002 792	60	
4	6,851 185	0,002 792	60	
5	6,857 514	0,002 792	60	
6	6,900 731	0,002 792	60	
7	6,901 737	0,002 792	60	
8	6,905 753	0,002 792	60	
9	6,916 715	0,002 792	60	
10	6,921 658	0,002 792	60	
11	6,934 397	0,002 792	60	
12	6,937 314	0002 792	60	
13	6,944 087	0,002 792	60	
14	6,955 593	0,002 792	60	
15	6,974 479	0,002 792	60	
16	6,984 716	0,002 792	60	
17	7,001 246	0,002 792	60	
18	7,025 538	0,002 792	60	
19	7,108 244	0,002 792	60	
20	7,130 099	0,002 792	60	

Number	ln *t*	x_1	x_2	
1	7,454 918	0,002 872	80	Group D
2	7,540 276	0,002 872	80	
3	7,553 358	0,002 872	80	
4	7,595 322	0,002 872	80	
5	7,610 634	0,002 872	80	
6	7,638 060	0,002 872	80	
7	7,663 173	0,002 872	80	
8	7,673 915	0,002 872	80	
9	7,687 122	0,002 872	80	
10	7,708 528	0,002 872	80	
11	7,730 831	0,002 872	80	
12	7,748 371	0,002 872	80	
13	7,763 199	0,002 872	80	
14	7,785 036	0,002 872	80	
15	7,800 846	0,002 872	80	
16	7,828 687	0,002 872	80	
17	7,859 160	0,002 872	80	
18	7,859 351	0,002 872	80	
19	7,928 609	0,002 872	80	
20	7,969 480	0,002 872	80	
1	8,604 288	0,002 957	80	Group E
2	8,653 471	0,002 957	80	
3	8,684 063	0,002 957	80	
4	8,718 337	0,002 957	80	
5	8,752 500	0,002 957	80	
6	8,768 885	0,002 957	80	
7	8,786 365	0,002 957	80	
8	8,799 662	0,002 957	80	
9	9,811 503	0,002 957	80	
10	8,821 630	0,002 957	80	
11	8,833 463	0,002 957	80	
12	8,844 336	0,002 957	80	
13	8,859 079	0,002 957	80	
14	8,868 976	0,002 957	80	
15	8,882 172	0,002 957	80	
16	8,893 573	0,002 957	80	
17	8,904 087	0,002 957	80	
18	8,916 506	0,002 957	80	
19	8,930 890	0,002 957	80	
20	8,931 860	0,002 957	80	
21	8,950 273	0,002 957	80	
22	8,965 335	0,002 957	80	
23	8,981 556	0,002 957	80	
24	8,995 546	0,002 957	80	
25	9,017 968	0,002 957	80	
26	9,036 582	0,002 957	80	
27	9,053 219	0,002 957	80	
28	9,071 078	0,002 957	80	
29	9,099 744	0,002 957	80	
30	9,153 982	0,002 957	80	

Table B.4 — Regression analysis results

Estimated regression coefficients			Estimated log standard deviation
$\hat{\beta}_0$	$\hat{\beta}_1$	$\hat{\beta}_2$	$\hat{\sigma}_{lsm}$
-35,381 1	15 789,57	-0,029 74	0,132 35

Step 5 $\ln\hat{B}_{50}$ and $\ln\hat{B}_5$ at the Controlled storage-condition (25 °C / 50 % RH) are obtained using the estimated regression coefficients $\hat{\beta}_0$, $\hat{\beta}_1$ and $\hat{\beta}_2$ and estimated log standard deviation $\hat{\sigma}$ that were obtained in Step 4.

Then B_{50} Life, B_5 Life and 95% lower confidence bound of B_5 Life at the Controlled storage-condition (25 °C /50 % RH) can be calculated using $\ln\hat{B}_{50}$ and $\ln\hat{B}_5$ (see A.1.3).

$$\ln\hat{B}_{50} = \hat{\beta}_0 + \hat{\beta}_1 x_{10} + \hat{\beta}_2 x_{20}$$

$$= - 35{,}381\,1 + 15\,789{,}57 \times 0{,}003\,354 - 0{,}029\,74 \times 50$$

$$= 16{,}090\,1.$$

B_{50} Life = exp (16,090 1) = 9 724 120 hours (1 110 years)~~.~~,

$$\ln\hat{B}_5 = \hat{\beta}_0 + \hat{\beta}_1 x_{10} + \hat{\beta}_2 x_{20} - 1{,}64\hat{\sigma} = \ln\hat{B}_{50} - 1{,}64\hat{\sigma}_{lsm}$$

$$= 16{,}090\,1 - 1{,}64 \times 0{,}132\,35$$

$$= 15{,}873\,0$$

B_5 Life = exp (15,873 0) = 7 826 297 hours (893 years).

The 95% lower confidence bound of B_5 Life is therefore

$$(B_5\ \text{Life})_L = \exp((\ln\hat{B}_5)_L) = \exp(\ln\hat{B}_5 + z_{5/100}\sqrt{\text{var}(\ln\hat{B}_5)}\ ) \cong \exp(\ln\hat{B}_5 - 1{,}64\sqrt{\text{var}(\ln\hat{B}_5)}\ )$$

$$= \exp\ (15{,}873\,0 - 1{,}64 \times \sqrt{0{,}021129}\,) = \exp\ (15{,}634\,6)$$

= 6 166 241 hours (704 years) (see E.4).

B.2 Data analysis and lifetime estimation using conventional acceleration-factor method (Step 4-7)

Step 4

Table B.5 shows log-mean time-to-failure for each stress group A, B, C, D, and E (see Table B.2).

Table B.5 — Log-mean failure time for each stress condition

Group	Log-mean	*Temp*(°C)	1/*T*	% *RH*
A	6,269 2	85	0,002 792	80
B	6,594 3	85	0,002 792	70
C	6,932 4	85	0,002 792	60
D	7.719 9	75	0,002 872	80
E	8,886 4	65	0,002 957	80

To determine the coefficients A, $\Delta H\ /\ k$ *and* B of the reduced Eyring equation, regression analysis is done using five log-mean values obtained at the temperature values and relative humidity values in Table B.5

$$log\text{-}mean_i = \ln(A) + (\frac{\Delta H}{k}) \times (\frac{1}{T_i}) + B \times RH_i + \varepsilon_i$$

where $i = 1 \sim 5$.

The estimated values are determined as follows.

$$\ln(\hat{A}) = \hat{\beta}_0 = -35{,}6889$$
$$\Delta\hat{H} / k = \hat{\beta}_1 = 15\,904{,}21$$
$$\hat{B} = \hat{\beta}_2 = -0{,}029968$$

Step 5

The acceleration factors are calculated from the difference between the estimated log-mean at each stress condition and the estimated log-mean at the Controlled storage-condition (25 °C / 50 % RH). They are listed in Table B.6.

Table B.6 — Calculated lifetime and acceleration factors for each stress condition

Stress condition	Calculated lifetime			Acceleration factor
	1/*T*	Ln (Lifetime)	Lifetime (hours)	
85 °C / 80 % RH	0,002 792	6,320 2	556	18 685
85 °C / 70 % RH	0,002 792	6,619 9	750	13 846
85 °C / 60 % RH	0,002 792	6,919 6	1 012	10 261
75 °C / 80 % RH	0,002 872	7,595 7	1 990	5 218
65 °C / 80 % RH	0,002 957	8,946 7	7 682	1 352
25 °C / 50 % RH	0,003 354	16,155 7	10 383 119	

Step 6

Using the acceleration factors in Table B.6, calculate normalized time-to-failure at 25 °C / 50 % RH for each specimen group A, B, C, D and E. Table B.7 shows data for a composite lognormal plot before sorting. Table B.8 shows data for a composite lognormal plot sorted in ascending order. Figure B.2 shows a lognormal plot using the composite data of Table B.8. The ordinate scale is the probability of failure. From the fitting line for those data, the log-mean ($\hat{\mu}_{acf} = 16{,}15$) and standard deviation ($\hat{\sigma}_{acf} = 0{,}132\,4$) can be obtained. These values are almost the same as the values that were calculated in Table B.7.

NOTE $(\hat{\sigma}_{acf})^2$ is the the estimated variance of population.

Table B.7 — Data before sorting for composite lognormal plot

Time to Failure	Group	Normalized to 25 °C / 50 % RH	Ln
429	A	8 015 865	15,896 933 3
451	A	8 426 935	15,946 943 7
476	A	8 894 060	16,000 894 2
484	A	9 043 540	16,017 561 2
493	A	9 211 705	16,035 985 5
495	A	9 249 075	16,040 034 1
501	A	9 361 185	16,052 082 4
512	A	9 566 720	16,073 801 0
521	A	9 734 885	16,091 226 4
526	A	9 828 310	16,100 777 6
534	A	9 977 790	16,115 872 2
540	A	10 089 900	16,127 045 5
542	A	10 127 270	16,130 742 3
548	A	10 239 380	16,141 751 6
557	A	10 407 545	16,158 041 6
576	A	10 762 560	16,191 584 0
579	A	10 818 615	16,196 778 8
586	A	10 949 410	16,208 796 1
618	A	11 547 330	16,261 964 8
645	A	12 051 825	16,304 726 7
613	B	8 487 598	15,954 116 6
640	B	8 861 440	15,997 219 8
649	B	8 986 054	16,011 184 4
675	B	9 346 050	16,050 464 4
679	B	9 401 434	16,056 372 8
696	B	9 636 816	16,081 101 3
703	B	9 733 738	16,091 108 6
709	B	9 816 814	16,099 607 2
719	B	9 955 274	16,113 613 0
732	B	10 135 272	16,131 532 2
739	B	10 232 194	16,141 049 6
743	B	10 287 578	16,146 447 7
747	B	10 342 962	16,151 816 8
751	B	10 398 346	16,157 157 3
766	B	10 606 036	16,176 933 8
778	B	10 772 188	16,192 478 2
785	B	10 869 110	16,201 435 4
804	B	11 132 184	16,225 350 9
856	B	11 852 176	16,288 022 0
896	B	12 406 016	16,333 692 1
864	C	8 865 504	15,997 678 3
913	C	9 368 293	16,052 841 5
915	C	9 388 815	16,055 029 6
945	C	9 696 645	16,087 290 5
951	C	9 758 211	16,093 619 6
993	C	10 189 173	16,136 836 2
994	C	10 199 434	16,137 842 8
998	C	10 240 478	16,141 858 9
1009	C	10 353 349	16,152 820 6
1014	C	10 404 654	16,157 763 8
1027	C	10 538 047	16,170 502 8
1030	C	10 568 830	16,173 419 7
1037	C	10 640 657	16,180 192 8
1049	C	10 763 789	16,191 698 2
1069	C	10 969 009	16,210 584 5
1080	C	11 081 880	16,220 821 9
1098	C	11 266 578	16,237 351 2
1125	C	11 543 625	16,261 643 9
1222	C	12 538 942	16,344 349 7
1249	C	12 815 989	16,366 204 1
1728	D	9 016 704	16,014 589 4
1882	D	9 820 276	16,099 959 8
1907	D	9 950 726	16,113 156 1
1989	D	10 378 602	16,155 256 7
2020	D	10 540 360	16,170 722 3
2076	D	10 832 568	16,198 067 7
2129	D	11 109 122	16,223 277 1
2151	D	11 223 918	16,233 557 6
2180	D	11 375 240	16,246 949 6
2227	D	11 620 486	16,268 280 1
2277	D	11 881 386	16,290 483 5
2318	D	12 095 324	16,308 329 5
2352	D	12 272 736	16,322 890 8
2404	D	12 544 072	16,344 758 8
2443	D	12 747 574	16,360 851 5
2512	D	13 107 616	16,388 704 0
2589	D	13 509 402	16,418 896 4
2590	D	13 514 620	16,419 282 6
2776	D	14 485 168	16,488 635 8
2891	D	15 085 238	16,529 227 2
5455	E	7 375 160	15,813 628 2
5730	E	7 746 960	15,862 811 1
5908	E	7 987 616	15,893 402 9
6114	E	8 266 128	15,927 676 8
6326	E	8 552 752	15,961 763 7
6431	E	8 694 712	15,978 225 6
6544	E	8 847 488	15,995 644 1
6632	E	8 966 464	16,009 002 0
6711	E	9 073 272	16,020 843 5
6779	E	9 165 208	16,030 925 1
6860	E	9 274 720	16,042 803 0
6935	E	9 376 120	16,053 676 6
7038	E	9 515 376	16,068 419 6
7108	E	9 610 016	16,078 316 4
7202	E	9 737 104	16,091 454 3
7285	E	9 849 320	16,102 913 0
7362	E	9 953 424	16,113 427 2
7454	E	10 077 808	16,125 846 3
7562	E	10 223 824	16,140 231 2
7569	E	10 233 288	16,141 156 5
7710	E	10 423 920	16,159 613 7
7827	E	10 582 104	16,174 674 8
7955	E	10 755 160	16,190 896 2
8067	E	10 906 584	16,204 877 2
8250	E	11 154 000	16,227 308 7
8405	E	11 363 560	16,245 922 3
8546	E	11 554 192	16,262 558 9
8700	E	11 762 400	16,280 418 6
8953	E	12 104 456	16,309 084 2
9452	E	12 779 104	16,363 321 9
		Mean	16,150 284 7
		Deviation	0,130 956 0

Table B.8 — Data sorted in ascending order for composite lognormal plot

Group	Normalized to 25 °C / 50 % RH	Order	Median rank
E	7 375 160	1	0,006 3
E	7 746 960	2	0,015 4
E	7 987 616	3	0,024 5
A	8 015 865	4	0,033 5
E	8 266 128	5	0,042 6
A	8 426 935	6	0,051 6
B	8 487 598	7	0,060 7
E	8 552 752	8	0,069 7
E	8 694 712	9	0,078 8
E	8 847 488	10	0,087 9
B	8 861 440	11	0,096 9
C	8 865 504	12	0,106 0
A	8 894 060	13	0,115 0
E	8 966 464	14	0,124 1
B	8 986 054	15	0,133 2
D	9 016 704	16	0,142 2
A	9 043 540	17	0,151 3
E	9 073 272	18	0,160 3
E	9 165 208	19	0,169 4
A	9 211 705	20	0,178 4
A	9 249 075	21	0,187 5
E	9 274 720	22	0,196 6
B	9 346 050	23	0,205 6
A	9 361 185	24	0,214 7
C	9 368 293	25	0,223 7
E	9 376 120	26	0,232 8
C	9 388 815	27	0,241 8
B	9 401 434	28	0,250 9
E	9 515 376	29	0,260 0
A	9 566 720	30	0,269 0
E	9 610 016	31	0,278 1
B	9 636 816	32	0,287 1
C	9 696 645	33	0,296 2
B	9 733 738	34	0,305 3
A	9 734 885	35	0,314 3
E	9 737 104	36	0,323 4
C	9 758 211	37	0,332 4
B	9 816 814	38	0,341 5
D	9 820 276	39	0,350 5
A	9 828 310	40	0,359 6
E	9 849 320	41	0,368 7
D	9 950 726	42	0,377 7
E	9 953 424	43	0,386 8
B	9 955 274	44	0,395 8
A	9 977 790	45	0,404 9
E	10 077 808	46	0,413 9
A	10 089 900	47	0,423 0
A	10 127 270	48	0,432 1
B	10 135 272	49	0,441 1
C	10 189 173	50	0,450 2
C	10 199 434	51	0,459 2
E	10 223 824	52	0,468 3
B	10 232 194	53	0,477 4
E	10 233 288	54	0,486 4
A	10 239 380	55	0,495 5
C	10 240 478	56	0,504 5
B	10 287 578	57	0,513 6
B	10 342 962	58	0,522 6
C	10 353 349	59	0,531 7
D	10 378 602	60	0,540 8
B	10 398 346	61	0,549 8
C	10 404 654	62	0,558 9
A	10 407 545	63	0,567 9
E	10 423 920	64	0,577 0
C	10 538 047	65	0,586 1
D	10 540 360	66	0,595 1
C	10 568 830	67	0,604 2
E	10 582 104	68	0,613 2
B	10 606 036	69	0,622 3
C	10 640 657	70	0,631 3
E	10 755 160	71	0,640 4
A	10 762 560	72	0,649 5
C	10 763 789	73	0,658 5
B	10 772 188	74	0,667 6
A	10 818 615	75	0,676 6
D	10 832 568	76	0,685 7
B	10 869 110	77	0,694 7
E	10 906 584	78	0,703 8
A	10 949 410	79	0,712 9
C	10 969 009	80	0,721 9
C	11 081 880	81	0,731 0
D	11 109 122	82	0,740 0
B	11 132 184	83	0,749 1
E	11 154 000	84	0,758 2
D	11 223 918	85	0,767 2
C	11 266 578	86	0,776 3
E	11 363 560	87	0,785 3
D	11 375 240	88	0,794 4
C	11 543 625	89	0,803 4
A	11 547 330	90	0,812 5
E	11 554 192	91	0,821 6
D	11 620 486	92	0,830 6
E	11 762 400	93	0,839 7
B	11 852 176	94	0,848 7
D	11 881 386	95	0,857 8
A	12 051 825	96	0,866 8
D	12 095 324	97	0,875 9
E	12 104 456	98	0,885 0
D	12 272 736	99	0,894 0
B	12 406 016	100	0,903 1
C	12 538 942	101	0,912 1
D	12 544 072	102	0,921 2
D	12 747 574	103	0,930 3
E	12 779 104	104	0,939 3
C	12 815 989	105	0,948 4
D	13 107 616	106	0,957 4
D	13 509 402	107	0,966 5
D	13 514 620	108	0,975 5
D	14 485 168	109	0,984 6
D	15 085 238	110	0,993 7

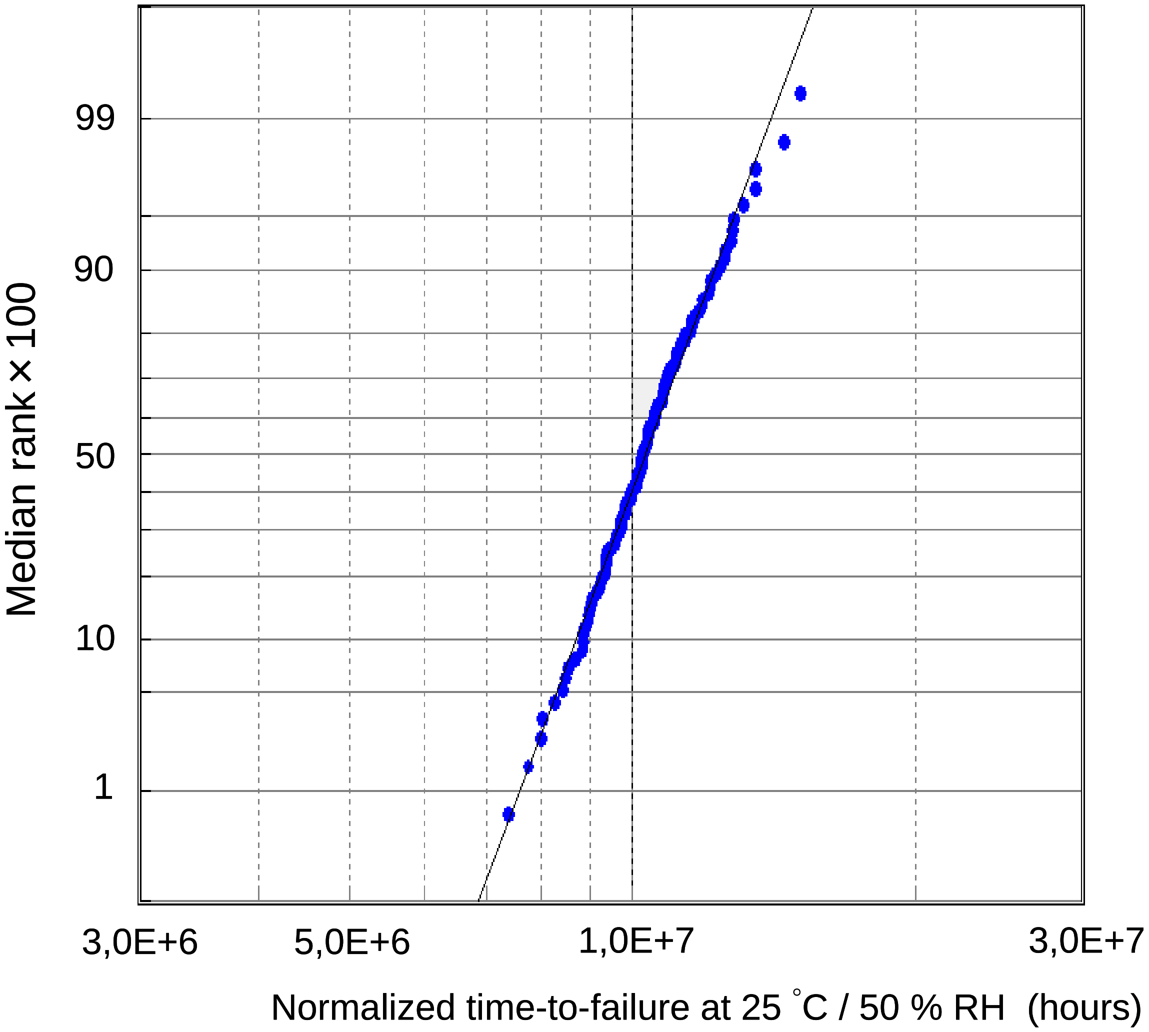


Figure B.2 — Plot of composite data on lognormal paper

Step 7

B_{50} Life, B_5 Life and B_{5V} Life at the Controlled storage-condition (25 °C/50 % RH) can be calculated as follows.

B_{50} Life = exp ($\hat{\mu}_{acf}$) = exp (16,15) = 10 324 187 hours (1 179 years)

B_5 Life = exp ($\hat{\mu}_{acf} - 1.64\hat{\sigma}_{acf}$) = exp (16,15 – 1,64 x 0,132 4) = exp(15,933)

=8 309 118 hours (949 years)

The 95% lower confidence bound of the normal distribution with variation $\hat{\sigma}^2_{acf}$ is $-1.64\hat{\sigma}_{acf}$.

Assuming that the population has a normal distribution, the population shifted by $-1{,}64\hat{\sigma}_{acf}$ with the mean value $\hat{\mu}_{acf} - 1{,}64\hat{\sigma}_{acf}$ and the standard deviation $\hat{\sigma}_{acf}$ is considered to be the 95% lower limit of the normal distribution of the population. On this normal distribution, the point estimates of the 5 percentile is defined as "the point estimates of the 5 percentile with variation." It is calculated as follows:

$$B_{5V}\text{ Life} = \exp(\ln\hat{B}_{5V}) = \exp(\hat{\mu}_{acf} - 1{,}64\hat{\sigma}_{acf} - 1{,}64\hat{\sigma}_{acf})$$

= exp (16,15 – 1,64 x 0,132 4 - 1,64 x 0,132 4) = 6 687 348 hours (763 years).

If the precise analysis or the precise interval estimation is required then the calculation based on maximum-likelihood method is recommended (see A.1.3 and E.3).

Annex C
(normative)

Disk-life estimation for Harsh storage-condition (Arrhenius method)

C.1 Stress conditions and data-analysis steps for Arrhenius method

Here, a test method is shown for the Harsh storage-condition at higher temperature and relative humidity than that of the Controlled storage-condition (25 °C and 50 % RH).

This test method follows the scope in this document, which is based on an environment of 30 °C and 80 % RH representing the most-severe condition in which users handle and store optical disks. This test method also uses a different stress-test design that makes the use of the Arrhenius method possible.

The same assumptions and data-analysis methods apply for the ambient storage-condition, stress design, and Arrhenius equation. The Controlled storage-condition of 25 °C and 50 % RH is replaced by an expected harsher user environment of 30 °C and 80 % RH.

Table C.1 and C.2 summarize the stress design for the Arrhenius method. In case a stress condition would be destructive for the disk to be tested see Annex D.

Table C.1 — Rigorous stress-condition for use with Arrhenius method

Test specimen group	Test stress condition (incubation)		Number of specimens	Maximum incubation sub-interval time	Minimum total incubation time	Intermediate relative humidity	Minimum equilibration duration time
	Temp (°C)	% *RH*		hours	hours	% *RH*	hours
A	85	80	20	300	1 500	30	5
B	80	80	20	400	2 000	31	7
C	75	80	20	600	3 000	32	8
D	65	80	30	800	4 000	35	10

Table C.2 — Basic stress-condition for use with Arrhenius method

Test specimen group	Test stress condition (incubation)		Number of specimens	Maximum incubation sub-interval time	Minimum total incubation time	Intermediate relative humidity	Minimum equilibration duration time
	Temp (°C)	% *RH*		hours	hours	% *RH*	hours
A	85	80	20	250	1 000	30	5
B	75	80	20	425	1 700	32	8
C	65	80	30	600	2 400	35	10

Regarding the data-analysis steps in Annex B**,** Step 4 is replaced as follows.

Regression coefficients and the standard error can be calculated using the least-squares method across all log time-to-failure data, which were obtained at the four or three stress conditions. This calculation can be performed by regression-analysis features of statistics software tools.

C.2 Data analysis

Step 1 and Step 2

For each stress condition, the specimens are ordered by increasing time-to-failure values. The median rank of the specimens is calculated using the estimate $(i-0{,}3)/(n+0{,}4)$. Table C.3 shows the result of ordered time-to-failure and median rank for the four stress groups A (85 °C), B (80 °C), C (75 °C) and D (65 °C) with relative humidity kept constant at 80 %.

Table C.3 — Ordered time-to-failure and median rank for example data (Rigorous testing)

Sample number	Sample group and stress conditions (80 % RH)							
	Group A (85 °C)		Group B (80 °C)		Group C (75 °C)		Group D (65 °C)	
	Time-to-failure (hours)	Median rank	Time-to-failure (hours)	Median rank	Time-to-failure (hours)	Median rank	Time-to-failure (hours)	Median rank
1	429	0,034	1 015	0,034	1 728	0,034	5 455	0,023
2	451	0,083	1 040	0,083	1 882	0,083	5 730	0,056
3	476	0,132	1 080	0,132	1 907	0,132	5 908	0,089
4	484	0,181	1 203	0,181	1 989	0,181	6 114	0,122
5	493	0,230	1 151	0,23	2 020	0,230	6 326	0,155
6	495	0,279	1 165	0,279	2 076	0,279	6 431	0,188
7	501	0,328	1 193	0,328	2 129	0,328	6 544	0,220
8	512	0,377	1 215	0,377	2 151	0,377	6 632	0,253
9	521	0,426	1 230	0,426	2 180	0,426	6 711	0,286
10	526	0,475	1 239	0,475	2 227	0,475	6 779	0,319
11	534	0,525	1 260	0,525	2 277	0,525	6 860	0,352
12	540	0,574	1 295	0,574	2 318	0,574	6 935	0,385
13	542	0,623	1 310	0,623	2 352	0,623	7 038	0,418
14	548	0,672	1 425	0,672	2 404	0,672	7 108	0,451
15	557	0,721	1 360	0,721	2 443	0,721	7 202	0,484
16	576	0,770	1 388	0,770	2 512	0,770	7 285	0,516
17	579	0,819	1 420	0,819	2 589	0,819	7 362	0,549
18	586	0,868	1 472	0,868	2 590	0,868	7 454	0,582
19	618	0,917	1 540	0,917	2 776	0,917	7 562	0,615
20	645	0,966	1 625	0,966	2 891	0,966	7 569	0,648
21							7 710	0,681
22							7 827	0,714
23							7 955	0,747
24							8 067	0,780
25							8 250	0,813
26							8 405	0,845
27							8 546	0,878
28							8 700	0,911
29							8 953	0,944
30							9 452	0,977

Step 3

Figure C.1 shows the lognormal plot of groups A, B, C and D from Table C.3. The ordinate scale is the probability of failure. Best-fit straight lines are drawn through the data plotted for each group. If the lines are judged to be sufficiently parallel, the assumption of equivalent log standard deviations among the individual data sets is verified.

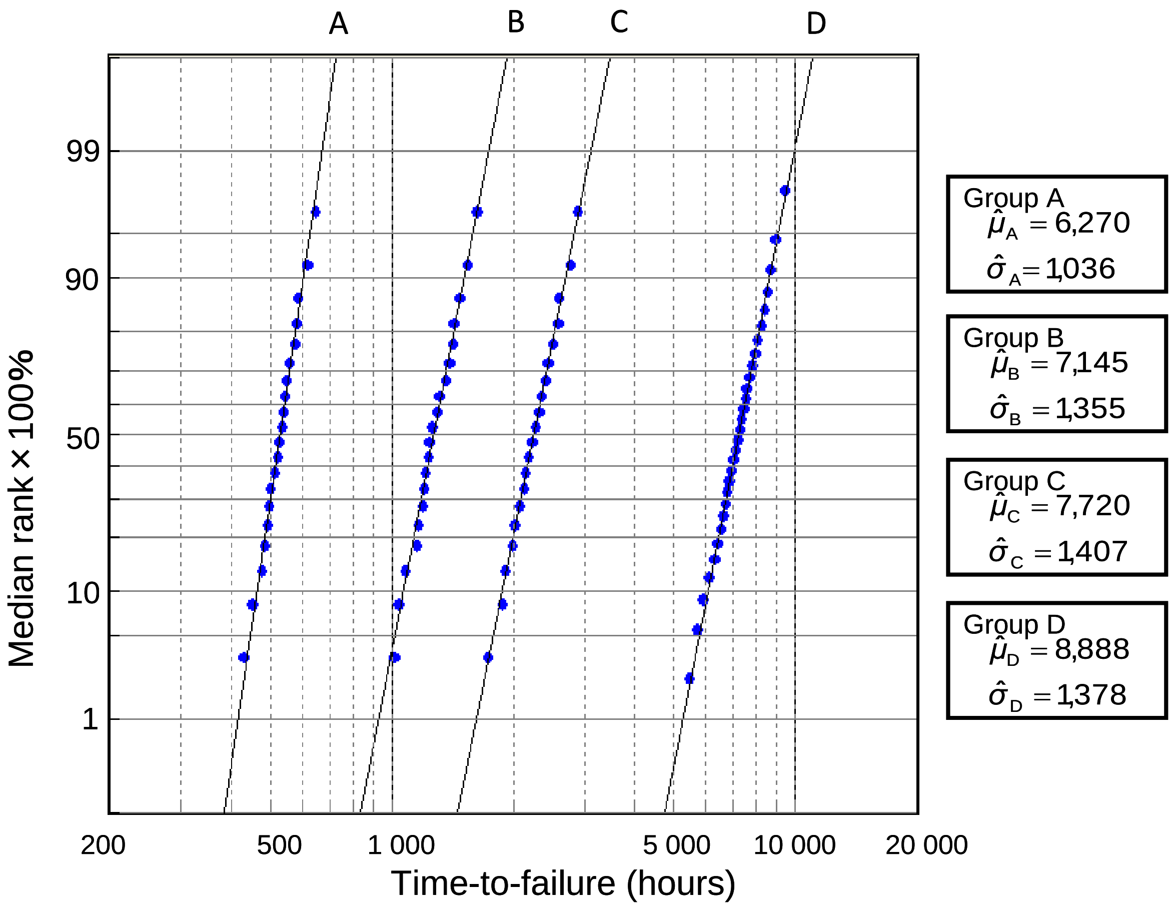


Figure C.1 — Best-fit lines of groups A, B, C and D on lognormal paper
(Verify that the fitting lines for all stress conditions are reasonably parallel to one another)

Step 4

Table C.4 shows a total of 90 sample data values belonging to specimen groups A, B, C and D for regression analysis. The regression coefficients and error variance are calculated by applying the least-squares method to 90 failure data sets that were obtained under the four stress conditions.

Table C.5 shows the result of regression analysis using a statistics software tool. The estimated log standard deviation $\hat{\sigma}$ and estimated regression coefficients $\hat{\beta}_0$ and $\hat{\beta}_1$ are obtained.

Table C.4 — 90 sample data values for regression analysis

Number	ln t	x_1	
1	6,061 05	0,002 792	Group A
2	6,111 47	0,002 792	
3	6,165 42	0,002 792	
4	6,182 18	0,002 792	
5	6,200 51	0,002 792	
6	6,204 56	0,002 792	
7	6,216 61	0,002 792	
8	6,238 32	0,002 792	
9	6,255 75	0,002 792	
10	6,265 30	0,002 792	
11	6,280 40	0,002 792	
12	6,291 31	0,002 792	
13	6,295 27	0,002 792	
14	6,306 28	0,002 792	
15	6,322 57	0,002 792	
16	6,356 11	0,002 792	
17	6,361 30	0,002 792	
18	6,373 32	0,002 792	
19	6,426 49	0,002 792	
20	6,469 25	0,002 792	
1	6,922 64	0,002 832	Group B
2	6,946 98	0,002 832	
3	6,984 72	0,002 832	
4	7,092 57	0,002 832	
5	7,048 39	0,002 832	
6	7,060 48	0,002 832	
7	7,084 23	0,002 832	
8	7,102 50	0,002 832	
9	7,114 77	0,002 832	
10	7,122 06	0,002 832	
11	7,138 87	0,002 832	
12	7,166 27	0,002 832	
13	7,177 78	0,002 832	
14	7,261 93	0,002 832	
15	7,215 24	0,002 832	
16	7,235 62	0,002 832	
17	7,258 41	0,002 832	
18	7,294 38	0,002 832	
19	7,339 54	0,002 832	
20	7,393 26	0,002 832	

Number	ln t	x_1	
1	7,454 92	0,002 872	Group C
2	7,540 28	0,002 872	
3	7,553 36	0,002 872	
4	7,595 32	0,002 872	
5	7,610 63	0,002 872	
6	7,638 06	0,002 872	
7	7,663 17	0,002 872	
8	7,673 91	0,002 872	
9	7,687 12	0,002 872	
10	7,708 53	0,002 872	
11	7,730 83	0,002 872	
12	7,748 37	0,002 872	
13	7,763 20	0,002 872	
14	7,785 04	0,002 872	
15	7,800 85	0,002 872	
16	7,828 69	0,002 872	
17	7,859 16	0,002 872	
18	7,859 35	0,002 872	
19	7,928 61	0,002 872	
20	7,969 48	0,002 872	
1	8,604 29	0,002 957	Group D
2	8,653 47	0,002 957	
3	8,684 06	0,002 957	
4	8,718 34	0,002 957	
5	8,752 50	0,002 957	
6	8,768 89	0,002 957	
7	8,786 36	0,002 957	
8	8,799 66	0,002 957	
9	8,811 50	0,002 957	
10	8,821 63	0,002 957	
11	8,833 46	0,002 957	
12	8,844 34	0,002 957	
13	8,859 08	0,002 957	
14	8,868 98	0,002 957	
15	8,882 17	0,002 957	
16	8,893 57	0,002 957	
17	8,904 09	0,002 957	
18	8,916 51	0,002 957	
19	8,930 89	0,002 957	
20	8,931 86	0,002 957	
21	8,950 27	0,002 957	
22	8,965 33	0,002 957	
23	8,981 56	0,002 957	
24	8,995 55	0,002 957	
25	9,017 97	0,002 957	
26	9,036 58	0,002 957	
27	9,053 22	0,002 957	
28	9,071 08	0,002 957	
29	9,099 74	0,002 957	
30	9,153 98	0,002 957	

Table C.5 — Results of regression analysis

Estimated regression coefficients		Estimated log standard deviation
$\hat{\beta}_0$	$\hat{\beta}_1$	$\hat{\sigma}_{lsm}$
-36,321 5	15 304,74	0,161 52

Step 5

Using the estimated regression coefficients $\hat{\beta}_0$ and $\hat{\beta}_1$ and the estimated log standard deviation $\hat{\sigma}$ in Table C.5, $\ln\hat{B}_5$ and $\ln\hat{B}_{50}$ can be calculated (see A.1.2).

The B_5 Life, B_{50} Life and the 95 % lower confidence bound of B_5 Life at the Harsh storage-condition (30 °C and 80 % RH) are then obtained using the calculated values of $\ln\hat{B}_5$ and $\ln\hat{B}_{50}$ as follows (see A.1.3)~~.~~,

$$\ln\hat{B}_{50} = \hat{\beta}_0 + \hat{\beta}_1 x_{10}$$

= - 36,321 5 + 15 304,74 x 0,003 298 7

= 14,164 25,

B_{50} Life = exp (14,164 25) = 1 417 280 hours (162 years),

$$\ln\hat{B}_5 = \hat{\beta}_0 + \hat{\beta}_1 x_{10} - 1{,}64\hat{\sigma}_{lsm}$$

= 14,164 25 - 1,64 x 0,161 52

= 13,899 36,

B_5 Life = exp (13,899 36) = 1 087 462 hours (124 years).

The 95 % lower confidence bound of B_5 Life becomes

$$(B_5\ \text{Life})_L = \exp((\ln\hat{B}_5)_L) = \exp(\ln\hat{B}_5 + z_{5/100}\sqrt{\mathrm{var}(\ln\hat{B}_5)}\ ) \cong \exp(\ln\hat{B}_5 - 1{,}64\sqrt{\mathrm{var}(\ln\hat{B}_5)}\ )$$

= exp (13,899 36 - 1,64 x $\sqrt{0{,}016\,598}$) = exp (13,688 1)

= 880 372 hours (100 years) (see E.3).

Annex D
(normative)

Alternative non destructive stress condition

In case a stress condition is destructive for the disk to be tested, an alternative stress condition shall be applied.

The stress conditions used in this Ecma Standard are 85 °C / 80 % RH, 85 °C / 70 % RH, 85 °C / 60 % RH, 80 °C / 80 % RH, 75 °C / 80 % RH, 70 °C / 75 % RH and 65 °C / 80 % RH.

Among these stress conditions, the most severe temperature is 85 °C. In case the stress condition with temperature 85 °C is considered to be destructive for a disk to be tested regardless of the relative humidity, it should be replaced with 80 °C in all the stress conditions with 85 °C. Recommended alternative stress-conditions for the Eyring and Arrhenius methods are shown in Table D.1, D.2, D.3 and D.4.

Table D.1 — Alternative Rigorous stress-condition for use with Eyring method

Test specimen group	Test stress condition (incubation)		Number of specimens	Maximum incubation sub-interval time	Minimum total incubation time	Intermediate relative humidity	Minimum equilibration duration time
	Temp (°C)	% *RH*		hours	hours	% *RH*	hours
A	80	80	20	300	1 500	31	7
B	80	70	20	400	2 000	31	6
C	80	60	20	600	3 000	31	5
D	75	80	20	600	3 000	32	8
E	65	80	30	800	4 000	35	9

Table D.2 — Alternative Basic stress-condition for use with Eyring method

Test specimen group	Test stress condition (incubation)		Number of specimens	Maximum incubation sub-interval time	Minimum total incubation time	Intermediate relative humidity	Minimum equilibration duration time
	Temp (°C)	% *RH*		hours	hours	% *RH*	hours
A	80	80	20	250	1 000	31	7
B	80	70	20	250	1 000	31	6
C	65	80	20	500	2 000	35	9
D	70	75	30	625	2 500	33	11

Table D.3 — Alternative Rigorous stress-condition for use with Arrhenius method

Test specimen group	Test stress condition (incubation)		Number of specimens	Maximum incubation sub-interval time	Minimum total incubation time	Intermediate relative humidity	Minimum equilibration duration time
	Temp (°C)	% *RH*		hours	hours	% *RH*	hours
A	80	80	20	300	1 500	31	7
B	75	80	20	400	2 000	32	8
C	70	80	20	600	3 000	33	9
D	65	80	30	800	4 000	35	10

Table D.4 — Alternative Basic stress-condition for use with Arrhenius method

Test specimen group	Test stress condition (incubation)		Number of specimens	Maximum incubation sub-interval time	Minimum total incubation time	Intermediate relative humidity	Minimum equilibration duration time
	Temp (°C)	% *RH*		hours	hours	% *RH*	hours
A	80	80	20	250	1 000	31	7
B	75	80	20	425	1 700	32	8
C	65	80	30	600	2 400	35	10

Annex E
(informative)

Interval Estimation for B_5 Life using Maximum Likelihood

E.1 Lower confidence bound

Lifetime-estimation analysis (point estimation and simple interval estimation) for B_5 Life and B_{50} Life are described in Annex A. In this annex, a more precise analysis method for interval estimation is introduced. One may consider only the lower bound of the confidence interval to estimate lifetime.

NOTE The equations shown in this annex are for the case of complete data.

E.2 Maximum-likelihood method

To ensure that log lifetime (y = Int) follows the normal distribution described in A.1.2, the likelihood function of parameters β and σ can be defined by the following equation.

$$L(\beta,\sigma) = \prod_{j=1}^{J}\prod_{i=1}^{n_j} f(y_{ij} | \mathrm{x_i}) \ = \prod_{j=1}^{J}\prod_{i=1}^{n_j} \frac{1}{\sqrt{2\pi}\,\sigma} \exp\left\{-\frac{1}{2}\left(\frac{y_{ij} - \boldsymbol{x}'\cdot\,\boldsymbol{\beta}}{\sigma}\right)^2\right\}$$

where J denotes the number of specimen groups, n_j denotes the number of specimens in the specimen group j and σ is the standard deviation of the population.

The log likelihood function is then

$$\mathrm{In}L(\beta,\sigma) = -\mathrm{In}\sqrt{2\pi}\sigma\sum_{j=1}^{J} n_j - \frac{1}{2\sigma^2}\sum_{j=1}^{J}\sum_{i=1}^{n_j}(y_{ij} - (\beta_0 + \beta_1 x_{1j} + \beta_2 x_{2j}))^2$$

The maximum-likelihood estimators β and σ can be obtained by maximizing the second member of the equation.

The estimates $\hat{\beta}_0$, $\hat{\beta}_1$ and $\hat{\beta}_2$ are coefficients in the multiple regression equation, and the estimate $\hat{\sigma}$ is the standard deviation.

The point estimation of $\mathrm{In}\hat{B}_p$ can be obtained using the estimates $\hat{\beta}_0$, $\hat{\beta}_1$, $\hat{\beta}_2$ and $\hat{\sigma}$ *as*

$$\mathrm{In}\hat{B}_p = \hat{\beta}_0 + \hat{\beta}_1 x_1 + \hat{\beta}_2 x_2 + z_{p/100}\,\hat{\sigma}.$$

Then the point estimates of 5 percentile and 50 percentile of the lifetime distribution are

$$\mathrm{In}\hat{B}_5 = \hat{\beta}_0 + \hat{\beta}_1 x_{10} + \hat{\beta}_2 x_{20} - 1{,}64\hat{\sigma} \text{ and}$$

$$\mathrm{In}\hat{B}_{50} = \hat{\beta}_0 + \hat{\beta}_1 x_{10} + \hat{\beta}_2 x_{20}$$

where x_{10}, x_{20} denotes the Controlled storage condition (25 °C and 50 % RH).

For interval estimation of the population for $\ln\hat{B}_p$ of an optical disk, one may consider only the lower bound. Therefore, the $(100-\alpha)$ % lower confidence bound of the log lifetime $\ln\hat{B}_p$ is given as

$$\left(\ln\hat{B}_p\right)_L = \ln\hat{B}_p + z_{\alpha/100}\sqrt{\mathrm{var}(\ln\hat{B}_p)}\ ,$$

The equation $\ln\hat{B}_\mathrm{p} = \hat{\beta}_0 + \hat{\beta}_1 x_{10} + \hat{\beta}_2 x_{20} + z_{\mathrm{p}/100}\hat{\sigma}$ can be modified as follows.

$$\ln\hat{B}_p = x'_p \times \hat{\theta}$$

where $x'_p \equiv \left[1, x_{10}, x_{20}, z_{p/100}\right]$

$$\hat{\theta} \equiv \left[\hat{\beta}_0, \hat{\beta}_1, \hat{\beta}_2, \hat{\sigma}\ \right]'.$$

Then $\mathrm{var}\left(\ln\hat{B}_p\right)$ can be given as

$$\mathrm{var}\left(\ln\hat{B}_p\right) = x'_p \times \mathrm{var}\left(\hat{\theta}\right) \times x_p$$

where $\mathrm{var}\left(\hat{\theta}\right)$ is given by the inverse matrix of the Fisher information matrix as

$$\mathrm{var}\left(\hat{\theta}\right) = \begin{bmatrix} \mathrm{var}\left(\hat{\beta}_0\right) & \mathrm{cov}\left(\hat{\beta}_0, \hat{\beta}_1\right) & \mathrm{cov}\left(\hat{\beta}_0, \hat{\beta}_2\right) & \mathrm{cov}\left(\hat{\beta}_0, \hat{\sigma}\right) \\ & \mathrm{var}\left(\hat{\beta}_1\right) & \mathrm{cov}\left(\hat{\beta}_1, \hat{\beta}_2\right) & \mathrm{cov}\left(\hat{\beta}_1, \hat{\sigma}\right) \\ & & \mathrm{var}\left(\hat{\beta}_2\right) & \mathrm{cov}\left(\hat{\beta}_2, \hat{\sigma}\right) \\ & & & \mathrm{var}\left(\hat{\sigma}\right) \end{bmatrix}$$

and $\mathrm{cov}(\hat{\beta}_a, \hat{\beta}_b)$ denotes the covariance between $\hat{\beta}_a$ and $\hat{\beta}_b$.

As the variances of $\ln\hat{B}_5$ and $\ln\hat{B}_{50}$ are represented by $\mathrm{var}(\ln\hat{B}_5)$ and $\mathrm{var}(\ln\hat{B}_{50})$ respectively, the 95 % lower confidence bounds of $\ln\hat{B}_5$ and $\ln\hat{B}_{50}$ are given as follows,

$$\left(\ln\hat{B}_5\right)_L = \ln\hat{B}_5 - 1{,}64\sqrt{\mathrm{var}(\ln\hat{B}_5)}$$

$$\left(\ln\hat{B}_{50}\right)_L = \ln\hat{B}_{50} - 1{,}64\sqrt{\mathrm{var}(\ln\hat{B}_{50})}$$

where $\mathrm{var}(\ln\hat{B}_5)$ and $\mathrm{var}(\ln\hat{B}_{50})$ can be calculated by the following equations.

$$\mathrm{var}(\ln\hat{B}_5) = \left[1\ \ x_{10}\ \ x_{20}\ \ -1{,}64\right] \begin{bmatrix} \mathrm{var}(\hat{\beta}_0) & \mathrm{cov}(\hat{\beta}_0, \hat{\beta}_1) & \mathrm{cov}(\hat{\beta}_0, \hat{\beta}_2) & \mathrm{cov}(\hat{\beta}_0, \hat{\sigma}) \\ & \mathrm{var}(\hat{\beta}_1) & \mathrm{cov}(\hat{\beta}_1, \hat{\beta}_2) & \mathrm{cov}(\hat{\beta}_1, \hat{\sigma}) \\ & & \mathrm{var}(\hat{\beta}_2) & \mathrm{cov}(\hat{\beta}_2, \hat{\sigma}) \\ & & & \mathrm{var}(\hat{\sigma}) \end{bmatrix} \begin{bmatrix} 1 \\ x_{10} \\ x_{20} \\ -1{,}64 \end{bmatrix}$$

$$\mathrm{var}(\ln\hat{B}_{50}) = \begin{bmatrix} 1 & x_{10} & x_{20} \end{bmatrix} \begin{bmatrix} \mathrm{var}(\beta_0) & \mathrm{cov}(\hat{\beta}_0,\hat{\beta}_1) & \mathrm{cov}(\hat{\beta}_0,\hat{\beta}_2) \\ & \mathrm{var}(\hat{\beta}_1) & \mathrm{cov}(\hat{\beta}_1,\hat{\beta}_2) \\ & & \mathrm{var}(\hat{\beta}_2) \end{bmatrix} \begin{bmatrix} 1 \\ x_{10} \\ x_{20} \end{bmatrix}$$

Then the 95 % lower confidence bound of B_5 Life is obtained as follows.

$$(B_5\ \mathrm{Life})_{\mathrm{L}} = \exp((\ln\hat{B}_5)_{\mathrm{L}}) = \exp(\ln\hat{B}_5 - 1{,}64\sqrt{\mathrm{var}(\ln\hat{B}_5)})$$

E.3 Calculation method of Fisher information matrix and variance

By using the function ln L = ln $L(\beta,\sigma)$, the Fisher information matrix I in E.2 can be expressed as follows.

$$I = -E\begin{bmatrix} \dfrac{\partial^2 \ln L}{\partial\beta_0^2} & \dfrac{\partial^2 \ln L}{\partial\beta_0\partial\beta_1} & \dfrac{\partial^2 \ln L}{\partial\beta_0\partial\beta_2} & \dfrac{\partial^2 \ln L}{\partial\beta_0\partial\sigma} \\ \dfrac{\partial^2 \ln L}{\partial\beta_0\partial\beta_1} & \dfrac{\partial^2 \ln L}{\partial^2\beta_1^2} & \dfrac{\partial^2 \ln L}{\partial\beta_1\partial\beta_2} & \dfrac{\partial^2 \ln L}{\partial\beta_1\partial\sigma} \\ \dfrac{\partial^2 \ln L}{\partial\beta_0\partial\beta_2} & \dfrac{\partial^2 \ln L}{\partial\beta_1\partial\beta_2} & \dfrac{\partial^2 \ln L}{\partial\beta_2^2} & \dfrac{\partial^2 \ln L}{\partial\beta_2\partial\sigma} \\ \dfrac{\partial^2 \ln L}{\partial\beta_0\partial\sigma} & \dfrac{\partial^2 \ln L}{\partial\beta_1\partial\sigma} & \dfrac{\partial^2 \ln L}{\partial\beta_2\partial\sigma} & \dfrac{\partial^2 \ln L}{\partial\sigma^2} \end{bmatrix}$$

where, $E(x_i)$ is the expectation of x_i.

Components in the matrix I are as follows;

$$-E\left[\frac{\partial^2 \ln L}{\partial\beta_0^2}\right] = \frac{n}{\sigma^2} \quad -E\left[\frac{\partial^2 \ln L}{\partial\beta_0\partial\beta_1}\right] = \frac{1}{\sigma^2}\sum_{j=1}^{J} n_j x_{1j} \quad -E\left[\frac{\partial^2 \ln L}{\partial\beta_0\partial\beta_2}\right] = \frac{1}{\sigma^2}\sum_{j=1}^{J} n_j x_{2j} \quad -E\left[\frac{\partial^2 \ln L}{\partial\beta_0\partial\sigma}\right] = 0$$

$$-E\left[\frac{\partial^2 \ln L}{\partial\beta_1^2}\right] = \frac{1}{\sigma^2}\sum_{j=1}^{J} n_j x_{1j}^2 \quad -E\left[\frac{\partial^2 \ln L}{\partial\beta_1\partial\beta_2}\right] = \frac{1}{\sigma^2}\sum_{j=1}^{J} n_j x_{1j} x_{2j} \quad -E\left[\frac{\partial^2 \ln L}{\partial\beta_1\partial\sigma}\right] = 0$$

$$-E\left[\frac{\partial^2 \ln L}{\partial\beta_2^2}\right] = \frac{1}{\sigma^2}\sum_{j=1}^{J} n_j x_{2j}^2 \quad -E\left[\frac{\partial^2 \ln L}{\partial\beta_2\partial\sigma}\right] = 0$$

$$-E\left[\frac{\partial^2 \ln L}{\partial\sigma^2}\right] = \frac{2n}{\sigma^2}$$

where, $n = \sum_{j=1}^{J} n_j$ and it denotes the total number of specimens.

Then *I* becomes,

$$I = \begin{bmatrix} \dfrac{n}{\sigma^2} & \dfrac{1}{\sigma^2}\sum_{j=1}^{J} n_j x_{1j} & \dfrac{1}{\sigma^2}\sum_{j=1}^{J} n_j x_{2j} & 0 \\ \dfrac{1}{\sigma^2}\sum_{j=1}^{J} n_j x_{1j} & \dfrac{1}{\sigma^2}\sum_{j=1}^{J} n_j x_{1j}^2 & \dfrac{1}{\sigma^2}\sum_{j=1}^{J} n_j x_{1j} x_{2j} & 0 \\ \dfrac{1}{\sigma^2}\sum_{j=1}^{J} n_j x_{2j} & \dfrac{1}{\sigma^2}\sum_{j=1}^{J} n_j x_{1j} x_{2j} & \dfrac{1}{\sigma^2}\sum_{j=1}^{J} n_j x_{2j}^2 & 0 \\ 0 & 0 & 0 & \dfrac{2n}{\sigma^2} \end{bmatrix}$$

By using the inverse matrix I^{-1}, $\mathrm{var}(\mathrm{ln}\hat{B}_{50})$ and $\mathrm{var}(\mathrm{ln}\hat{B}_{5})$ can be expressed as follows.

$$\mathrm{var}(\mathrm{ln}\hat{B}_{50}) = \begin{bmatrix} 1 & x_{10} & x_{20} \end{bmatrix} \begin{bmatrix} \dfrac{n}{\sigma^2} & \dfrac{1}{\sigma^2}\sum_{j=1}^{J} n_j x_{1j} & \dfrac{1}{\sigma^2}\sum_{j=1}^{J} n_j x_{2j} \\ \dfrac{1}{\sigma^2}\sum_{j=1}^{J} n_j x_{1j} & \dfrac{1}{\sigma^2}\sum_{j=1}^{J} n_j x_{1j}^2 & \dfrac{1}{\sigma^2}\sum_{j=1}^{J} n_j x_{1j} x_{2j} \\ \dfrac{1}{\sigma^2}\sum_{j=1}^{J} n_j x_{2j} & \dfrac{1}{\sigma^2}\sum_{j=1}^{J} n_j x_{1j} x_{2j} & \dfrac{1}{\sigma^2}\sum_{j=1}^{J} n_j x_{2j}^2 \end{bmatrix}^{-1} \begin{bmatrix} 1 \\ x_{10} \\ x_{20} \end{bmatrix}$$

$$\mathrm{var}(\mathrm{ln}\hat{B}_{5}) = \begin{bmatrix} 1 & x_{10} & x_{20} & -1{,}64 \end{bmatrix} \begin{bmatrix} \dfrac{n}{\sigma^2} & \dfrac{1}{\sigma^2}\sum_{j=1}^{J} n_j x_{1j} & \dfrac{1}{\sigma^2}\sum_{j=1}^{J} n_j x_{2j} & 0 \\ \dfrac{1}{\sigma^2}\sum_{j=1}^{J} n_j x_{1j} & \dfrac{1}{\sigma^2}\sum_{j=1}^{J} n_j x_{1j}^2 & \dfrac{1}{\sigma^2}\sum_{j=1}^{J} n_j x_{1j} x_{2j} & 0 \\ \dfrac{1}{\sigma^2}\sum_{j=1}^{J} n_j x_{2j} & \dfrac{1}{\sigma^2}\sum_{j=1}^{J} n_j x_{1j} x_{2j} & \dfrac{1}{\sigma^2}\sum_{j=1}^{J} n_j x_{2j}^2 & 0 \\ 0 & 0 & 0 & \dfrac{2n}{\sigma^2} \end{bmatrix}^{-1} \begin{bmatrix} 1 \\ x_{10} \\ x_{20} \\ -1{,}64 \end{bmatrix}$$

For the Arrhenius method temperature is the only variable and humidity is fixed, then the equation for estimation of the variances for the Arrhenius method are as follows:~~.~~

$$\mathrm{var}(\mathrm{ln}\hat{B}_{50}) = \begin{bmatrix} 1 & x_{10} \end{bmatrix} \begin{bmatrix} \dfrac{n}{\sigma^2} & \dfrac{1}{\sigma^2}\sum_{j=1}^{J} n_j x_{1j} \\ \dfrac{1}{\sigma^2}\sum_{j=1}^{J} n_j x_{1j} & \dfrac{1}{\sigma^2}\sum_{j=1}^{J} n_j x_{1j}^2 \end{bmatrix}^{-1} \begin{bmatrix} 1 \\ x_{10} \end{bmatrix}$$

$$\mathrm{var}(\mathrm{ln}\hat{B}_{5}) = \begin{bmatrix} 1 & x_{10} & -1{,}64 \end{bmatrix} \begin{bmatrix} \dfrac{n}{\sigma^2} & \dfrac{1}{\sigma^2}\sum_{j=1}^{J} n_j x_{1j} & 0 \\ \dfrac{1}{\sigma^2}\sum_{j=1}^{J} n_j x_{1j} & \dfrac{1}{\sigma^2}\sum_{j=1}^{J} n_j x_{1j}^2 & 0 \\ 0 & 0 & \dfrac{2n}{\sigma^2} \end{bmatrix}^{-1} \begin{bmatrix} 1 \\ x_{10} \\ -1{,}64 \end{bmatrix}$$

E.4 Example of variance calculation

Calculation of variances for the data in Annex B.1 is as follows:

Table E.1 — Group data

Temp 1	*Temp* 2	*Temp* 3	*Temp* 4	*Temp* 5	$\hat{\sigma}_{lsm}$
85	85	85	75	65	0,132 35
%*RH* 1	%*RH* 2	%*RH* 3	%*RH* 4	%*RH* 5	
80	70	60	80	80	
n_1	n_2	n_3	n_4	n_5	Σn_j
20	20	20	20	30	110

Table E.2 — x_{1j} and x_{2j}

x_{11}	x_{12}	x_{13}	x_{14}	x_{15}
0,002 792 13	0,002 792 13	0,002 792 13	0,002 872 33	0,002 957 27
x_{21}	x_{22}	x_{23}	x_{24}	x_{25}
80	70	60	80	80

Table E.3 — Fisher-information matrix *I*

6 279,785	17,908 35	468 129,4	0
17,908 35	0,051 101 81	1 337,029	0
468 129,4	1 337,029	35 280 980	0
0	0	0	12 559,57

Table E.4 — Inverse matrix I^{-1}

0,303 502 4	-117,650 6	4,315 019E-4	0
-117,650 6	47 91,963	-0,254 791 9	0
4,315 019E-4	-0,254 791 9	3,958 656E-6	0
0	0	0	7,962 056E-5

NOTE The inverse matrix can be obtained by using a spreadsheet such as the EXCEL function "MINVERSE".

Then $\operatorname{var}(\ln\hat{B}_{50})$ is calculated as,

$\operatorname{var}(\ln\hat{B}_{50})$ = [1, 0,003 354 016, 50] x

$$\begin{bmatrix} 0{,}303\ 502\ 4 & -117{,}650\ 6 & 4{,}315\ 019\text{E-}4 \\ -117{,}650\ 6 & 39\ 119{,}189 & -0{,}254\ 791\ 9 \\ 4{,}315\ 019\text{E-}4 & -0{,}254\ 791\ 9 & 3{,}958\ 656\text{E-}6 \end{bmatrix} \begin{bmatrix} 1 \\ 0{,}003\ 354\ 016 \\ 50 \end{bmatrix}$$

= 0,020 915

$\mathrm{var}(\ln \hat{B}_5) = [1,\ 0{,}003\ 354\ 016,\ 50,\ -1{,}64]\ \mathrm{x}$

$$\begin{bmatrix} 0{,}303\ 502\ 4 & -117{,}650\ 6 & 4{,}315\ 019\mathrm{E-4} & 0 \\ -117{,}650\ 6 & 39\ 119{,}189 & -0{,}254\ 791\ 9 & 0 \\ 4{,}315\ 019\mathrm{E-4} & -0{,}254\ 791\ 9 & 3{,}958\ 656\mathrm{E-6} & 0 \\ 0 & 0 & 0 & 7{,}962\ 056\ \mathrm{E-5} \end{bmatrix} \begin{bmatrix} 1 \\ 0{,}003\ 354\ 016 \\ 50 \\ -1{,}64 \end{bmatrix}$$

$$= 0{,}021\ 129.$$

NOTE The matrix multiplication can be calculated using a spreadsheet such as the EXCEL function "MMULT".

Annex F
(informative)

RSER measurement of BD disks

The Max RSER value of 10^{-3} was adopted as suitable for evaluating the time-to-failure in accelerated stress testing of BD disks. The ECC used for BD is powerful enough and has better error-correction capability than that of DVD at RSER = 10^{-3}.[8]

RSER excludes burst errors of length ≥ 40 bytes. But it is still affected by bursts shorter than 40 bytes.

When measuring disks, manual handling of disks is inevitable. In order to avoid introducing short bursts, it is important to take care not to leave fingerprints on the surface of disks, especially before recording initial data.

If the RSER should increase unexpectedly (especially near the outer edge of disk), it is recommended to wipe off any fingerprints and re-measure the RSER.

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