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COMPACT DISC SERVICE LIFE:
AN INVESTIGATION OF THE ESTIMATED SERVICE LIFE OF PRERECORDED COMPACT DISCS (CD-ROM)

Chandru J. Shahani, Michele H. Youket, Norman Weberg

Prepared for the Library of Congress by
William P. Murray
Consultant
St. Paul, MN

Preservation Directorate
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Objective

The objective of this research was to use accelerated aging to study the Life Expectancy (LE) of information stored on prerecorded compact discs. Accelerated aging in a laboratory setting requires the samples to be subjected to appreciably harsher conditions than the ambient conditions under which they normally age. The purpose of such studies is to determine the failure rates at several temperature and relative humidity levels in order to establish a quantitative relationship of the failure rate with these two all-important parameters. Once such a relationship is established, it can be mathematically extrapolated to normal room temperature and humidity conditions. In this manner, after determining the life of CDs at different accelerated aging conditions, we can estimate how long an average CD might last in real life storage conditions. We can even go farther and estimate how long we might extend this estimated lifetime by lowering the temperature and the relative humidity. By determining the rate at which optical and physical changes occur, we may be able to anticipate when discs in the collection need to be reformatted to ensure that no information is lost.

The effect of temperature and relative humidity on Block Error Rate (BLER) was modeled using a modified Eyring equation. The goodness of fit of the experimental data was compared to four common distributions including Weibull, lognormal, normal and exponential. The lognormal failure time relationship was determined to best describe the distribution of measured or estimated life expectancies. The life expectancy is expressed as the percentage of discs surviving, with a given confidence level, when stored at a prescribed temperature and relative humidity.

For the purposes of this report, a prerecorded compact disc is considered to be a CD-ROM or a CD-Audio. It does not include recordable CDs (CD-R), rewritable CDs (CD-RW), or DVDs.

Introduction

Since their introduction in the 1980's, there has been much published regarding the suitability of the compact disc to serve as a media for archiving music, art, and other information. Most publications offer only anecdotal information. Some offer actual data but at undefined conditions. Fewer yet provide sufficient data to actually allow meaningful disc life expectancies to be determined. Understanding the service life expectancies and the factors that influence service life is important for all users. This understanding is essential for all institutions and repositories that provide archival storage of, and access to, digital information on compact disc media.

The growth of the CD media form is unprecedented in any other media format. So prolific has this product become that what was once an expensive means for producing classical music is now available free in magazines and books. CD Media is even mailed unsolicited as an inducement to affiliate with on-line internet services.

The process for production of prerecorded CDs is such that it is not economical for production of quantities less than a few hundred. One of the major expenses is the production of an encoded master and injection molding stampers. Set up time requires hours of factory labor and the total time from recording to final CD could range from a few hours to several days. Thus the CD-ROM process is conducive to mass production and distribution of inexpensive prerecorded compact discs such as those that constitute the majority of the Library of Congress CD-Audio holdings.

The compact disc format is governed by standards referred to as the Yellow Book (CD-ROM) and the Red Book (CD-Audio). These standards specify the data layout, dimensions, and specific optical properties required in the production of CD-ROM media.

However, these standards do not place any requirement on the chemical or physical stability of the disc. As such, there are variations of process and construction being used in disc manufacture. Differences exist in the stability of the reflector material and the protective lacquer coating. These differences are considered to be significant variables in the permanence of information stored on the compact disc.

The samples chosen for this study were selected from duplicate CDs that had been submitted to the Library of Congress for copyright registration and represent a variety of CD-ROM constructions. By virtue of a limited random sampling of these discs, the resulting estimate represents a composite lifetime estimate of various product constructions utilized by the manufacturers at the time the disc was produced. A more detailed description of the sampling is contained in the Test Description section of this report.

Definitions

Baseline: The condition representing the disc at the time of manufacture. This is customarily the value of test parameters taken prior to the application of any aging stress. The time designation is usually "t=0" to indicate time equal to zero hours.

Block Error Rate: (BLER) The number of blocks per second with one or more errors measured at the input of the C1 decoder.

Maximum Block Error Rate: (max BLER / BLER max) The maximum BLER measured in any area of the disc. IEC 60908 specifies that BLER, averaged over any 10 second interval on the disc, shall be less than 3×10^{-2}. At a rate of 7350 blocks per second entering the C1 decoder, this sets the limit for max BLER at 220 erroneous blocks per second.

Compact Disc – Recordable (CD-ROM): For the purposes of this test plan, a CD-ROM is a disc which has been prerecorded by injection molding and metallization. CD-Audio is included in this definition.

End-of-life: (EOL) The occurrence of any loss of information. The loss will be determined as the point at which the error correction methods are unable to correct the error within the allotted time for such correction. For the purposes of this study, the EOL is assumed to be an error rate of 220 sec^{-1}.

F(t): The probability that a random unit drawn form the population fails by time = (t). F(t) is also numerically equal to the fraction of all units in the population which fail by time = (t).

Information: The signal or image recorded using the system.

Life Expectancy: (LE) The length of time that information is predicted to be retrievable in a system under extended term storage conditions.

R(t): The probability that a unit drawn from the population will survive at least time = (t). R(t) is also numerically equal to the fraction of all units in the population which survive at least time = (t).

Retrievability: The ready access to the information recorded on the medium. The access shall be restricted to the manner intended using the prescribed system.

Standardized Life Expectancy (SLE): The minimum life span that one can expect, with 95% confidence that 95% of the product will attain if stored at conditions of 25 °C and 50% relative humidity. .

Stress: The experimental variable to which the specimen is exposed for the duration of the test interval. In this test plan, the stress variables are confined to temperature and relative humidity.

System: A system consists of recording medium, hardware, software, and documentation to retrieve information.

Test Cell: The device that controls the experimental environment in which the specimens receive the stress variable.

Test Pattern: The distribution of 1's and 0's within a block.

Usage Stress: The condition that media are likely to experience in normal exposure. For the purposes of this test plan, these conditions are defined in ISO 18921 as 25 °C (77 °F) and 50 % relative humidity. These conditions are slightly warmer than a normal household or office environment so the life expectancies calculated are correspondingly conservative for those environments.

Test Description

Test Overview: CD-ROMs of good manufacture should last several years or even decades. Consequently, if one is to determine the life expectancy of this media, it is necessary to conduct accelerated aging studies. The principal accelerating factors, or stresses, for CD-ROMs have been shown to be temperature and relative humidity (RH). By determining the life expectancy distribution of samples at various elevated levels of these stresses, and by using established acceleration models, the life expectancy distribution at usage stresses may be estimated.

The ability of a CD-ROM to perform is measured by the Block Error Rate (BLER). A BLER of 220 sec^{-1}, as defined by section 12.5.2 of ISO/IEC 10149, is considered to be the disc's end-of-life threshold. By measuring the time to reach a BLER failure threshold of 220 sec^{-1} for a sample of discs exposed to a given accelerated temperature and RH, it is possible to estimate the EOL distribution at that stress. If several different temperature and RH combinations are properly chosen, a mathematical model may be developed to relate life expectancy to a specific storage or use temperature and RH.

For this study, a sample of 80 pairs of prerecorded CD-DA (Audio) discs was obtained from duplicates discarded by the Library of Congress Motion Picture, Broadcast, and Recorded Sound Division. Reliance on these discards limited the test population to discs with a date of manufacture between 1992 and 1999, except for one disc from 1982.

One disc of each pair was tested in an "as received" condition and each has the suffix "D" appended to the specimen number. The remaining discs were property stamped by laser engraving a mark within the flat area of the CD between the center hole and the stacking ring prior to testing. Each disc in this half has the suffix "C" appended to the specimen number.

The paired discs represent two copies of the same title and the construction was assumed to be the same for both. These paired discs were used to determine the effect, if any, of applying a laser-engraved property stamp to discs in the Library's collection. The effect of the laser engraving is discussed in a separate report, *The Effects of Laser Engraving on the Estimated Service Life of Prerecorded Compact Discs (CD-ROM),* Preservation Research & Testing Series No. 11, 2009.

The discs were divided into five groups, one group for each stress condition. The distribution of the discs is shown in Table 1:

Table 1: Distribution of Discs by ID, Temperature and Relative Humidity

Disc ID	Number	Temperature (˚C)	Relative Humidity (%)
1 through 30	30	60	85
31 through 45	15	70	85
46 through 60	15	80	55
61 through 70	10	80	70
71 through 80	10	80	85

NOTE The total number of discs per set of Temperature and Relative Humidity stress condition is actually twice the number listed in Table 1, as the "C" and "D" versions were combined for the purpose of this test.

The process of CD-ROM accelerated aging requires that discs in each stress condition be a.) ramped from ambient conditions to the accelerated stress condition in an environmental chamber, b.) maintained at that stress condition for a particular period of time and then c.) ramped back to ambient conditions. This incubation cycle was scheduled for a minimum of 4 times during the course of testing. The ramp duration and conditions were chosen to allow sufficient equilibration of absorbed substrate moisture. Large departures from equilibrium conditions can result in the formation of liquid water droplets inside the substrate or at its interface with the data recording layer. Gradients in the water concentration through the thickness of the substrate must also be limited. These gradients drive expansion gradients, which can cause significant disc curvature and possible damage to the metallic reflector layer.

In order to minimize any negative effects of moisture concentration gradients in large chambers, the ramp profile outlined in Table 2 was used. As an illustration, the ramp profile for the 80 °C / 85 % RH stress is portrayed graphically in Fig 1.

Table 2 — Temperature and RH ramp profile

Process step	Temperature (ºC)	RH (% RH)	Duration (hours)
Start	at T_{amb}	at RH_{amb}	---
T, RH ramp	to T_{inc}	to RH_{int}	1.5 ± 0.5
RH ramp	at T_{inc}	to RH_{inc}	1.5 ± 0.5
Incubation	at T_{inc}	at RH_{inc}	see Table 3
RH ramp	at T_{inc}	to RH_{int}	1.5 ± 0.5
Equilibration	at T_{inc}	at RH_{int}	see Table 3
T, RH ramp	to T_{amb}	to RH_{amb}	1.5 ± 0.5
End	at T_{amb}	at RH_{amb}	---

NOTE T_{amb} and RH_{amb} are room ambient temperature and RH, T_{inc} and RH_{inc} are the stress incubation temperature and RH, RH_{int} is the intermediate RH that, at T_{inc}, supports the same equilibrium moisture sorption in polycarbonate as that supported at T_{amb} and RH_{amb} (see "Ramp Profiles for Optical Disc Incubation", J. J. Wroebel, SPIE Vol. 2338, 1994)

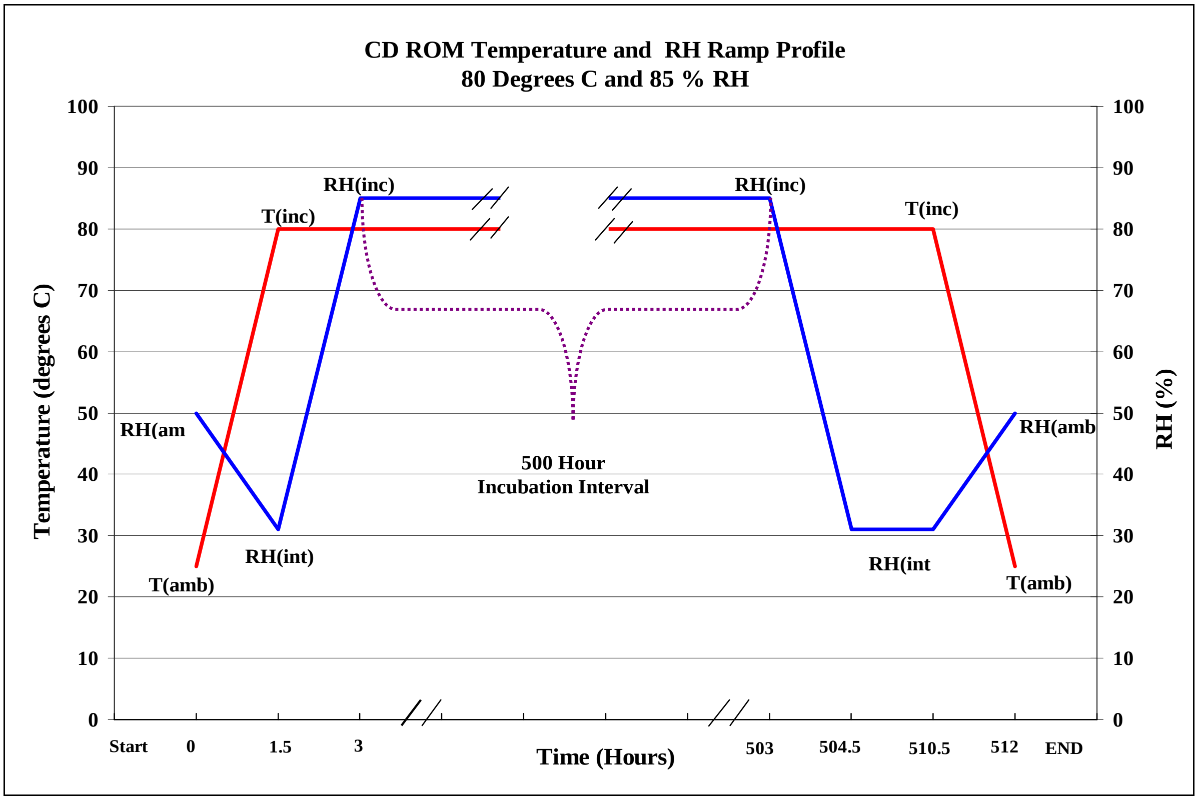

Figure 1: Temperature and Relative Humidity as a function of Time (hrs) of the 80 °C and 85 % RH incubation cycle

A summary of the Test Stress conditions, the incubation interval, the total incubation time scheduled, the Intermediate Relative humidity and the Equilibration Durations selected for this study are summarized in Table 3.

Table 3: Stress Conditions and Test Intervals for CD-ROM Media

Test Stress T (inc) / RH(inc)	Incubation Interval	Total Time	Intermediate RH (RHinc)	Equilibration Duration
60 °C / 85% RH	1000 Hrs	4000 Hrs.	36%	11 Hrs
70°C / 85% RH	750 Hrs	3000 Hrs	33 %	8 Hrs
80°C / 55% RH	500 Hrs	2000 Hrs	31 %	4 Hrs
80°C / 70% RH	500 Hrs	2000 Hrs	31 %	5 Hrs
80°C / 85% RH	500 Hrs	2000 Hrs	31 %	6 Hrs

Data Collection: Discs were tested on a Datarius CDCS-4.2L Compact Disc Quality Tester with CDCS-40T Optitest System at the Library of Congress. Discs were tested according to the Datarius Basic Sequence using Redbook standard parameters for CD-DA (Digital Audio). One hundred percent of the disc's recorded surface was tested. All disc test parameters were recorded and considered. For the purposes of this report, the ten second average block error rate (BLER) was used to indicate the deterioration rate of the specimen. This is in accordance with the ISO standard, ISO 18921:2002 "Imaging materials -- Compact discs (CD-ROM) -- Method for estimating the life expectancy based on the effects of temperature and relative humidity".

Testing was performed prior to the disc receiving any accelerated stress and then after exposure to the accelerated stress conditions at pre-determined incubation intervals shown in Table 3. Contingencies that arose during testing necessitated modifications that were taken into account for life estimation.

Standard test methods for determining the life expectancy of compact discs, ISO 18921 and ISO 18927, consider a change in BLER in response to the time at an elevated temperature and humidity as the principal quality parameter for establishing the ability of a system to retrieve information on a compact disc using a standard drive A maximum BLER of 220 sec^{-1}, as specified in ISO/IEC 10149 and IEC 60908, is used to represent end-of-life in these test methods. Optical disc quality test systems typically measure and report 3 figures for BLER: minimum, maximum, and average. The number reported for BLER max represents the worst section of the disc rather than an overall BLER mean of the entire disc. By measuring the BLER max as a function of exposure time (hours) at elevated stress conditions, the rate of change of BLER max for any given disc at that stress was easily determined by linear regression. This regression produced an equation of the form:

$$\text{BLER}(t) = \text{Rate} \times \text{Time (hours)} + \text{Intercept}$$

By substituting 220 sec^{-1} as the BLER at end of life into the above equation, the time to reach this value is readily obtained. The time is equivalent to the estimated service life and was determined for each disc in the study on an individual basis. This produced 160 opportunities for EOL estimates including both the un-engraved "D" and laser engraved "C" versions of tested media.

It is important to understand what is meant by 'end-of-life' as defined by optical media standards. A disc with a localized area reporting a BLER max of 220 sec^{-1} does not necessarily mean that the disc cannot be read, or that the disc will not 'play', when it is inserted into the appropriate drive.

On audio CDs, if the error correction scheme applied during play cannot read the data in a particular area because the BLER is too high it will return a null value to the decoder, which may result in a random drop-out of sound. This drop-out may not be readily apparent to the listener.

The inability to retrieve information in such an area on a data disc would be more noticeable, but much of the data on the disc would still be recoverable.

For the general consumer such minimal losses may not be construed as 'end-of-life' for that disc.

However, for institutions such as the Library of Congress, whose mission entails the archiving and preservation of the historical and cultural record, the loss of any information on these discs is much more significant. The goal of any preservation program is to minimize the degradation of collection materials and avoid losses to the greatest extent possible. For this reason, the point at which any data becomes unrecoverable would indeed constitute end-of-life from an archival perspective.

The data collected for this study is summarized in Attachment 1.

The calculated estimates for EOL for each disc are shown in Attachment 2.

Due to a variety of reasons, some of the calculated values in this study were censored or excluded. Reasons include:

- Early Failure (Maximum recordable BLER achieved prior to the first test interval)
- Insufficient change in BLER during the test period
- Assignable cause for exclusion. The data for the specimens exposed to the 80 °C / 70 %RH were excluded. The rationale for this exclusion is described in the Data Analysis Section.

Data Analysis

The probability of each disc to reach end-of-life (EOL) by time t within a stress condition, (temperature / relative humidity chamber) was compared to four standard distributions. These included the Weibull, lognormal, normal and exponential distributions. These four were considered to be the most common mathematical estimates of a population based on a sample treated to accelerated stress condition. Selection of the distribution equation best fitting the observations was based on a least squares fit of the data to the line. Figures 2 through 6 show the comparisons for each of the four distributions and for each stress condition.

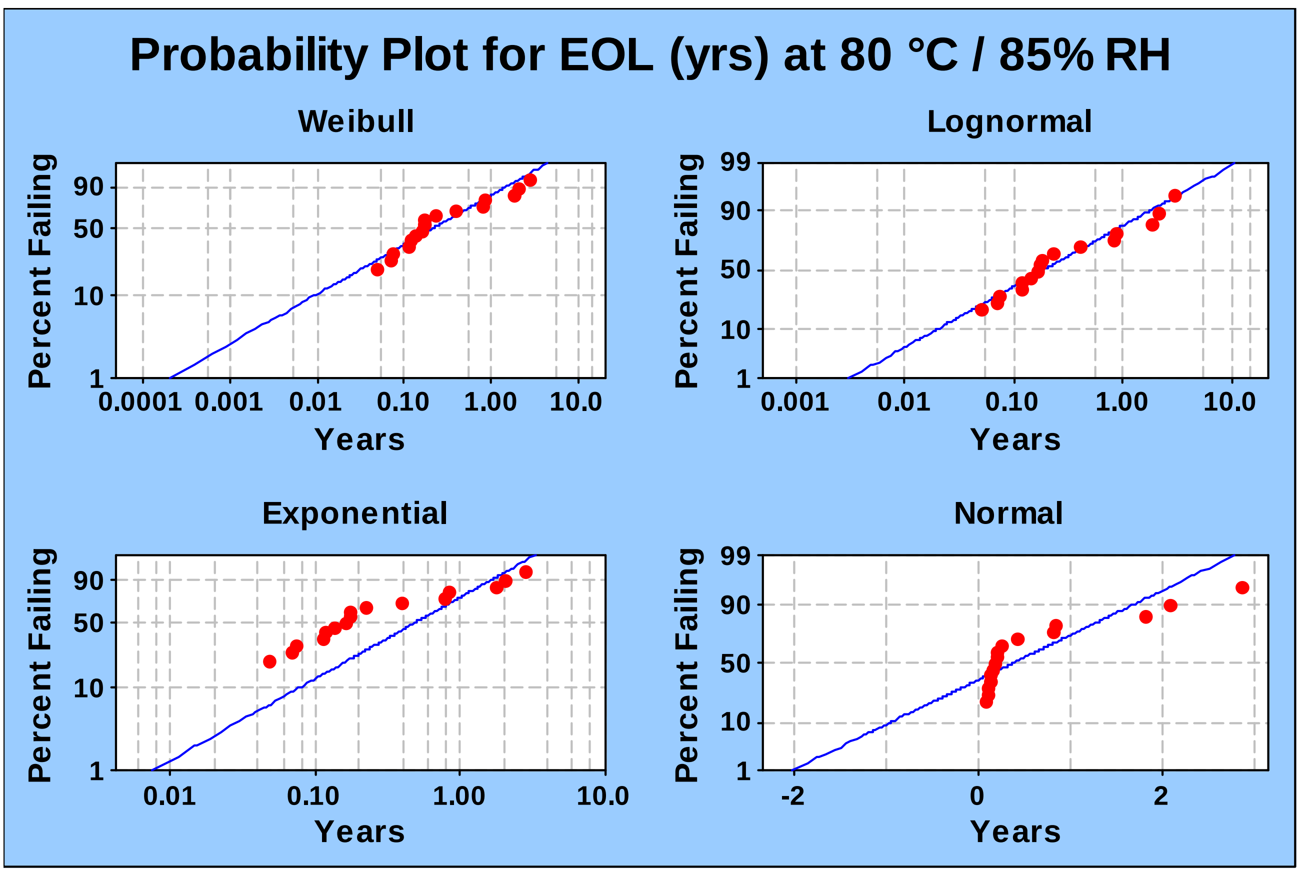

Figure 2: Comparison of Distribution Estimates for 80 ˚C / 85% RH

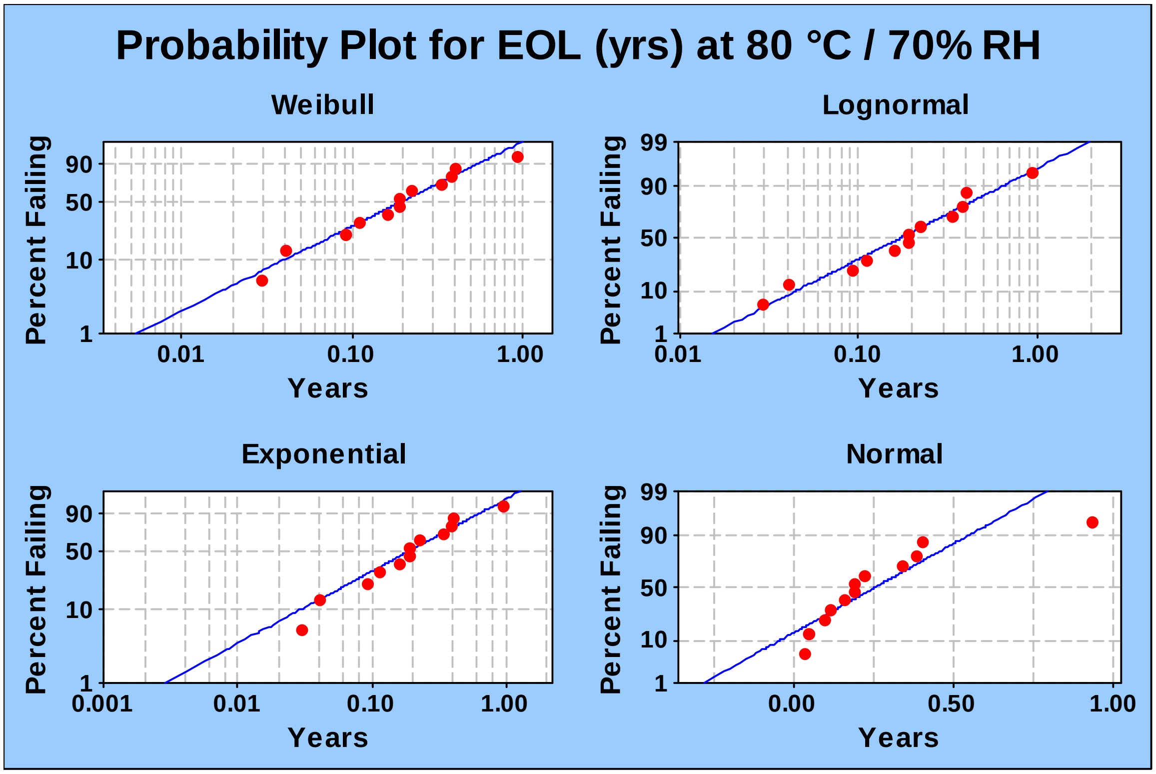

Figure 3: Comparison of Distribution Estimates for 80 ˚C / 70% RH

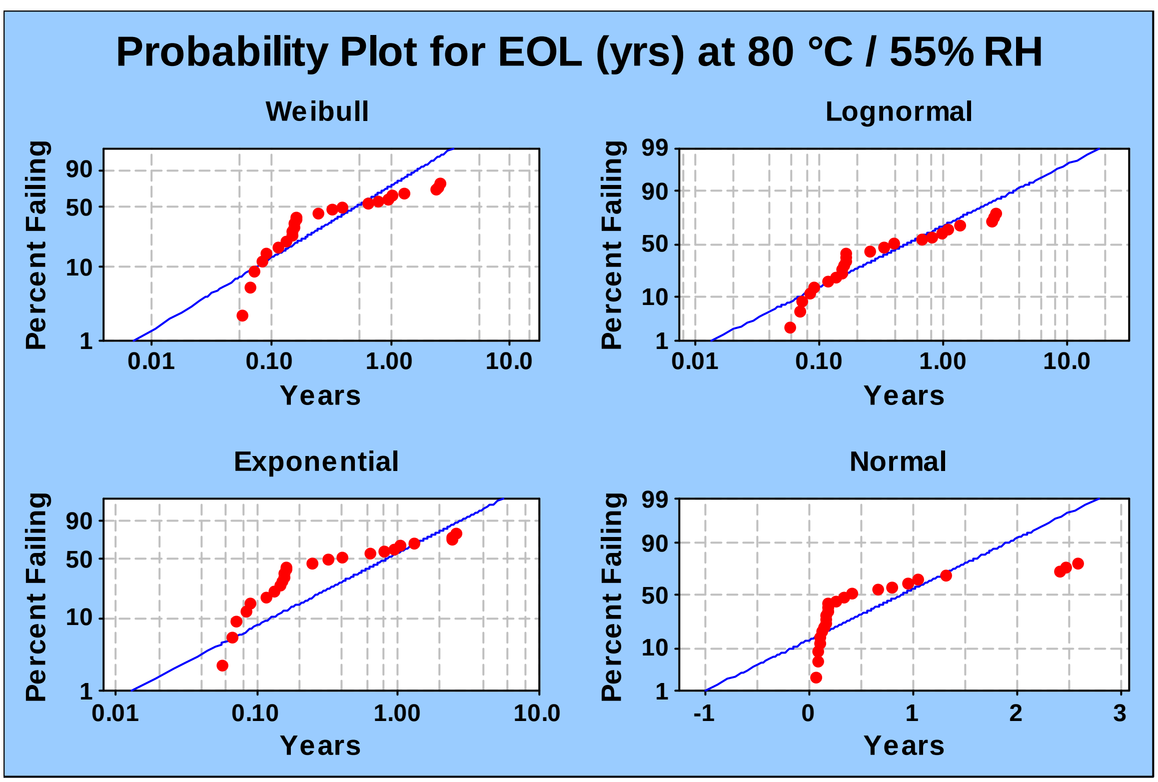

Figure 4: Comparison of Distribution Estimates for 80 ˚C / 55% RH

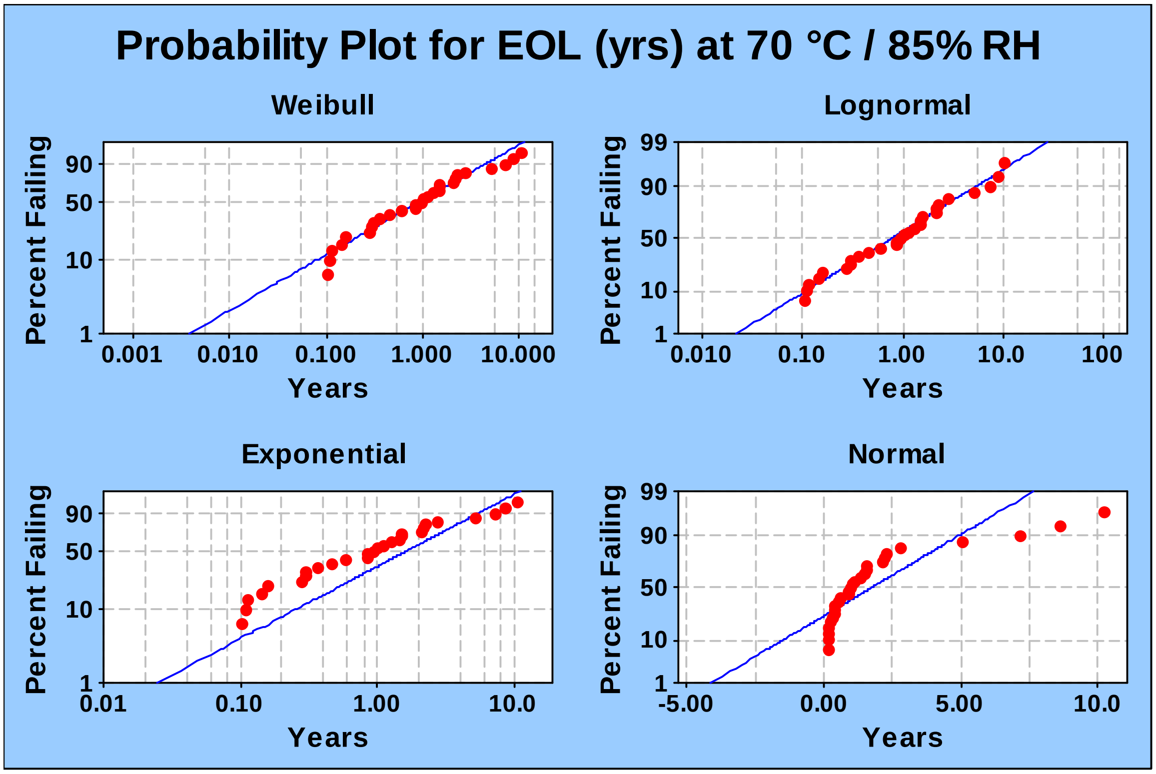

Figure 5: Comparison of Distribution Estimates for 70 ˚C / 85% RH

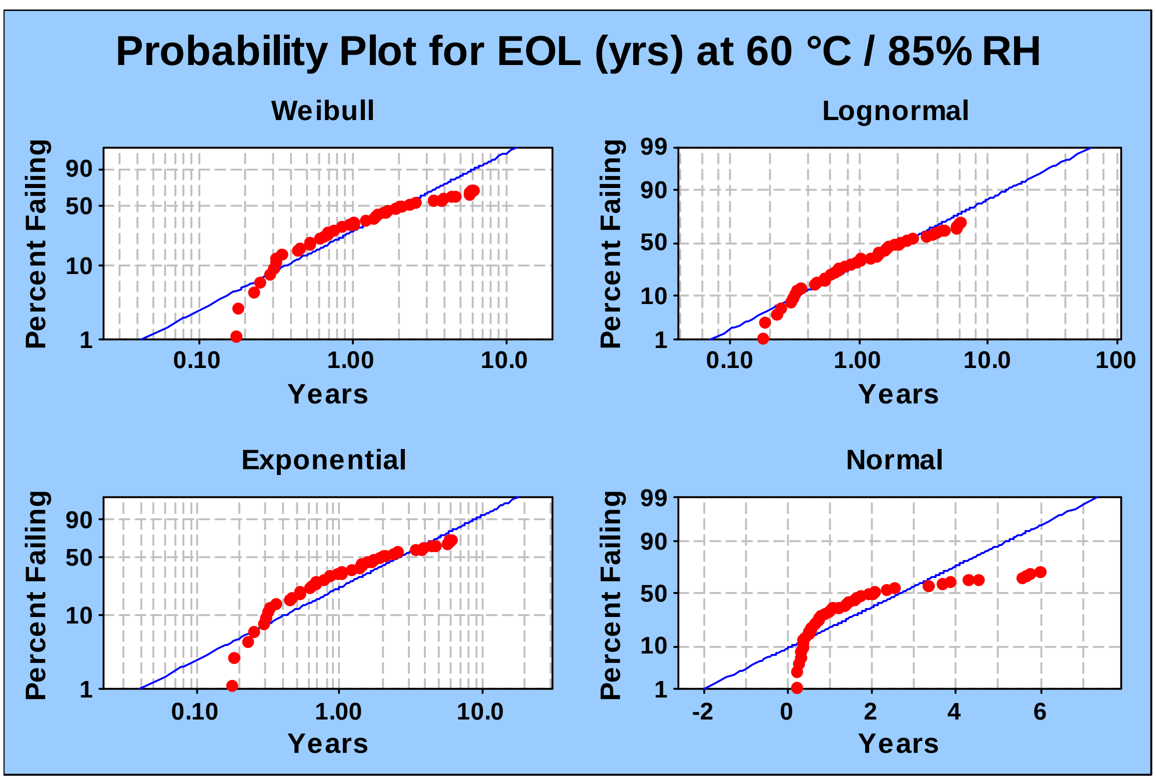

Figure 6: Comparison of Distribution Estimates for 60 ˚C / 85% RH

Table 4 summarizes the regression coefficients for the Weibull, lognormal and normal distribution technique for comparison for each stress. The correlation for the exponential distribution was made graphically.

Table 4: Summary of Regression Coefficients for Stress Conditions 1 through 5

Stress	Weibull	Lognormal	Normal
80 ˚C/85% RH	.962	.979	.872
80 ˚C/70% RH	.989	.983	.874
80 ˚C/55% RH	.874	.932	.753
70 ˚C/85% RH	.980	.991	.831
60 ˚C/85% RH	.933	.976	.814

The higher the regression coefficient for least squares regression, the better the fit of the experimental data is to the estimated distribution. A regression coefficient of 1.00 indicates a perfect fit. It may be seen that, as expected, both the Weibull and the lognormal distribution provide an acceptable fit to the experimental data. In each case used for the EOL estimate, the lognormal distribution was the best fit and was chosen for further analysis in favor of the other distribution estimates. Calculations of mean EOL are made using linear regression.

Figures 7 through 11 show, by stress, the mean EOL and fit of the experimental data to the lognormal distribution:

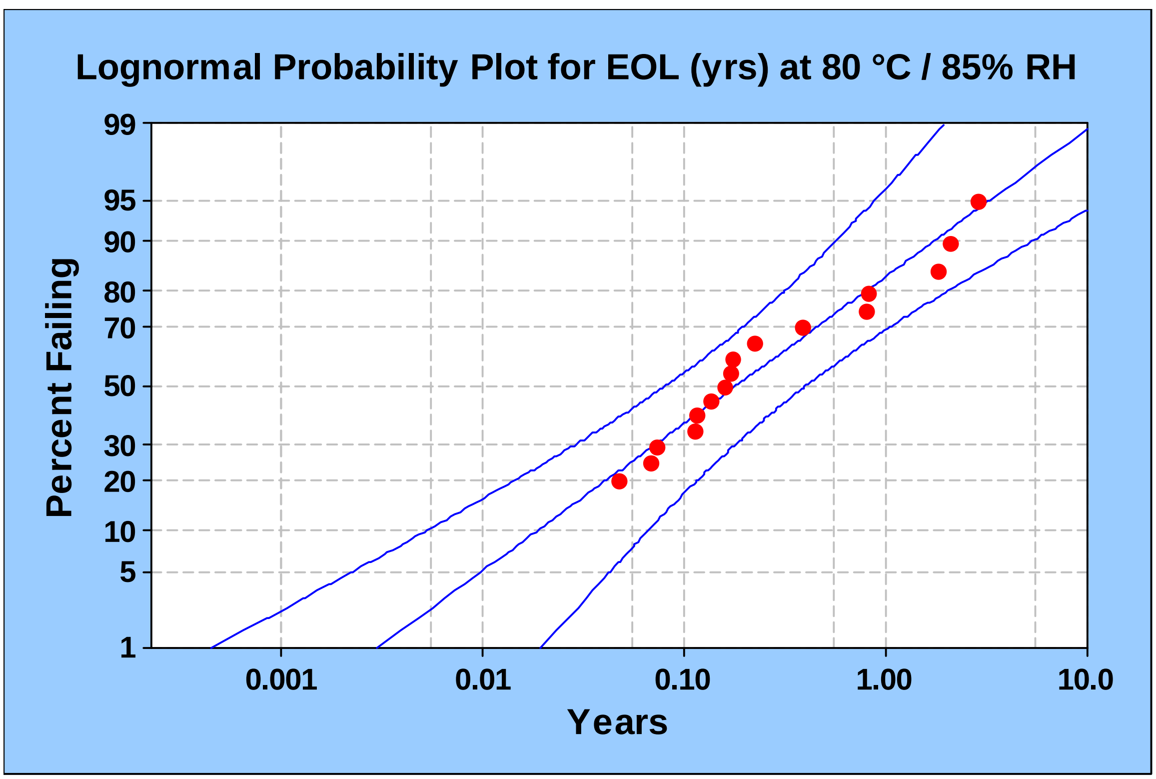

Figure 7: Lognormal Probability Plot for 80 ˚C / 85% RH

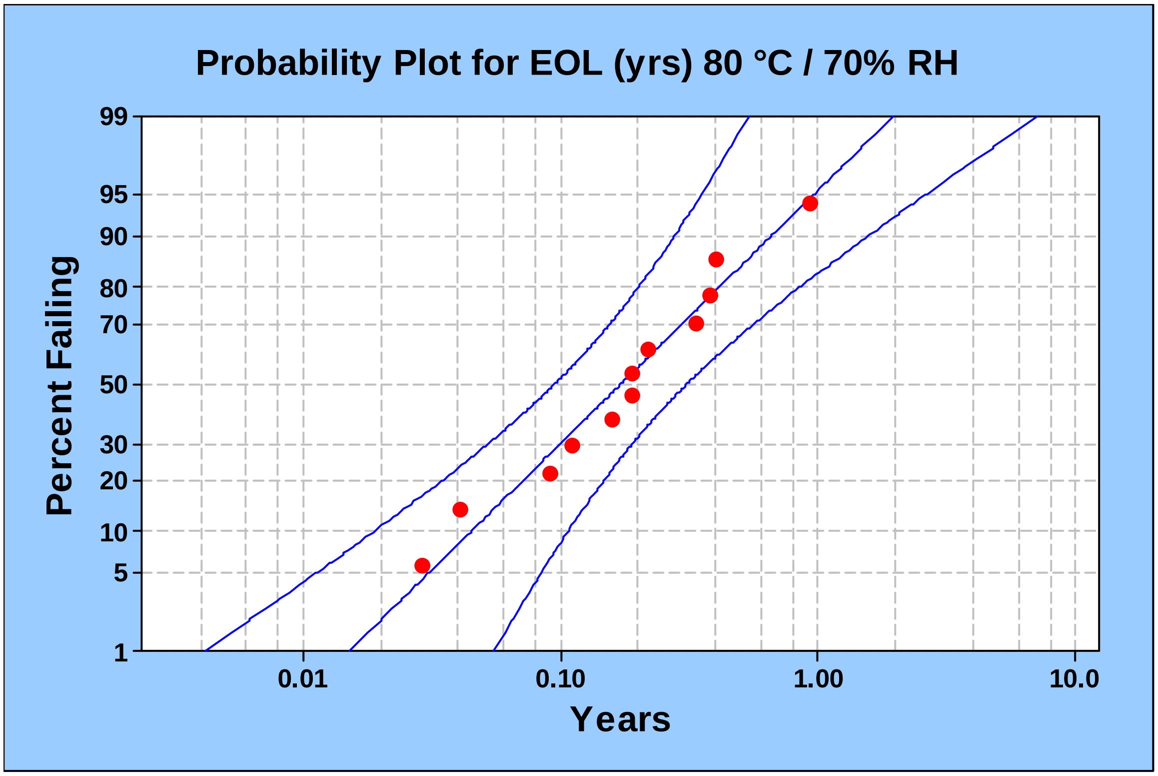

Figure 8: Lognormal Probability Plot for 80 ˚C / 70% RH

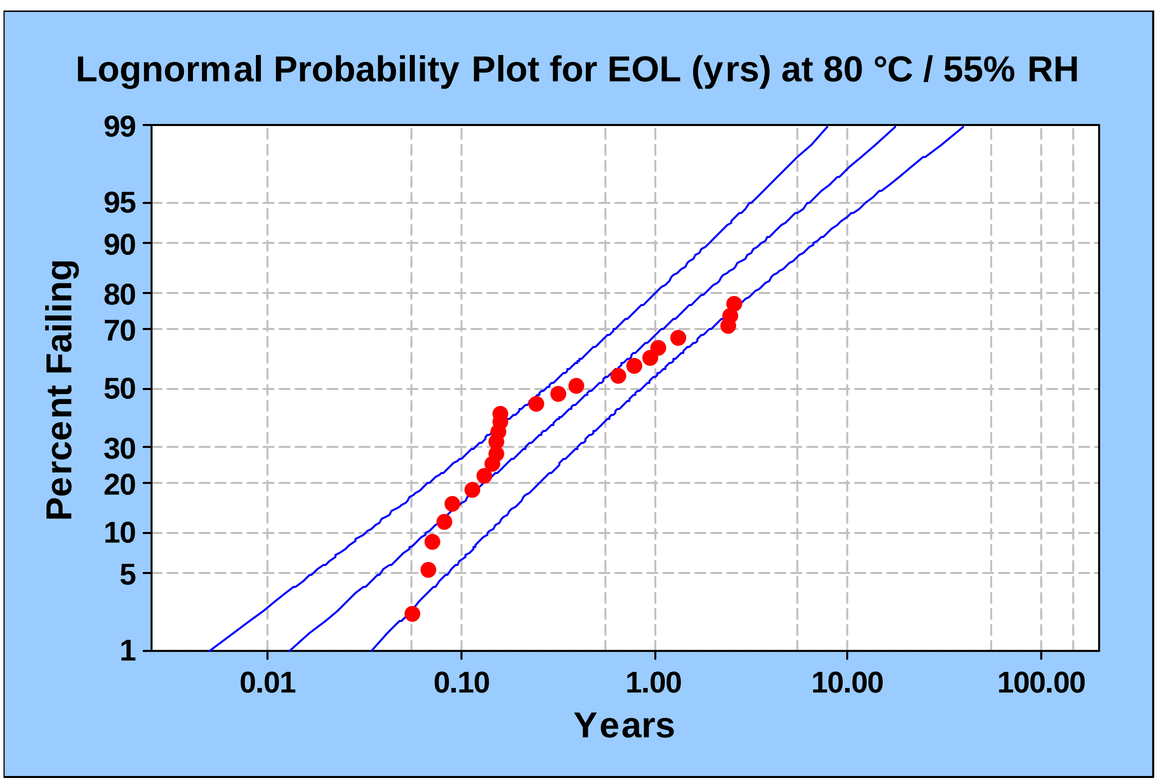

Figure 9: Lognormal Probability Plot for 80 ˚C / 55% RH

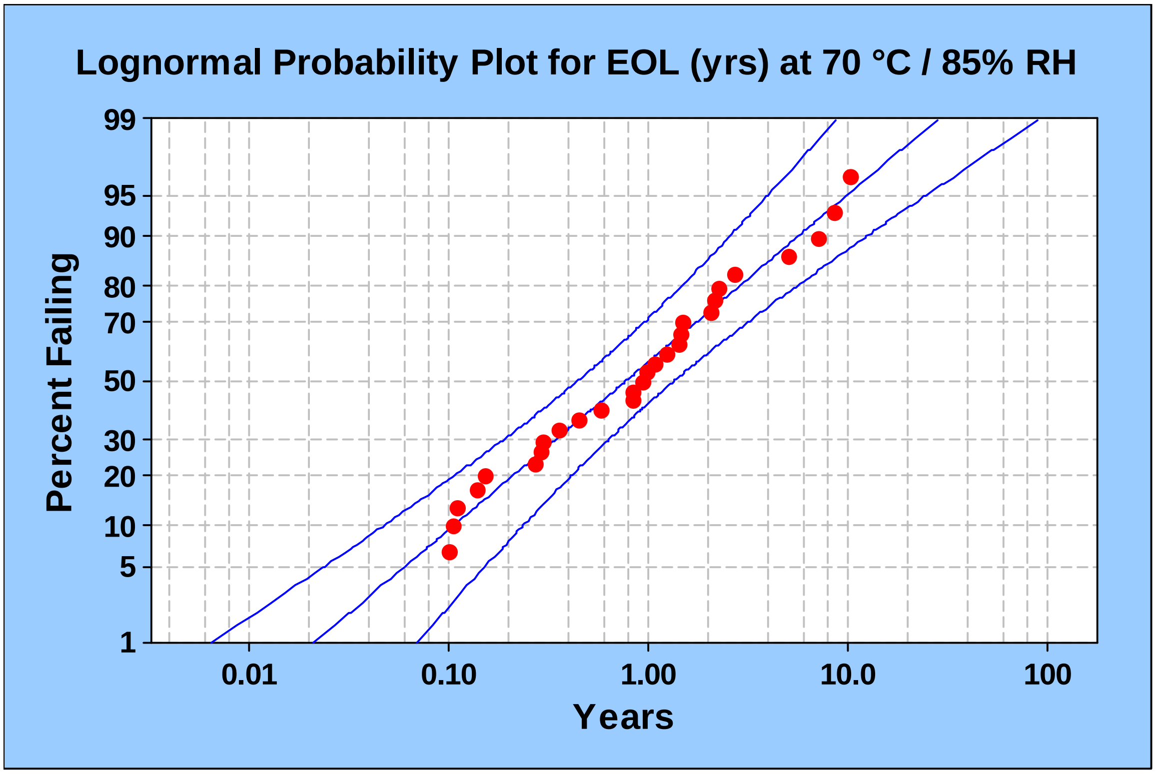

Figure 10: Lognormal Probability Plot for 70 ˚C / 85% RH

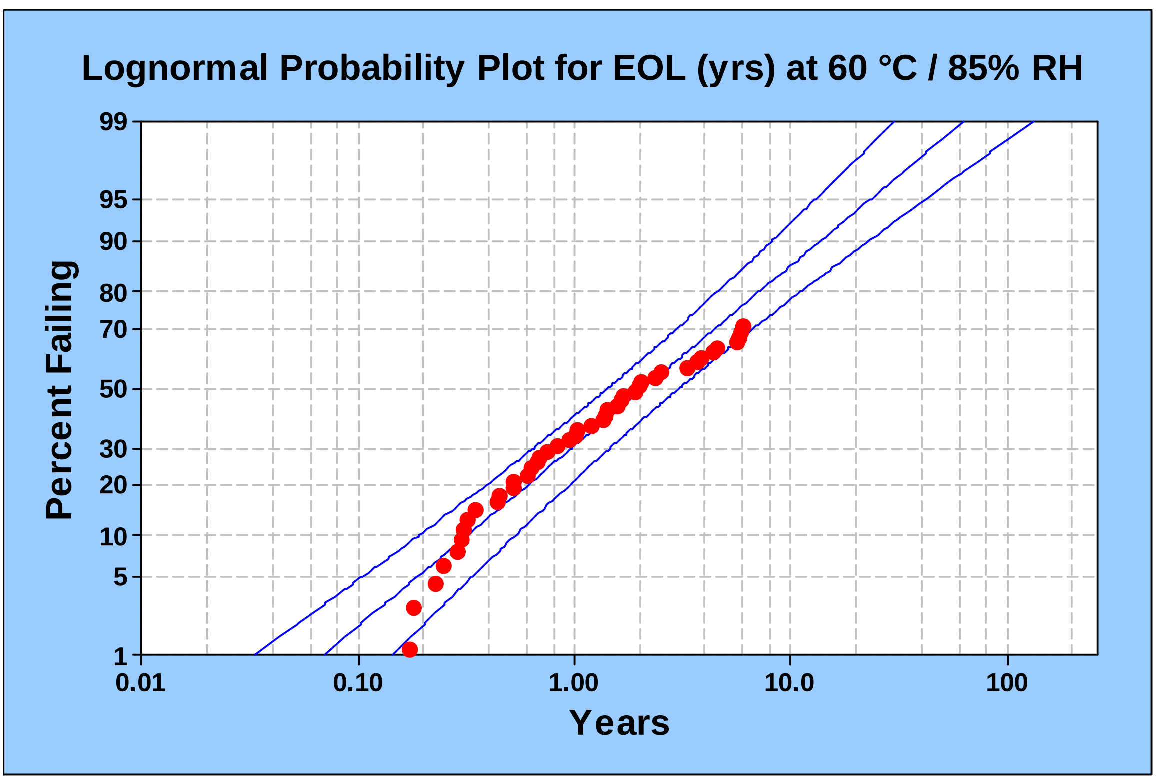

Figure 11: Lognormal Probability Plot for 60 ˚C / 85% RH

At this point of the analysis, a table was prepared of the mean EOL determined from the lognormal regressions above (Figures 7 through 11) versus the temperature and relative humidity conditions at which the discs were stressed. This information is summarized in Table 5:

Table 5: Summary of Mean EOL by Temperature and Relative Humidity

Mean (EOL) (yrs)	Temperature (˚C)	Relative Humidity (%)
0.839	80	85
0.296	80	70
1.60	80	55
2.53	70	85
6.10	60	85

It may be seen that the Mean EOL for the 80 ˚C / 70% RH is out of line with the other stress levels. This is counter-intuitive. Discussions with the test analyst and the recorded notes in the test data summary sheets indicate that the probability of early EOL values may have been the effect of a malfunction of the stress chamber. As the minimum requirements for solving the Eyring equation may be met without the EOL estimates from the 80 ˚C / 70% RH stress condition, they were excluded from further consideration.

Acceleration Factors

As specified in the ISO test procedure 18921:2002, a reduced form of the Eyring acceleration model was used to relate Mean EOL, Temperature and Relative Humidity. The Equation:

$$Time_{End-ofLife} = Ae^{\Delta H/kT}e^{(B)RH}$$

was solved by converting it to a linear model:

Log(Time) = Log(A) + ΔH/kT +B(RH)

Where ΔH = Activation Energy
K = Boltzman's Constant
T = Temperature (Kelvin) = (T °C + 273.1)
B = pre-exponential factor for relative humidity
RH = Relative Humidity expressed as a fraction.

With our four experimental equations, and only three unknowns, the Eyring equation may be solved. The solution yields:

Log(A) = -31.40
ΔH/k = 11639 ΔH = 1.00 eV per ˚C
B = -1.99

Substituting the values for 1/T (k) and RH corresponding to 25 ˚C and 50% RH produces an estimated ln(mean) of 6.654. This corresponds to a mean lifetime of 776 years for CD-ROMs stored at 25 ˚C and 50% RH. The condition of 25 °C / 50% RH was chosen to coincide with the Standard Life Expectancy condition of the ISO test procedure 18921:2002

To obtain the distribution for the combined group of discs, the mean time to fail at 25 ˚C / 50% RH was divided by the mean time to fail at each of the accelerated conditions. By knowing this ratio, the relative acceleration may be assigned to each of the stress conditions. The results of this operation are shown in Table 6:

Table 6: Summary of Acceleration Factors Relative to 25 ˚C / 50% RH

Temperature (˚C)	Relative Humidity (%)	Mean (EOL) (yrs)	Acceleration Factor
80	85	0.839	924
80	70	0.296	Not Used
80	55	1.60	485
70	85	2.53	306
60	85	6.10	127
25	50	776	1

The acceleration factors in Table 6 relate the rate of aging that occurs at a given combination of T and RH to the rate of aging estimated for the usage condition of 25 °C / 50%RH. For example, the rate of aging at 60 °C / 85% RH was estimated to be 127 times faster than the rate of aging at 25 °C / 50% RH. If the individual disc EOLs measured at 60 °C / 85% RH are each multiplied by the acceleration factor of 127, the result would represent the EOL should the disc have actually been stored at 25 °C / 50% RH.

By multiplying the EOL times measured in a given accelerated stress by the acceleration factor for that stress, all of the measured EOLs were normalized to the estimated EOL had they been stored at 25 °C / 50% RH. Once this was done, all of the disc normalized EOLs were combined into one data set representing a storage condition of 25 °C / 50% RH. The combined normalized EOL data set was then analyzed for its distribution characteristics.

The result of this operation is shown in Figure 12. Again, the lognormal distribution is a better fit than the Weibull. This is an indication of an excellent fit of the normalized accelerated data to a single lognormal distribution.

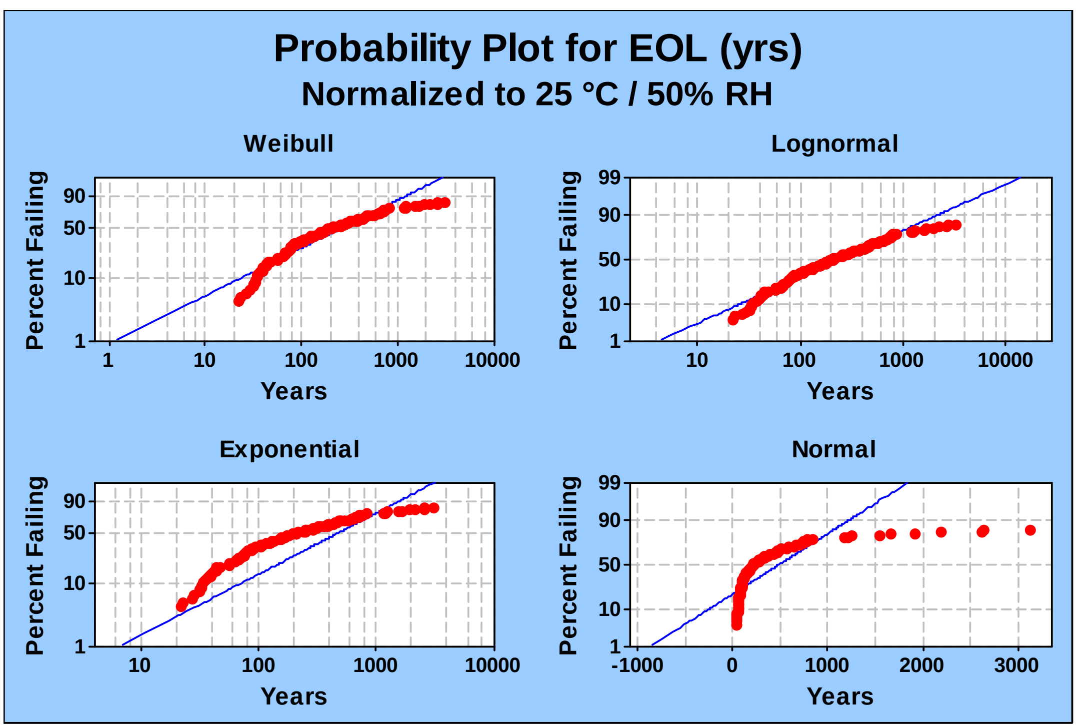

Figure 12: Comparison of Distribution Estimates for Combined Data Normalized to 25 ˚C and 50% RH

Figure 13 is a more detailed graph of the probability of failure as a function of time, using the lognormal distribution of the Combined Data Normalized to 25 ˚C and 50% RH.

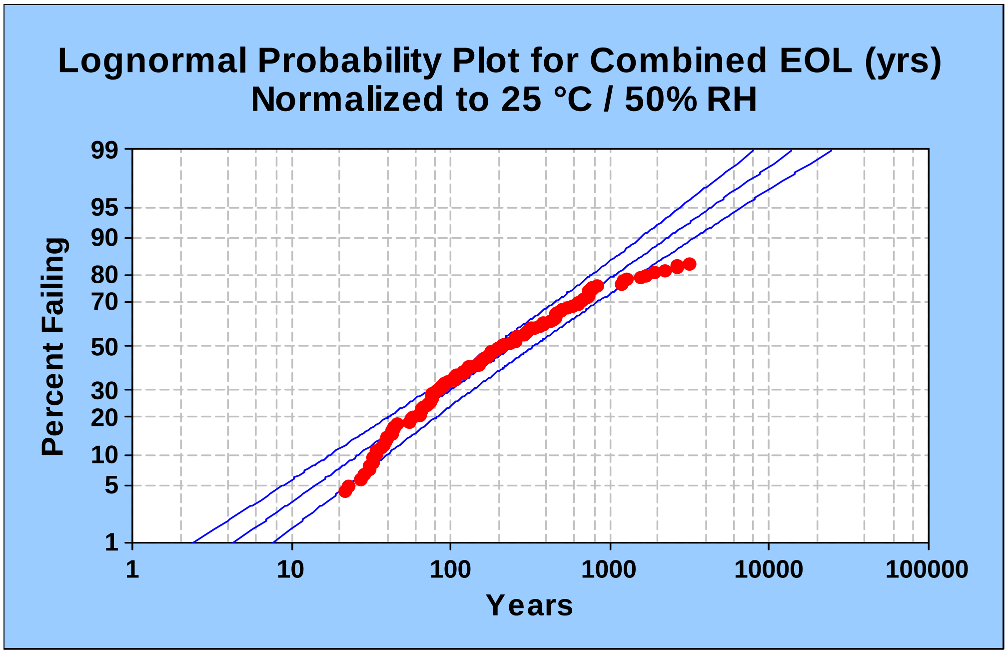

Figure 13: Lognormal Probability Plot of Combined Data Normalized to 25 ˚C / 50% RH

The mean life expectancy of 776 years calculated earlier from the Eyring model is within the 95% confidence limits of the mean life expectancy of 1101 calculated here from the normalized data set. These numbers are therefore considered to be in agreement.

A check for linearity of the mean life versus the temperature at which it was incubated was made and the results are shown in Figure 14. This figure shows good linear agreement of the measured ln(mean) and the reciprocal Kelvin temperature as required by the model. As end-of-life estimates were only obtained for discs exposed to two of the three relative humidity conditions used in this study, due to the failure of the chamber for test cell #2, a linearity determination was not made on this variable.

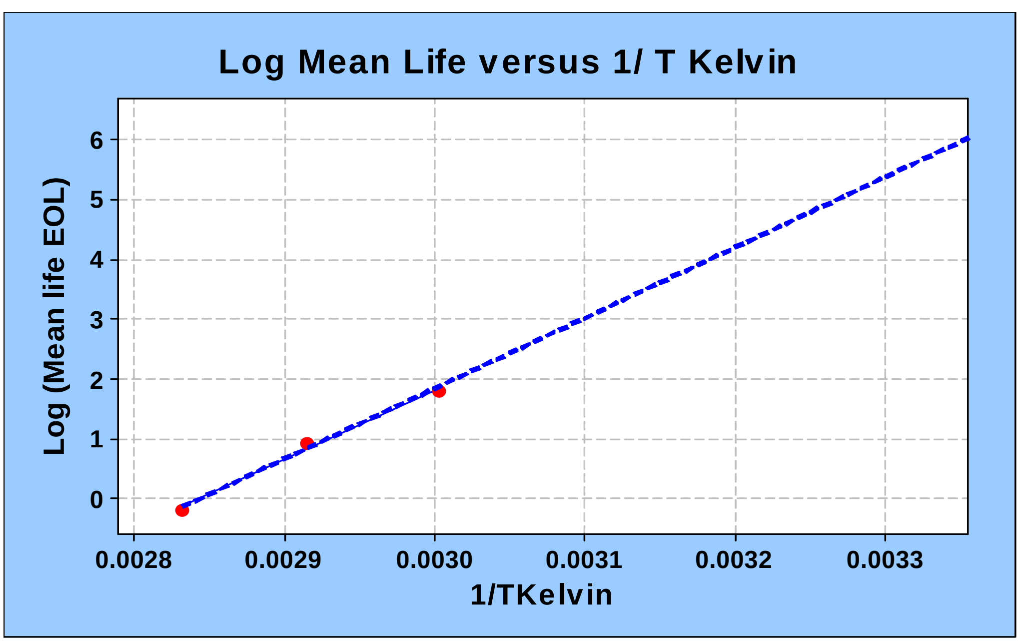

Figure 14: Log Mean Life versus Reciprocal Kelvin Temperature

The same data used for Figure 13, “Lognormal Probability Plot of Combined Data Normalized to 25 ˚C / 50% RH”, may be re-plotted using a linear axis to show the percent failing versus time. Figure 15 is a Cumulative Failure Plot of the combined data normalized to 25 ˚C / 50% RH. It indicates the percent of the total discs that are estimated to have failed, by years, stored at 25 °C and 50% relative humidity.

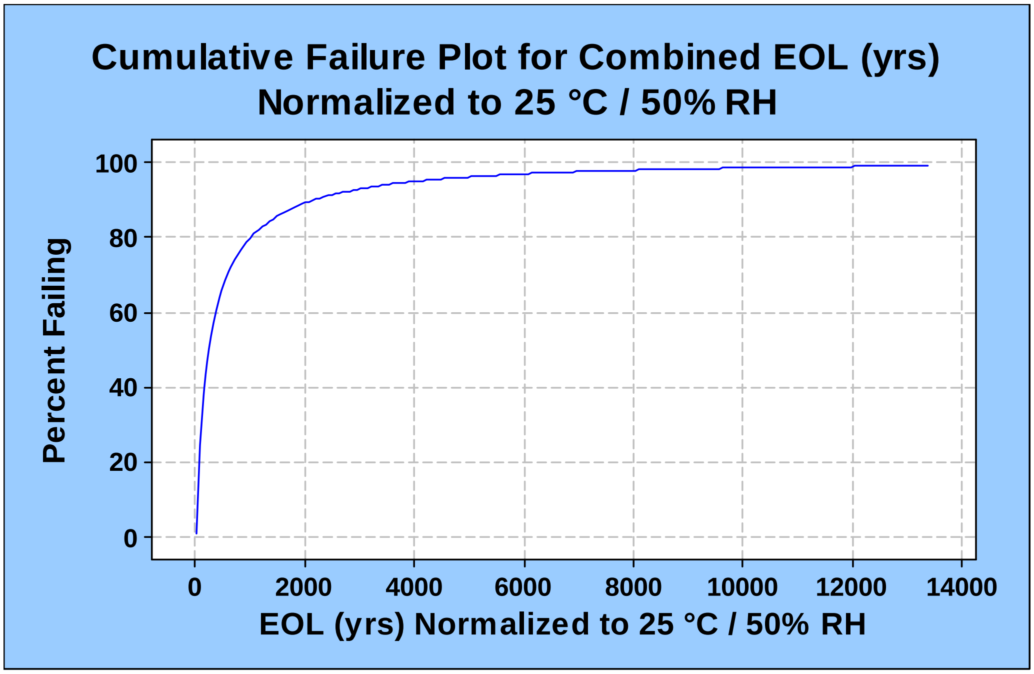

Figure 15: Cumulative Failure Plot for Combined Data Normalized to 25 ˚C / 50% RH

Figure 16 is the same graph as Figure 15, but with a scale chosen to show the percent failures expected during the first 200 years.

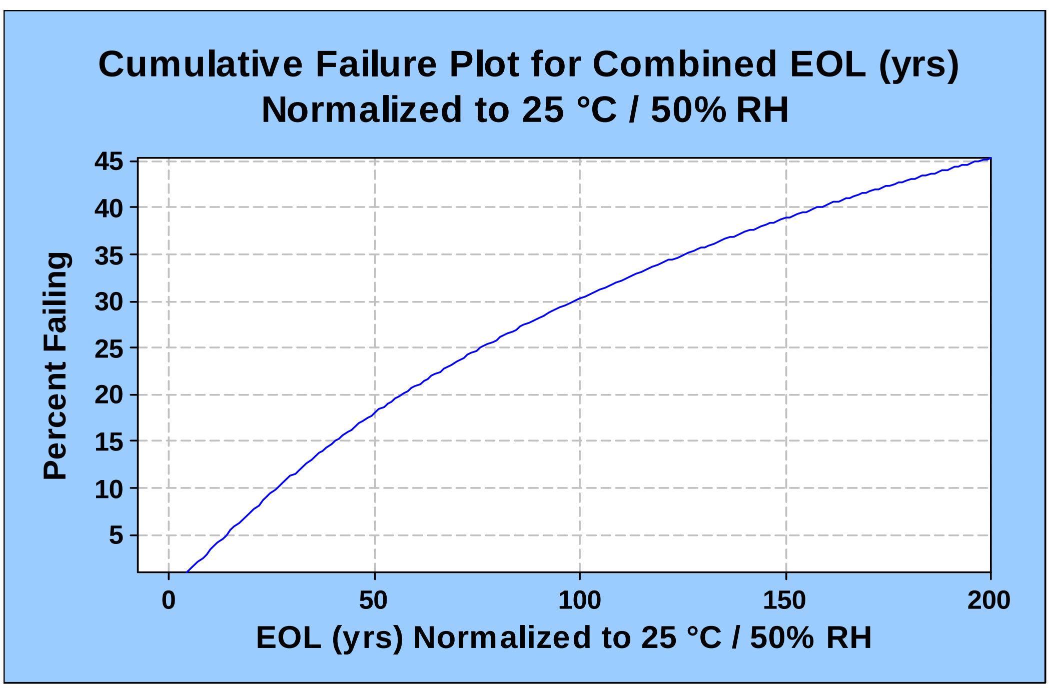

Figure 16: Cumulative Failure Plot for Combined Data Normalized to 25 ˚C / 50%

Table 7 indicates the disc failure probability, or percent of the population failing, by some selected periods of time.

Table 7: Cumulative Failure Percent by years of age

Time (years)	Cumulative Percent Failing
1	0.10
5	1.25
10	3.28
20	7.47
25	9.46
50	18.05
75	24.83
100	30.36
150	38.95
200	45.43

The calculated percentage of discs reaching end-of-life in Table 7 is based on the assumption that the relative composition of the disc population at the Library of Congress is constant. The actual composition of the LC holdings is a cross-section of the probability of survival distributions of material being produced by the media manufacturers. The lifetime expectancies are dependent upon the evolution of CD construction and manufacturing processes. If better media evolve, the life expectancies will shift toward longer lifetimes. Should a decrease in media stability occur, then the life expectancy profile will shift toward shorter lifetimes.

A histogram was prepared showing the number of discs estimated to fail within blocks of time. For Figure 17, the time for the X-axis was truncated at 2000 years and the width of each block was 100 years. The number of discs failing within each 100 year block is shown on the Y-axis.

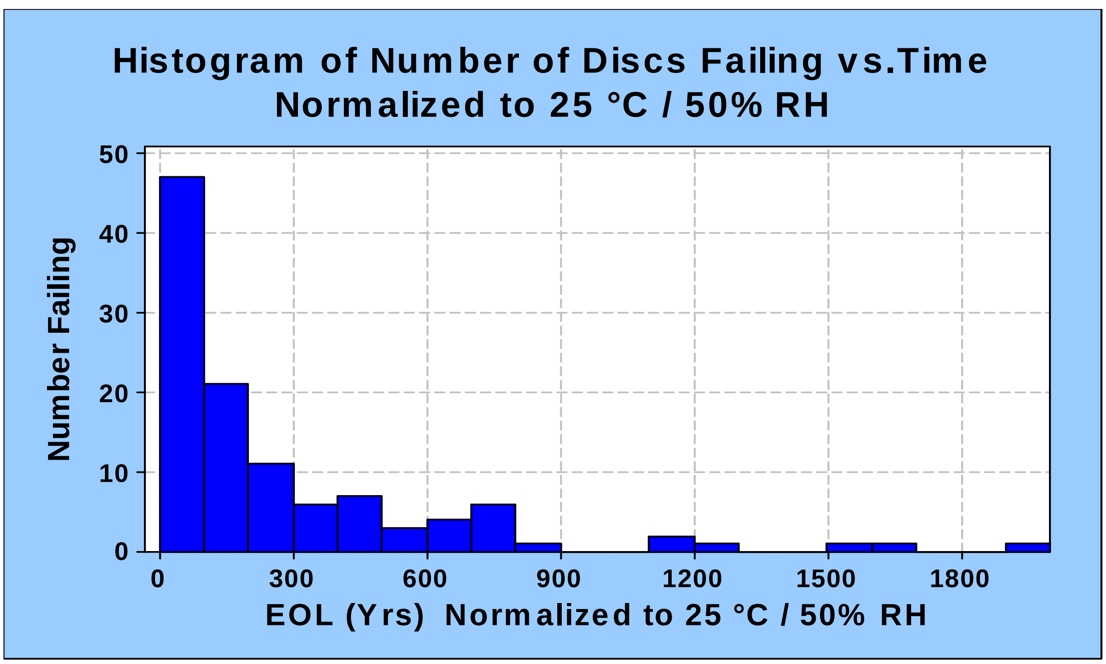

Figure 17: Histogram of Number of Discs Failing by 100 year time blocks

Figure 18 shows the same data in smaller blocks of time to get a better picture of the distribution of failures during the first 500 years. The width of each block represents 25 years. The number failing within each 25 year block is shown on the Y-axis.

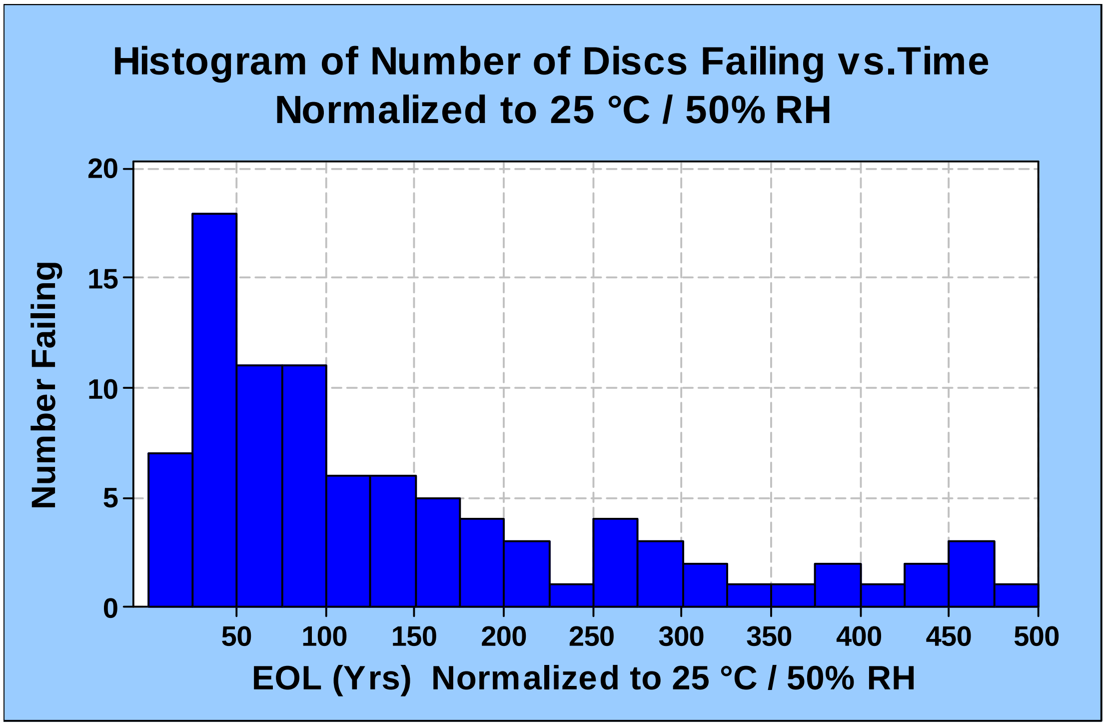

Figure 18: Histogram of Number of Discs Failing by 25 year time blocks

Viewing the data as a histogram shows that the data is distributed in clusters of life expectancy values, with the majority of failures clustered at the beginning of the graph, and smaller clusters popping up at various points further out along the X-axis, showing a wide range in the quality of compact disc media relative to factors that affect longevity.

This distribution of life expectancy may be the result of various construction parameters such as type and cure of sealcoat layer, paint used to print the label, presence of corrosion inhibitors in the reflector layer, thickness and purity of materials, or other physical characteristics. The results of this experiment demonstrate how differences in disc composition make it difficult to predict the lifetime of optical discs on a grand scale, or define an "average lifetime" for this type of media. There are too many variables in the manufacturing process, and formulations change over time.

The solution of the Eyring Model shown in the Acceleration Factors section resulted in an equation relating disc life to temperature and relative humidity. This equation was determined to be:

$$\mathrm{Ln(Time)} = -31.4 + 11639/\mathrm{T(Kelvin)} - 1.99(\mathrm{RH})$$

From this equation, a table may be constructed showing mean life expectancy in years as a function of temperature and relative humidity. If all of the calculated values are divided by the 776 years determined earlier for the 25 °C / 50 %RH, then the result is the ratio of the EOL at a given temperature / relative humidity compared to the EOL of 776 years at 25 °C / 50 %. Table 8 shows the calculated values for temperatures ranging from 5 °C to 30 °C, and relative humidity ranging from 30% RH to 75% RH.

Table 8: Disc Life Expectancy by Temperature (°C) and Relative Humidity relative to 25 °C / 50 % RH

°C %RH	5	7	10	15	20	21	22	23	24	25	26	27	28	29	30
30	25.50	18.91	12.18	5.97	2.99	2.62	2.29	2.00	1.75	1.54	1.35	1.19	1.04	0.92	0.81
35	23.09	17.12	11.02	5.40	2.71	2.37	2.07	1.81	1.59	1.39	1.22	1.07	0.94	0.83	0.73
40	20.90	15.50	9.98	4.89	2.45	2.14	1.88	1.64	1.44	1.26	1.11	0.97	0.85	0.75	0.66
45	18.92	14.03	9.04	4.43	2.22	1.94	1.70	1.49	1.30	1.14	1.00	0.88	0.77	0.68	0.60
50	17.13	12.70	8.18	4.01	2.01	1.76	1.54	1.35	1.18	1.00	0.91	0.80	0.70	0.62	0.54
55	15.51	11.50	7.40	3.63	1.82	1.59	1.39	1.22	1.07	0.94	0.82	0.72	0.63	0.56	0.49
60	14.04	10.41	6.70	3.28	1.65	1.44	1.26	1.10	0.97	0.85	0.74	0.65	0.57	0.51	0.44
65	12.71	9.43	6.07	2.97	1.49	1.30	1.14	1.00	0.87	0.77	0.67	0.59	0.52	0.46	0.40
70	11.51	8.53	5.49	2.69	1.35	1.18	1.03	0.90	0.79	0.69	0.61	0.54	0.47	0.41	0.36
75	10.42	7.72	4.97	2.44	1.22	1.07	0.93	0.82	0.72	0.63	0.55	0.48	0.43	0.37	0.33

*The value for 25 °C / 50 %RH is highlighted for reference.

One can use this table to see the effect on disc life resulting from a change of temperature, relative humidity, or both. Reducing the storage temperature from 25 °C to 24 °C increases the mean life expectancy by 18%. If instead the temperature remained at 25 °C but the relative humidity was reduced from 50 % to 45 %, the mean life expectancy would be increased by 14%. Reducing both the temperature to 24 °C and the relative humidity to 45 % produces a 30 % increase in mean life expectancy. Based on the data from this study, storing discs at 7 °C and 35 % relative humidity, conditions that are equivalent to the 45 °F / 35% RH standard storage vaults at the Library's National Audio Visual Conservation Center in Culpepper, VA, could produce a 17-fold increase in media life than would be expected at 25 °C and 50% RH. The information in Table 8 is displayed as a three dimensional surface plot in Figure 19.

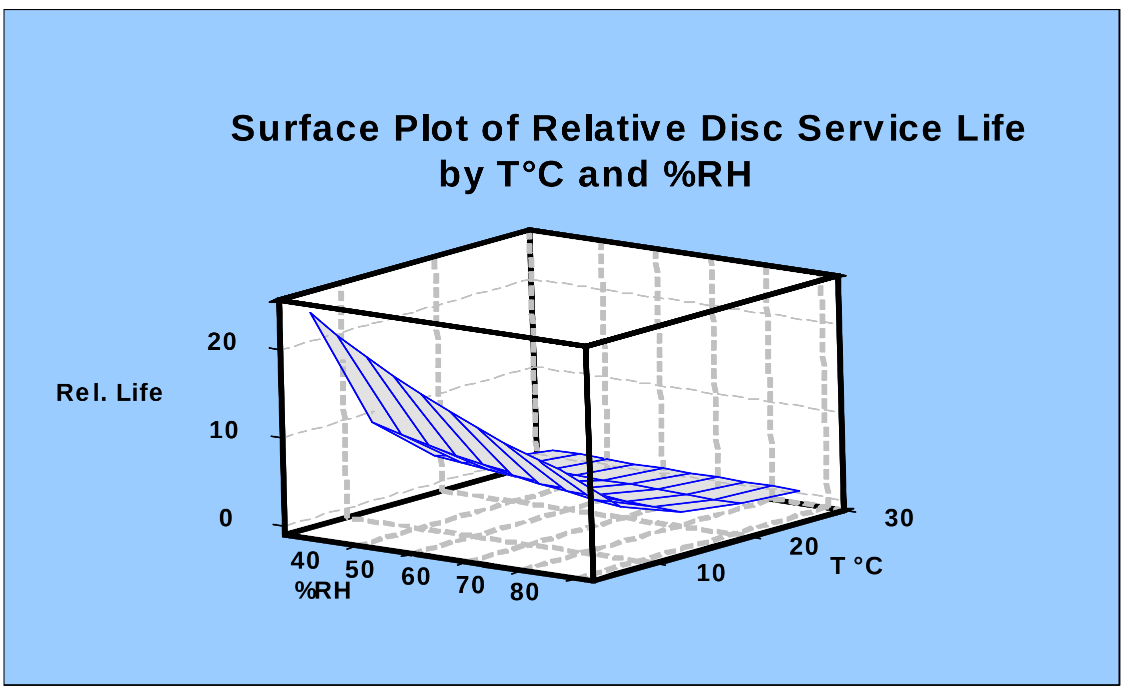

Figure 19: Surface Plot of Relative Disc Service Life by T °C and RH%

Figure 19 represents, graphically, the effect that changes in temperature and humidity can have on disc life. The axis labeled "Rel. Life" represents the increase or decrease in the estimated longevity of a disc relative to changes in the environmental storage conditions. In Table 8 the estimated lifetime of a disc stored at 25 °C / 50% RH is represented as 1.00. The mean lifetime for the disc population as a whole was calculated to be 776 years for the discs used in this study. As demonstrated in the histograms in Figures 18 and 19, that lifetime could be less than 25 years for some discs, up to 500 years for others, and even longer.

This surface plot shows how a disc with an expected life on the lower end of the scale, such as 25 years, may be able to increase that life by 25 times that initial estimate if stored at conditions of 5 °C and 30% RH. This hypothetical 25-fold increase in relative life is represented as the highest point on the plot, shown in the upper left quadrant. The modeling of the data from this study in this fashion demonstrates how the useful life of an individual disc may be extended past what might be considered its "natural" lifetime, regardless of the quality of the disc, by storing the discs under environmental conditions designed to slow the degradation rate by reducing the effect of chemical changes in the materials over time.

ISO 18925 includes a graphical representation demonstrating how the life expectancy of optical media can be extended by controlling storage conditions using different temperature-relative humidity combinations, modeled using data for a Tellurium Selenium ablative type of Worm disc. Annex A of this standard discusses how modeling life expectancy as a function of temperature and humidity, as we have done in this report, can provide data that can be used by storage vault designers to evaluate trade-offs of controlling temperature versus humidity. This type of information is important for institutions that need to balance the health of their collections against their desire to reduce energy costs and limit its impact on the environment.

Conclusion

The results of this study show that individual CD-ROM life expectancies in a large collection such as that held by the Library of Congress can be expected to cover a wide range. In addition, the BLER degradation rate of individual discs will be dependant on the environmental conditions to which the disc is exposed. Selecting optimal conditions for temperature and relative humidity in facilities where compact discs are stored can be expected to have a significant impact on service life.

Other factors not covered in this study, such as handling, labeling, and exposure to certain materials or chemicals, also affect service life and must be considered as part of a comprehensive approach to preserving digital information on compact disc media.

The test population selected for this experiment was extremely diverse; representing discs constructed using different materials, from different manufacturers and record labels. Although the selected discs covered a relatively limited period of manufacture the wide distribution of life expectancies demonstrates the effect of these varied construction parameters on disc life. 10% of the discs failed at an estimated life of less than 25 years, including 6 discs (5%) that failed too early to obtain meaningful data or a meaningful lifetime estimate. 23 discs (16%) had insufficient increase in errors during the test, and thus, had infinite lifetimes, by the standards of the ISO test method. These results illustrate why it is so difficult to make broad generalizations about the lifetime of optical media.

The Library of Congress plans to conduct analyses of the material composition of selected discs from both this study and the on-going Natural Aging Study to look for trends in failure modes as they relate to the chemistry of the disc. An understanding of these failure modes can help in identifying discs that are prone to early failure so that the data can be transferred to more stable media before they reach end-of-life.

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Attachment 1

Data

Maximum Block Error Rate per Disc per Exposure Interval

Notes:

The highest value returned by the Datarius CDCS-4.2L test system for BLER is 500. Therefore, results for BLER reported by the test equipment as 500 are not considered as the actual value of this parameter. Values of 500 shown in these tables are used to indicate that the BLER has reached a level that is out of the measurable range of the tester, and therefore were not used in any calculation.

Blank cells in this table represent discs that were un-readable by the test equipment due to some sort of catastrophic failure of the disc, and have effectively reached their end-of-life.

Data for 80°C / 85% RH Test Cell					
OrdName	**BLERmax 0 hrs**	**BLERmax 500 hrs**	**BLERmax 1000 hrs**	**BLERmax 1500 hrs**	**BLERmax 2000 hrs**
EG71C	36	ND	80	350	500
EG71D	28	ND	44	250	500
EG72C	18	ND	106	348	500
EG72D	26	ND	28	38	52
EG73C	26	ND	350	500	500
EG73D	32	ND	174	242	272
EG74C	108	ND	378	500	500
EG74D	26	ND	332	500	500
EG75C	10	ND	28	46	70
EG75D	10	ND	20	32	78
EG76C	20	ND	500	500	500
EG76D	28	ND	500	500	500
EG77C	6	ND	58	92	134
EG77D	38	ND	64	74	260
EG78C	12	ND	26	28	28
EG78D	16	ND	32	36	38
EG79C	12	ND			
EG79D	22	ND			
EG80C	20	ND	56	262	500
EG80D	26	ND	32	310	500

Data for 80°C / 70% RH Test Cell					
OrdName	BLERmax 0 hrs	BLERmax 500 hrs	BLERmax 1000 hrs	BLERmax 1500 hrs	BLERmax 2000 hrs
EG61C	16	500	500	500	500
EG61D	16	500	500	500	500
EG62C	54	54	54	56	104
EG62D	38	40	48	98	286
EG63C	124	316	500	500	500
EG63D	106	116	120	168	230
EG64C	46	500	500	500	500
EG64D	16	500	500	500	500
EG65C	20	306	500	500	500
EG65D	20	56	272	500	500
EG66C	60	28	106	500	500
EG66D	12	28	32	58	154
EG67C	24	114	158	182	500
EG67D	32	118	168	500	500
EG68C	20	500	500	500	500
EG68D	20	500	500	500	500
EG69C	16	500			
EG69D	500				
EG70C	20	20	20	42	180
EG70D	22	24	26	72	298

Data for 80°C / 55% RH Test Cell					
OrdName	**BLERmax 0 hrs**	**BLERmax 500 hrs**	**BLERmax 1000 hrs**	**BLERmax 1500 hrs**	**BLERmax 2000 hrs**
EG46C	18	20	22	22	22
EG46D	24	26	30	44	58
EG47C	12	126	196	240	500
EG47D	20	124	186	214	338
EG48C	24	100	146	160	170
EG48D	80	120	178	198	206
EG49C	30	32	30	30	30
EG49D	30	30	32	32	32
EG50C	26	184	500	500	500
EG50D	16	148	500	500	500
EG51C	10	10	12	24	500
EG51D	16	18	26	60	86
EG52C	22	26	44	174	320
EG52D	28	32	60	228	414
EG53C	10	40	60	98	134
EG53D	10	52	58	60	64
EG54C	16	14	14	14	16
EG54D	14	14	14	16	16
EG55C	24	32	362	500	500
EG55D	20	26	302	500	500
EG56C	10	132	446	500	500
EG56D	12	94	500	500	500
EG57C	12	112	238	286	308
EG57D	12	106	252	294	316
EG58C	4	22	26	26	26
EG58D	4	10	20	20	24
EG59C	18	28	30	36	38
EG59D	22	28	42	68	74
EG60C	18	42	52	58	72
EG60D	12	14	24	130	412

Data for 70°C / 85% RH Test Cell					
OrdName	BLERmax 0 hrs	BLERmax 750 hrs	BLERmax 1500 hrs	BLERmax 2250 hrs	BLERmax 3000 hrs
EG31C	26	16	358	500	500
EG31D	18	26	344	500	500
EG32C	32	500	500	500	500
EG32D	32	500	500	500	500
EG33C	10	52	144	500	500
EG33D	10	58	112	500	500
EG34C	16	32	40	54	64
EG34D	16	26	60	86	138
EG35C	44	18	44	44	46
EG35D	18	44	20	26	66
EG36C	20	32	500	500	500
EG36D	18	20	500	500	500
EG37C	4	6	12	12	14
EG37D	6	10	8	12	14
EG38C	10	18	24	32	100
EG38D	16	18	22	24	54
EG39C	6	40	106	232	116
EG39D	8	56	74	88	102
EG40C	34	104	68	398	500
EG40D	112	26	106	108	108
EG41C	14	36	62	76	84
EG41D	30	36	68	78	84
EG42C	22	50	66	76	108
EG42D	56	58	94	94	86
EG43C	12	24	338	500	500
EG43D	12	26	270	500	500
EG44C	16	62	126	216	236
EG44D	16	64	174	220	238
EG45C	28	40	28	40	68
EG45D	30	26	42		

Data for 60°C / 85% RH Test Cell					
OrdName	BLERmax 0 hrs	BLERmax 1000 hrs	BLERmax 2000 hrs	BLERmax 3000 hrs	BLERmax 4000 hrs
EG01C	16	16	16	18	18
EG01D	14	16	16	18	18
EG02C	18	18	84	240	296
EG02D	16	28	70	274	500
EG03C	8	38	52	68	114
EG03D	10	22	46	120	500
EG04C	22	20	22	22	22
EG04D	18	16	16	16	16
EG05C	16	22	74	126	138
EG05D	42	26	92	178	200
EG06C	18	30	44	50	54
EG06D	24	34	46	50	50
EG07C	6	26	26	26	28
EG07D	14	16	26	32	32
EG08C	22	22	42	236	500
EG08D	12	12	32	266	500
EG09C	34	38	170	500	500
EG09D	34	34	86	310	500
EG10C	14	80	292	500	500
EG10D	16	60	280	500	500
EG11C	18	18	18	36	36
EG11D	18	18	18	18	18
EG12C	12	20	24	26	30
EG12D	12	18	28	32	36
EG13C	16	18	50	108	128
EG13D	58	24	48	84	94
EG14C	10	14	18	22	26
EG14D	8	16	18	18	28
EG15C	6	6	6	8	8
EG15D	12	14	14	14	14
EG16C	22	24	22	22	54
EG16D	32	34	32	40	82
EG17C	34	34	34	34	32
EG17D	16	24	24	26	28
EG18C	16	18	16	16	16
EG18D	56	52	38	62	54
EG19C	24	20	22	26	30
EG19D	26	26	36	66	100
EG20C	12	14	16	40	70
EG20D	12	12	60	44	70
EG21C	20	26	90	152	178
EG21D	18	24	72	120	142
EG22C	18	20	18	28	18
EG22D	16	18	18	18	16
EG23C	40	28	28	52	80
EG23D	10	52	54	60	84
EG24C	16	18	46	134	184

EG24D	14	14	44	80	98
EG25C	8	30	62	80	112
EG25D	8	28	46	46	64
EG26C	40	32	26	40	40
EG26D	68	68	68	70	68
EG27C	14	24	80	108	114
EG27D	12	22	84	132	146
EG28C	28	20	60	110	168
EG28D	8	14	28	54	76
EG29C	26	30	30	58	500
EG29D	62	64	62	108	500
EG30C	38	44	72	146	220
EG30D	78	80	78	80	500

Attachment 2

Normalized End-of-Life (years) Estimates for Each Disc

Notes:

Discs that exceeded BLER max too early in testing to determine a meaningful life estimate are designated as left censored. Such discs had very short lifetimes. Discs that did not show sufficient change in BLER max during the course of testing to determine a meaningful life estimate are designated as right censored. Such discs had very long lifetimes.

Disc ID	Years to EOL
1C	Right Censored
2C	38
3C	127
4C	Right Censored
5C	85
6C	318
7C	705
8C	43
9C	40
10C	21
11C	542
12C	718
13C	94
14C	761
15C	Right Censored
16C	463
17C	Right Censored
18C	Right Censored
19C	Right Censored
20C	212
21C	66
22C	Right Censored
23C	251
24C	65
25C	119
26C	Right Censored
27C	105
28C	75
29C	293
30C	57
31C	31
32C	Left Censored
33C	82
34C	453
35C	1537
36C	437
37C	2177
38C	284
39C	136
40C	46
41C	300
42C	262
43C	33
44C	90
45C	629
46C	5592
47C	76
48C	154

Disc ID	Years to EOL
1D	Right Censored
2D	36
3D	86
4D	Right Censored
5D	55
6D	418
7D	574
8D	39
9D	31
10D	22
11D	Right Censored
12D	486
13D	178
14D	732
15D	Right Censored
16D	257
17D	1138
18D	Right Censored
19D	150
20D	204
21D	85
22D	Right Censored
23D	195
24D	128
25D	236
26D	Right Censored
27D	80
28D	175
29D	168
30D	Right Censored
31D	32
32D	Left Censored
33D	108
34D	176
35D	678
36D	2646
37D	3115
38D	652
39D	252
40D	Right Censored
41D	332
42D	448
43D	42
44D	89
45D	830
46D	631
47D	76
48D	117

49C	Right Censored
50C	34
51C	1321
52C	74
53C	190
54C	Right Censored
55C	32
56C	27
57C	75
58C	1246
59C	1165
60C	451
61C	105
62C	106
63C	63
64C	44
65C	760
66C	Left Censored
67C	358
68C	2630
69C	Left Censored
70C	147

49D	Right Censored
50D	43
51D	310
52D	55
53D	501
54D	Right Censored
55D	39
56D	70
57D	72
58D	1196
59D	381
60D	63
61D	157
62D	1658
63D	160
64D	67
65D	729
66D	Left Censored
67D	205
68D	1902
69D	Left Censored
70D	125