Compact Disc Service Life Studies by the Library of Congress

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Abstract

This paper reports on research studies conducted by the Library of Congress (LC) on the factors affecting the service life of compact discs.

A natural aging pilot study was initiated in 1996 as part of a plan to formulate a strategy to preserve the Library's growing collection of music on CD by periodic monitoring of the condition of the discs. After 10 years of testing the original sample set of 125 discs at selected intervals the study was expanded to include 1050 more discs to achieve a more representative sampling of the Library's collection to date. Sampling, testing, storage, and data analysis for both studies are discussed.

Two accelerated aging studies were conducted to explore the mechanisms of optical disc degradation. The first study used a single stress condition to evaluate the effect of security labels on CDs. The second study used multiple elevated stress conditions to observe the differences in disc failure rates in a heterogeneous population, and to evaluate the effect of laser engraving a property stamp on the disc. The initial Block Error Rate (BLER) and its rate of change was used as the indicator of service life, with the value of 220 per second signaling the end-of-life. Observations of physical degradation on both a macro and micro scale and their effect on disc life are included.

Aluminum oxidation is widely considered to be the primary cause of disc deterioration. Results of the accelerated aging studies suggest that several factors are at work. Initial work to correlate life expectancy with chemical composition is described.

Introduction

The compact disc was introduced in the 1980s as a new storage medium for audio and other digital data. By the mid 1990s the collection of music on CD-DA (Compact Disc-Digital Audio) held at the Library of Congress had grown to approximately 60,000 discs and is now estimated to be over 219,000 items. It is the responsibility of the Library to preserve these collections and ensure that the discs remain in a usable state. To this end the Preservation Research and Testing Division has been conducting studies to determine the reasonable life expectancy (LE) of optical media, the mechanisms of disc deterioration, and to quantify methods of optimum preservation and protection of the Library's holdings. Results from these studies will be used to establish optimal environmental storage conditions, and to develop a non-destructive method of determining the condition of a disc that can be used to help prioritize the duplication of the collection by transferring the data on vulnerable discs to a more stable media.

LC Research Studies on Optical Media

In 1990 the Library's Information Technology Division prepared an internal report summarizing its research into the longevity of Write Once Read Many (WORM) optical discs. The report described the results of an experiment to investigate test methods that could be used to determine the stability of the digital data written on the disc. The project also considered how to tabulate and analyze the test results, and the feasibility of applying the Arrhenius equation to the data from accelerated aging to make estimates of optical disc longevity. The study was intended to explore the effects of aging on the life of the discs, the effects of physical wear and handling, and the error correction capabilities of drives used to retrieve the data. Although the number of test specimens was small the results were consistent with published literature that proposed a reasonable expectation of disc life of a 100 years or more, under optimal conditions.

This initial study served as the impetus to continue to investigate test methods, instruments, and the use of accelerated aging to evaluate the potential life expectancy of other digital optical media as new technologies were introduced into the market and became part of the Library's collection. In 1996, research began on CD-ROM media from the Library's CD-DA collection with a pilot scale natural aging study, followed by two accelerated aging studies. Analysis of the data from these studies, as well as macro and microscopic observations of degraded discs, suggested that several modes of data loss exist. Corollary investigations into the use of non-destructive methods of chemical analysis to characterize the modes of failure are in progress.

For the purposes of these studies CD-DA and CD-ROM are considered to be equivalent with respect to degradation mechanisms and acceleration rates.

Natural Aging Studies

The only true estimate of service life is made by exposing a sample to actual usage conditions and monitoring the time to failure for each specimen. The effects of temperature, relative humidity, labeling, and handling may then be evaluated in a combined set of stresses with the cumulative effect taken into full account. Unfortunately, for a product with a long life expectancy, this process may consume many years without producing final and conclusive results. Accelerated aging studies offer the advantage of providing faster results, but are limited to general estimations of predicted behavior by extrapolating the LE at elevated temperature stress to natural conditions. The Library of Congress is conducting investigations into CD service life using both approaches.

A small scale natural aging pilot study was initiated in 1996 to assess the feasibility of using periodic testing to monitor the long-term effects of real-life storage and use conditions on disc service life. At the time the pilot study began, the CD-DA population at the Library was approximately 60,000 discs. A sample of 125 randomly chosen specimens was selected for study.

Testing of the discs was performed on a CD-CATS/SA3 disc tester which measures and reports static, dynamic and optical characteristics of the disc. The tester was designed specifically for CDs according to the Philips Red/Green/Orange book standards, and ISO 9660 [1]. The tester reports on 25 parameters according to the physical specifications defined by ISO 10149 [2]. BLER (Block Error Rate), E32 errors, and jitter are widely recognized as parameters that indicate disc quality and operability. BLER is the parameter most often used to assess the condition of the disc as it represents the combined effects of all factors affecting disc readability, and is the most sensitive to disc degradation [3].

The ISO/IEC 10149 standard for CD-ROM defines end-of-life (EOL) as the loss of any information, and sets a maximum level of BLER at 220 as the onset of unacceptable errors that signal the end of disc life. E32 errors indicate localized uncorrectable errors and data loss [4], and may exist in the absence of high BLER [5]. Burst errors represent sustained consecutive errors commonly associated with physical damage such as scratches or surface contamination [4]. Other out-of-spec parameters such as radial noise, push-pull, and reflectivity may not signal end-of-life, but can adversely affect audio quality.

Baseline testing of the discs was completed in January 1997. Testing was repeated in 3-year intervals. The storage of the discs between test intervals was the same as normal collection storage and subject to the same probability of playing and handling as other members of the collection.

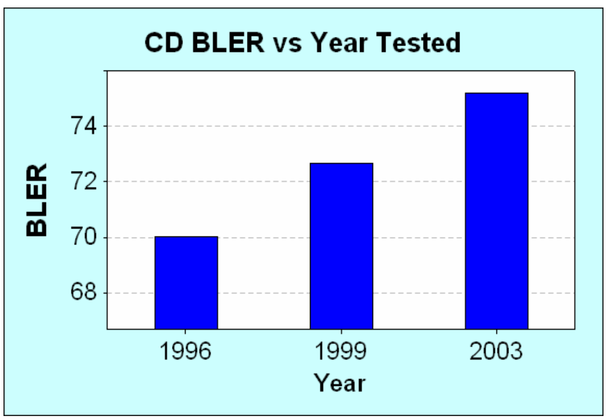

***Figure 1**: Average BLER versus year measured*

The change for BLER for most of the discs studied to date is about 10 points or less. Eight discs showed much larger increases in BLER, pushing one disc above the 220 limit. Four of these discs had BLER above 220 at the start of the study [6], and continued to accumulate errors at a faster rate than the other discs. The large increase in BLER for the remaining three discs is related to physical damage to the read side of the disc, which is also indicated by the presence of high E32 and Burst errors.

The average upward drift in BLER for the discs in this study confirms that errors continue to accumulate over time, but at different rates depending on the quality of manufacture, or due to damage acquired during handling. Figure 1 shows graphically the average BLER for each test interval to date in the pilot natural aging study [6].

Three of the discs that developed high BLER before the start of the study showed 'pin-hole' defects in the reflective layer where light can be seen through the disc. Several other discs had small numbers of these defects, but not enough to create a significant number of errors. Figure 2 shows an example of one of the larger holes in relation to the data pits. Although these three discs have high BLER and holes in the reflector they are still playable. The fact that these discs can still be played, despite the large number of data pits obliterated by these holes, demonstrates the robustness of the Reed-Solomon error correction. Defects of this type would be much more significant on a data disc, but the effect on the playback of the audio signal may not be readily apparent. We plan to evaluate the effect of these defects, and other out-of-spec parameters, on the audio using a newly acquired Prism Sound Scope dSeries audio analyzer.

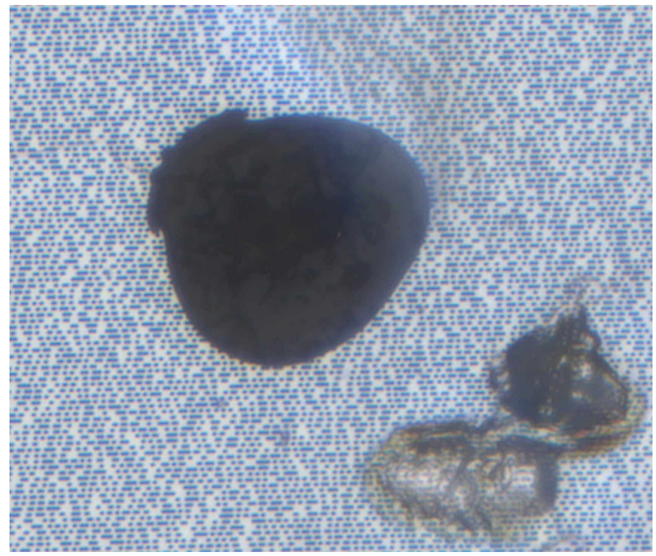

***Figure 2:** Photomicrograph of a 'pin-hole' defect in the reflector among data pits*

Accelerated Aging Studies

In 1999 an accelerated aging study was conducted to study the effect of security devices designed for application to CDs in library collections. The devices consisted of a clear polyester film circle slightly smaller than the diameter of the disc laminated with a pressure-sensitive adhesive and two magnetic metal strips that activate an alarm when passed through security gates at the exits of library buildings. A set of 37 pairs of discarded extra copies of CD-Audio discs were selected for this study. The security label was applied to one disc of each pair of discs.

The discs were exposed to conditions of 80°C and 60% RH in an environmental chamber and tested at intervals of 350, 500, 750, and 1000 hours. During the course of this study various cleaning techniques were employed to remove filmy deposits on the read surface of the discs caused by volatilizing degradation products in the chambers. A significant drop in BLER between 750 and 1000 hours exposure was observed after making a change in the solution used for cleaning the discs. For this reason it was not possible to plot the change in BLER against the hours of exposure to the accelerated stress conditions. Anomalies were also seen in the data for some discs in the pilot Natural Aging study that were also attributed to the lack of a defined cleaning procedure. Our experience in both studies points up the need for specifying this important step in test methods for optical discs.

Although we must consider the data gathered from the earlier intervals suspect, we were able to use the data at 1000 hours to compare the changes in BLER, Burst, and E32 from the baseline between the labeled and un-labeled discs. Data from discs that showed damage from handling or other unexplained anomalies in the measurements from the testers were discarded, leaving a sample set of 31 pairs for comparison. In 20 sets the labeled discs showed a significantly higher increase in BLER compared to its un-labeled mate. The remaining pairs showed equivalent increases in BLER for both discs. Five of the labeled discs had large bubbles on the read surface of the discs. These defects in the polycarbonate substrate may be due to degradation of the disc, or may have been caused by water droplets striking the disc as it lay on a horizontal axis in the test chamber. If we remove these discs from the calculations the increases in BLER for the labeled discs are still twice that of the un-labeled discs. This trend holds true for both 'good' and 'bad' discs. In pairs where both discs suffered catastrophic failure the labeled discs had higher rates of errors than its un-labeled counterpart. As a result of the data derived from this study the Library rejected the use of such devices on CDs in the collection.

Figure 3: *Delamination of the reflector after thermal cycling*

A second study conducted in 1999 used thermal cycling to examine the effects of rapid shifts in temperature, such as might occur to CDs kept in an automobile when rapidly warmed by the heater after sitting in the cold during the winter. Figure 3 shows a disc from this study on which the reflector delaminated from the polycarbonate substrate. The mechanism for this failure is the result of differences in the thermal and hygroscopic expansion of the polycarbonate substrate and the aluminum reflector layer as the discs cycled through the elevated conditions. The stress caused by these differences has resulted in adhesion failure between the reflector and substrate [7]. Although this is an extreme case from this study, other discs showed various degrees of flaking of the metal layer on the surface of the disc. This study also demonstrates the importance of allowing discs to equilibrate to conditions slowly when moved in and out of cold storage vaults.

In 2001the Library began work on an accelerated aging study modeled after the ANSI/NAPM IT9.21 [8] standard for estimating the service life of compact discs (now ISO 18921:2002). The standard calls for five groups of discs to be aged at five different conditions, for different lengths of exposure at each condition. This method permits extrapolation of the EOL data obtained at accelerated conditions to estimate a real-time service life for the disc. Aging conducted at a single stress, as in the security label experiment, is best used only for comparative studies to achieve relative ranking of stability [9].

In this study the discs were tested for BLER and other parameters at baseline, and then after each of four incubation periods. The discs were exposed to three temperatures, 60, 70, and 80°C, all at 85% RH, and 80°C at 55% and 70% RH. To compensate for the decreased change expected at the lower temperatures, the number of CDs per stress and the incubation interval were both increased [3]. Table 1 summarizes the stress levels, sample distribution, and incubations intervals.

Table 1: Summary of accelerated aging conditions

Test Condition T °C/ %RH	No. of CDs	Incubation Time (Hours)	Total Time (Hours)
80 / 85	10	500	2000
80 / 70	10	500	2000
80 / 55	10	500	2000
70 / 85	15	750	3000
60 / 85	30	1000	4000

Aside from the use of multiple stress conditions this experiment built upon the previous studies in several important ways. The ANSI and ISO test methods employ a standardized ramp sequence to allow for equilibration of moisture absorbed by the disc at the stress incubation temperature. The ramp-down profile is based on the diffusion coefficient of water in polycarbonate. If the disc is not allowed to equilibrate water droplets can form within the substrate or at the substrate/reflector interface. Moisture gradients within the substrate can cause expansion gradients that result in severe disc deflection [7]. To prevent water droplets caused by condensation inside the chamber from falling on the surface of the discs, and to maximize the number of discs in the chamber, the discs were aged vertically rather than horizontally. Finally, the cleaning procedure was defined at the start and used consistently throughout the experiment. The discs were cleaned at the start of the experiment, and after every incubation period before testing.

For this project we used the Datarius CDCS-4.2L Compact Disc Quality Control with CDCS-40T Compact Disc Optitest System. Discs were tested according to the Datarius Basic Sequence using Redbook standard parameters for CD-DA. All disc test parameters were recorded and considered for possible cause of mortality. The mean BLER of 220 / sec was again used as the primary signal for EOL.

As before, discarded replicate discs were used in this experiment. A set of 80 discs were selected to meet the distribution requirements specified in the standard. A duplicate of each disc was included in the experiment to evaluate the effect of a proposed strategy to enhance the security of collection CDs by the application of a laser-engraved Library of Congress property mark. One disc of each pair was so engraved on the inner hub within the stacking ring. The objective of this twin set was to compare the life expectancy estimates of the laser engraved and non-engraved specimens.

The time to reach a BLER of 220 / sec was measured by interpolation or extrapolation of the values obtained at the end of each incubation interval. The values obtained were used to determine a lognormal distribution of EOL at each stress condition.

The logmean for discs within each test condition were then fit to the reduced Eyring equation [3],

Time to End of Life = $Ae^{\Delta H/k(T)}e^{B(RH)}$
(1)

and the logmean estimated at the standardized life expectancy condition of 25°C / 50% RH.

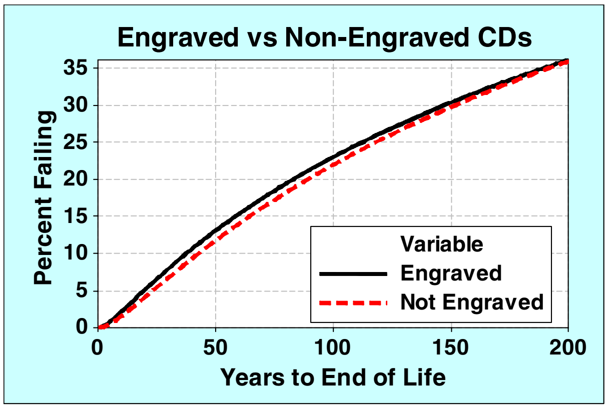

Figure 4: *Cumulative Failure Plot of engraved and non- engraved discs*

Figure 4 shows a cumulative failure plot for both the engraved and non-engraved specimens following the accelerated aging studies. The estimated service life results indicate that there is no significant difference in estimated life and the engraving had no effect on disc life [10].

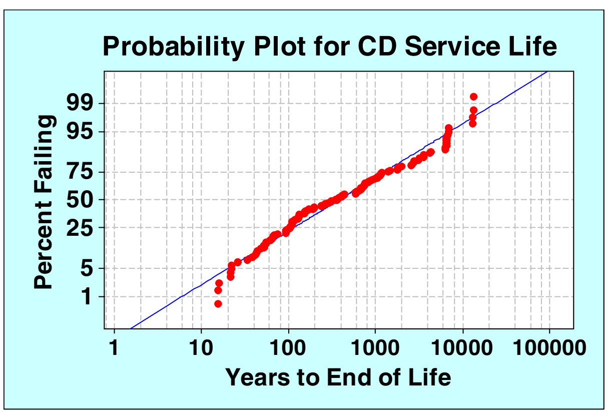

Figure 5*:* *Lognormal Probability Plot for combined discs*

As there was no significant difference detected, the two sets of estimated service life data were combined for the purpose of statistical analysis. Figure 5 shows the results of the engraved and un-engraved discs combined into one data set and estimated EOL for 25°C / 50% RH . The plot shows a wide distribution of service life estimates, which demonstrates the effect of differences in disc quality and the difficulty in making broad generalizations on the longevity of optical media [11]. The Eyring equation relates service life to both temperature and relative humidity allowing one to see the effect, quantitatively, of both variables individually. This data can then be used to determine optimal storage conditions to achieve the longest possible life, and make decisions based on the cost of adjusting each variable separately. The custodians can then relate the cost of controlling temperature and relative humidity to the effect on the life expectancy of the discs in their collection.

During the course of this study we observed a variety of different physical manifestations of degradation on the discs. A number of discs developed spots of varying size and color in the polycarbonate substrate, as shown in Figure 6. These spots occurred on the read surface, within the substrate, and at the reflector/substrate interface. Analysis of these areas by Fourier Transform Infra-red spectrophotometry characterized them as bispehnol A (BPA). Contaminants in the polycarbonate react with moisture in air to initiate the hydrolytic degradation of polycarbonate into bisphenol A. As moisture diffuses through the substrate the phenolic degradation products will absorb the water, leading to autocatalytic degradation by converting surrounding areas of polycarbonate into bisphenol A [12]. As the bisphenol A recrystallizes the volume increases from the added water and disrupts the substrate, creating defects in the substrate that interfere with the laser and increase birefringence.

Figure 6: *Spots on CD representing degradation of polycarbonate*

Some discs developed tiny fissures at all levels within the substrate, giving a cloudy appearance to the disc. Any change in the polycarbonate that affects the ability of the read laser to focus on the data pits will be read as an error. The more defects in the polycarbonate, the higher the BLER. Surface presentations of discs with multiple tiny fissures show high BLER across the disc.

The reflective layer is also subject to degradation, as we observed in the CDs with the tiny pin-holes. As some forms of aluminum oxide are transparent [13], these holes are evidence of oxidation of the reflector caused by atmospheric moisture penetrating the seal-coat on the label side of the disc [9]. An extreme example of this effect was seen in disc 69D. The reflector layer has become transparent across the entire surface of the disc. Figure 7 compares discs 69C and 69D, which appeared to be identical, after 500 hours of accelerated aging at 80°C, 70% RH. There is clearly something different about these two discs that has allowed the reflector to oxidize completely. The only areas in which the reflector is still visible are those covered by the black printing. The black paint in these areas has created a barrier that has protected the reflector, indicating that the clear seal-coat is the determining factor in this case of deterioration.

***Figure 7**: Discs 69C and 69D after 500 hours accelerated aging*

Research in Progress

There are two research projects regarding Compact Disc Service Life currently being conducted at the Library of Congress. The first project is a large scale natural aging study. The second project involves the chemical analysis of discs to look for causes of degradation and disc failure.

Expansion of Natural Aging Study

The results, observations, and experience gained from the first natural aging study have laid the foundation for the expanded natural aging study that began in 2006. For this research, 1050 discs were selected from the Library's collection using a random number generator to choose the specimens. The beginning of life dates range from 1985 to 2005. Of the 978 that have been baseline tested to date, 345 have already aged 10 years or more. Five of the specimens over 10 years old have already shown levels of BLER, E32, or Burst errors that lead to disc failure. One disc is approaching the EOL indicator for BLER, with a BLER of 200. The discs will be stored at the Library's National Audio-Visual Conservation Center in Culpepper, VA. The test interval is yet to be determined. To make the maximum use of resources as well as improve accuracy of End of Life, a progressive test frequency is under consideration. In this scenario, the time interval between tests would decrease as the disc approaches BLER indicating approaching EOL.

Chemical Analysis

A histogram of the EOL data from the second accelerated aging study, Figure 8, shows the distribution of disc life expectancy using a subset of the overall data. What we see in this histogram is not the expected smooth and continuous data but rather indications of discrete distribution clusters along the X axis.

These clusters of EOL 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. These differences in disc composition are the reason that it is not possible to predict the lifetime of optical discs on a grand scale. There are too many variables in the manufacturing process, and formulations change over time.

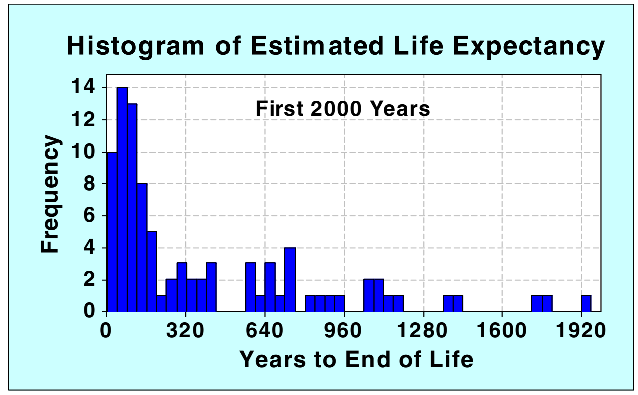

***Figure 8:** Histogram of the Estimated Service Life of CDs*

The Library plans to conduct chemical analyses of the discs used in the natural and accelerated aging studies. The analytical methods to be explored are expected to be non-destructive, such as FTIR and XRF, to show the organic and inorganic components within the disc. If a strong correlation between chemical composition and disc life can be shown it may be possible to use non-destructive analyses as predictors of degradation rates. This information, combined with test information such as BLER, would then allow an estimate of remaining life for each disc and permit prioritization of transfer.

Chemical analysis of selected discs from the natural and accelerated aging studies has provided some initial clues to early disc failure. During the course of our studies there have been stories in the media about a phenomenon referred to as CD-Rot. CD-Rot is an inexact term that applies to three different types of disc degradation most commonly referred to as 'pin-holes', 'edge-rot', and 'bronzing' [14, 15, 16].

Several discs were obtained from collectors who had noticed these defects in their audio CDs to compare with the types of defects observed in the LC studies. FTIR analysis of discs exhibiting pin-hole defects, from both the LC natural aging studies and the collectors, showed that the common factor is the use of a nitrocellulose seal-coat. Nitrocellulose lacquers were used as a clear seal-coat on discs up until the mid 1990s. Acrylic lacquers were also used during this period, and remain in use today. The nitrocellulose coatings are not an effective barrier against moisture, making them more susceptible to degradation and to diffusion of atmospheric moisture into the reflector, leading to oxidation of the metal.

Three of the discs from the first natural aging study with BLER above 220, and all four of those from the second natural aging study, have nitrocellulose coatings. However, a nitrocellulose coating is not necessarily a death sentence for a disc. All discs from the first natural aging study that have a clear seal-coat with minimal printed information on the label side were analyzed by FTIR. Out of a total of 76 discs 22 have the nitrocellulose coating, but only 3 reached EOL as defined by BLER. The high BLER for these discs is related to multiple clustered pin-holes in one or more areas of the disc.

One of the discs from the second natural aging study to have reached EOL exhibited 'bronzing' of the reflector. This disc also has a nitrocellulose seal-coat, but in this case the degradation is primarily related to the reflector. The reflector was identified by

XRF as silver. The silver reflectors are prone to oxidation and tarnishing, particularly when combined with the nitrocellulose coating. Atmospheric sulfur, or sulfur released by the housing or paper insert accompanying the CD, penetrates the seal-coat and attacks the silver reflector. This phenomenon has been tied to one pressing plant, Phillips PDO in Blackburn, Lancashire [17], and indeed, this disc is stamped "Made in U.K. by PDO".

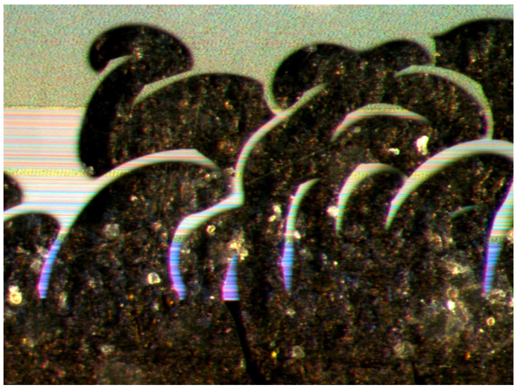

***Figure 9**: Deterioration of reflector characteristic of 'Edge-rot'*

No discs exhibiting the 'edge-rot' observed by some collectors have been seen in any of the LC studies so far. Examination of the discs obtained from collectors shows a creeping transparency of the reflector from the edge of the disc inward, having a scalloped appearance, as shown in Figure 9. This type of degradation does not appear to be related to the type of seal-coat, as two of the most severely affected discs have acrylic coatings, with the rest identified as nitrocellulose. These defects appear to be mostly related to physical damage at the edges of the discs that has compromised the integrity of the seal-coat, either from scratches on the surface on the label side, or nicks in the edge. Early discs did not have the seal-coat applied around the edge of the disc, and these may be most vulnerable to this type of damage.

More detailed reports on the individual studies discussed in this paper, and the results of future investigations as they become available, can be found on the Library of Congress web site.

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Biography

Nels Olson received his PhD in analytical chemistry from the University of Washington, (1997). Since then he has been Senior Staff Scientist at Molecular Dynamics and Illumina. He is currently the Chief of the Preservation Research and Testing Division in the Library of Congress, where his specialty is the management of multi disciplinary teams of scientists, conservators, engineers, and preservation specialists dedicated to research in the area of preservation for the Library's diverse collections.

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