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CHARACTERIZING OPTICAL DISC LONGEVITY AT THE LIBRARY OF CONGRESS

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ABSTRACT

Because they are not subject to the same physical wear and tear during playback as other recorded media, optical discs at one time had a strong appeal for preservation-conscious institutions. Additionally, considerable "born digital" material is created by people authoring their own CDs and DVDs. However, optical media may be as vulnerable as (if not more than) traditional media. We have been engaged in ongoing research into the longevity of optical discs, including CD-ROM, audio CD, CD-R, and DVD formats. We report the results of studies focused on the effects of adhesive labeling and laser engraving on discs. In addition, we describe accelerated aging studies performed in collaboration with the National Institute of Standards and Technology, Washington, D.C. While almost all discs showed predicted longevity greater than five years, our results indicate that most CD products tested showed a high probability of prolonged lifetime relative to their DVD counterparts.

INTRODUCTION

The Packard Campus of the Library of Congress, Washington, D.C., is home to the National Audio-Visual Conservation Center, where more than 4 million moving image and recorded sound collection pieces are housed. A growing portion of that collection consists of optical discs. Optical storage media once had a strong appeal for preservation-conscious institutions because of their inferred stability, as they are not subject to the same physical wear and tear that degrades other recorded media, as the reading mechanism does not require contact with the object for playback or readout. Thus, the Library of Congress has long been committed to understanding the longevity of optical storage media, especially as more collection

data arrive on discs. Initial studies focused on the service life of CD-ROMs, when the Library's Motion Picture, Broadcast, and Recorded Sound division began collecting music published in the CD format. As an increasing number of authors and independent musicians began to use recordable CD and DVD media to submit their work to the Library for copyright or collection, the research program was expanded to include CD-R, DVD+R, and DVD+RW formats. Optical media require specific storage and handling conditions to minimize degradation and data contained on optical discs are machine-dependent. Thus, it is important for the Library of Congress, as curators of these materials, to understand how and why they degrade, and how to better provide access long-term.

OVERVIEW OF DISC FORMATS AND EVALUATION OF STABILITY

The current diverse arrays of optical media formats are all variations of the original basic CD-ROM discs. CD-ROMs have a layered structure: at the bottom is a poly-

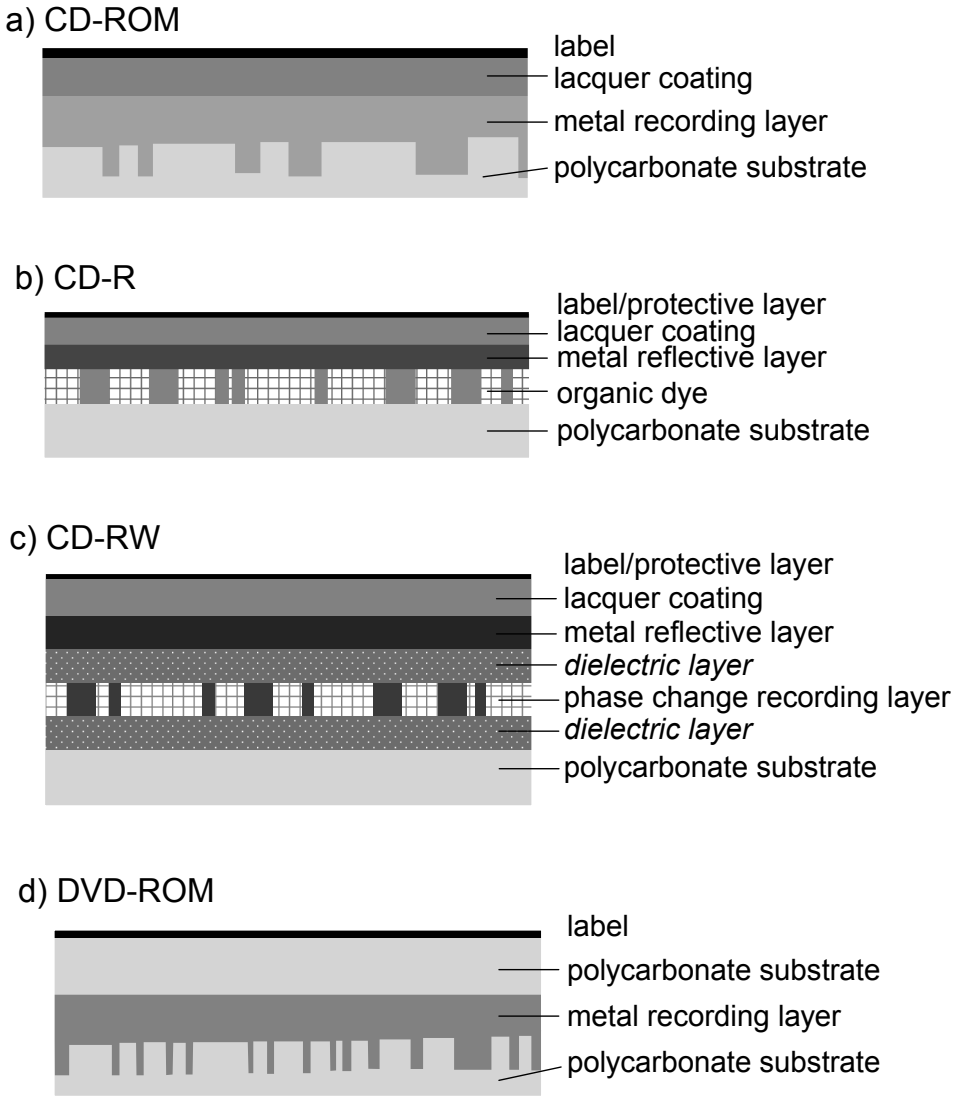

Fig. 1. Simplified cross-sectional structures of four types of optical media: CD-ROM, CD-R, CD-RW, and DVD-ROM. Based on descriptions from Hartke, 2005.

carbonate substrate, followed by a metal reflective layer, and a protective lacquer coating (fig. 1a). Most often there is another layer over the protective coating, either an additional protective coating or a printable surface where disc information is printed using some type of ink. This top layer is often referred to as a label, and the top surface as the label side. The polycarbonate substrate is referred to as the read side (Byers 2003).

CD-ROMs are a form of "read only" memory; the discs are factory-pressed when manufactured. The data is written to the disc by molding pits into the polycarbonate substrate. The metal reflective layer is applied directly over the pits, molding into the shape of the pits on the surface. When the disc is read by a laser, light is either reflected or scattered off the reflective layer, depending on the presence of a pit or a land. As the light moves from a pit to a land (or vice versa), the transition from reflection to scattering is read as a "one." The distance between these transitions is read as a series of zeroes, the number of zeroes determined by the length of the pit or land, generating the series of ones and zeros that together provide digital information (Buddine and Young 1987). The pits and lands are generally referred to as the data layer. In the case of ROM discs, the metal layer is integrated with the pits and lands and is sometimes referred to as the reflective data layer. This type of format has been used mainly for large-volume duplication, such as music CDs or software distribution. The information contained on a CD-ROM cannot be changed, thus its "read only" designation.

CD-Rs, on the other hand, use a photosensitive organic dye as the data layer. There are three organic dyes that are most commonly used for this data layer: cyanine, azo, and phthalocyanine (fig. 1b) (Byers 2003). Information is written onto CD-Rs by the user, in a pattern that replicates the pit and land structure in CD-ROM, via a high-power writing laser that causes a permanent change in the optical properties of the organic dye layer. Once data is burned onto the disc, it cannot be changed; hence its designation as a "write once, read many" medium. A lower-power reading laser reads the information off the disc without affecting the dye.

CD-RW disc structure contains a phase-changing metal-alloy film sandwiched between two dielectric layers as the data layer (fig. 1c). The metal-alloy film recording layer undergoes a phase change while being written, making RW a "write many, read many" medium; the information burned onto the disc can be erased and re-written multiple times. Because the data layer and the metallic reflector on all CD formats are protected by only a few thin layers of coatings, damage to the top label side of the disc is more serious than damage to the bottom polycarbonate substrate read side.

DVD formats are similar to CD formats ROM, -R, and -RW, but includes two additional formats, the +R and +RW, though there are some key differences in disc structure between the two. The pits and lands on a DVD that contain the digital information are much smaller than the size of the pits and lands on a CD, and more closely spaced together (figs. 1d, 2). The width of the pit on a CD is 0.5 μm, compared to 0.35 μm on a DVD (Hartke 2005). Pit length on a CD ranges from a minimum of 0.83 μm to a maximum of 3.6 μm, compared to 0.4–2.0 μm for DVD (Buddine and Young 1987). Unlike CD formats, the data layer and the metallic reflector in DVD formats sit in the center of the disc, sandwiched between two thin layers of polycarbonate. For this reason, damage to the label side is no more serious than damage to the read side of a DVD. DVD-ROM discs can also accommodate two-sided data storage, meaning they can be read from both sides. In this structure there is no lacquer layer or printing applied to either side of the disc.

There is certainly diversity in the compositions of recording layers, materials and methods of manufacture, etc. However, while each type of optical disc may have its own intrinsic and unique longevity issues, there are some basic ways to evaluate optical disc stability, and make

some predictions about their service lifetime. The most common measure of disc failure for CDs is BLER, or the Block Error Rate. BLER represents frame error, and a frame is simply the smallest integral data package on a disc, containing 24 bytes of data. To put this in perspective, if a disc on your shelf holds 700 megabytes (MB) of data, there are more than 30 million frames on that disc. BLER measures the rate of bad frames that contain one or more read errors. When a CD is played, the data on that disc are read at a rate of 7350 frames per second. If 1% of the frames contain errors, then BLER will be 73.5 per second. The ISO/IEC standard 10149:1995: Information Technology—Data Interchange on Read-Only 120 mm Optical Data Disks (CD-ROM) specifies a frame error rate less than 3%, or a 1x BLER of 220 per second. Standard test methods for estimating the longevity of CD media, such as ISO (2002a) for CD-ROM, use a limit of 220 per second for BLER as the endpoint for defining "end-of-life" (EOL). This doesn't necessarily mean that a disc will not play. It is simply a standardized way of evaluating the quality of a CD, using BLER > 220 to signal the approach of the onset of uncorrectable

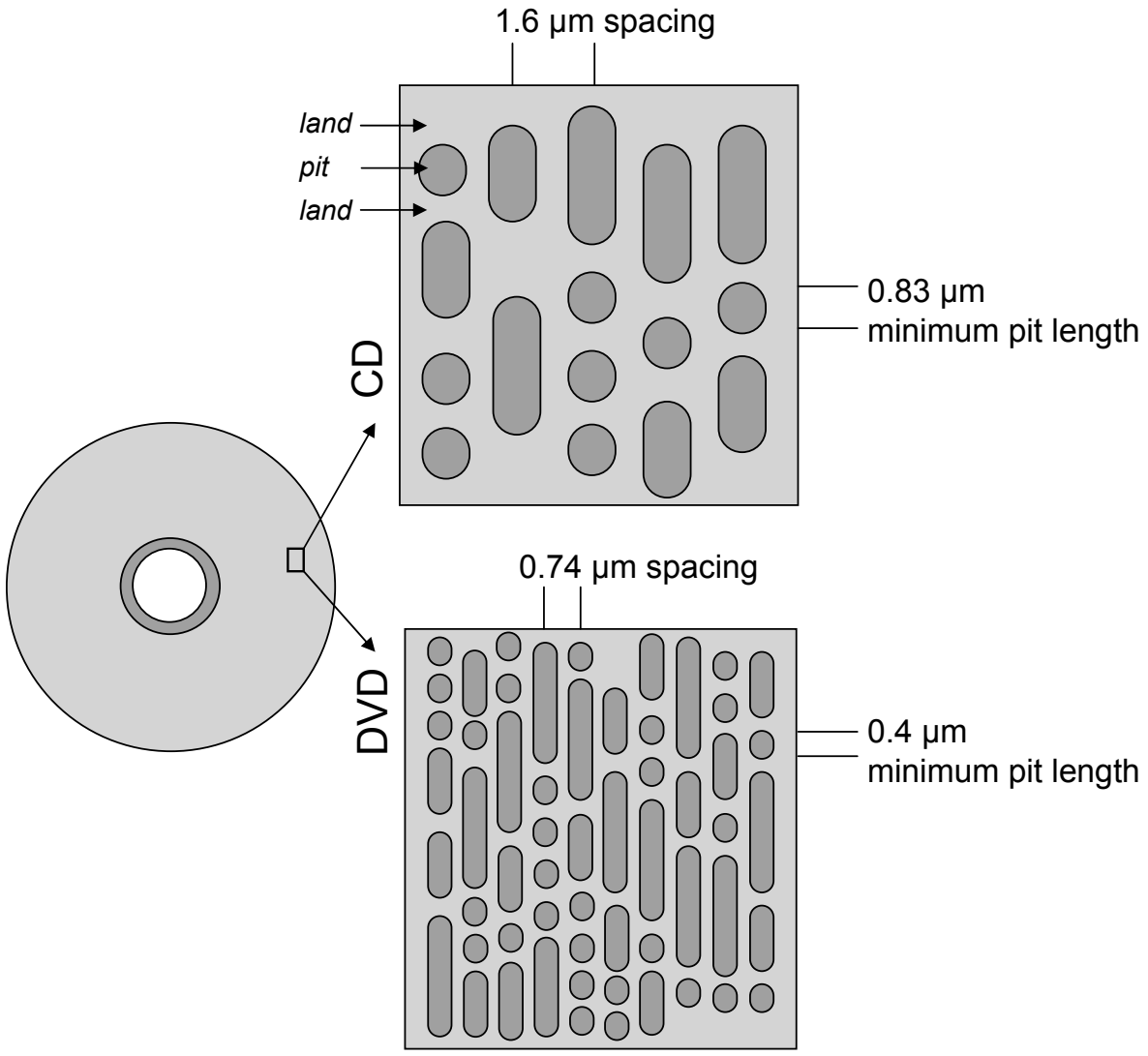

Fig. 2. A comparison of data pit spacing on CDs and DVDs.

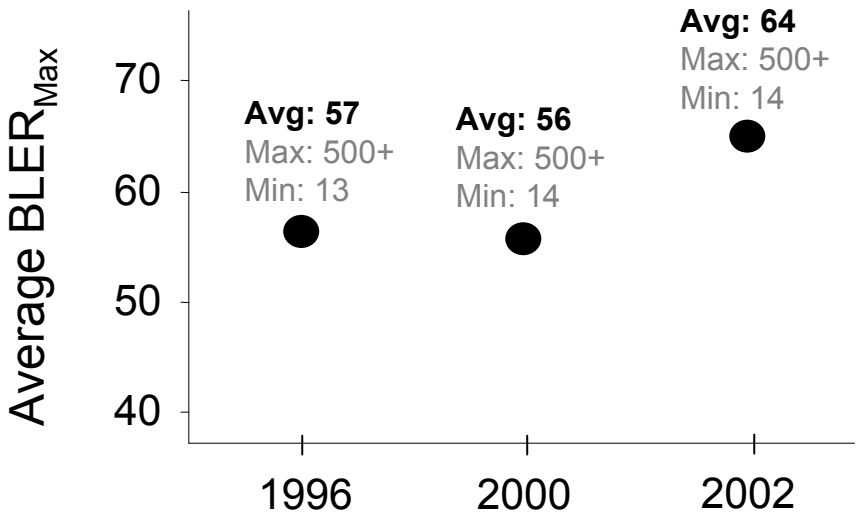

Fig. 3. Changes in average maximum BLER over time during a natural aging study of 125 discs, as measured by an AudioDev CATS tester following ISO (1995). It should be noted that the instrument has a BLER read-ceiling of 500. Data derived from Shahani et al. (2004).

errors, which result in the loss of data. Uncorrectable errors are reported as E32 errors. An E32 value above 0 indicates that data in one or more areas of the disc is not recoverable.

Many other parameters play a role in disc quality, but for research purposes BLER is used to define EOL (>220). To minimize data loss and preserve the discs in our collection, it is important to take action before uncorrectable errors occur. For this reason the Library of Congress has initiated a research program to study disc degradation in an attempt to understand the physical and chemical characteristics of discs that are behind deterioration and that may lead, ultimately, to disc failure.

"NATURAL" AGING OF CD-ROMS

In an effort to study predicted lifetime of CD-ROMs in the Library of Congress collections, a pilot study was implemented to evaluate the long-term effects of storage and use conditions on the stability of a sample population of 125 discs selected randomly from the Library's CD collection (Shahani et al. 2004). The randomly-selected discs had all been in circulation for at least one year when the study began. Starting in 1996, the discs were pulled from circulation and tested for BLER and other quality parameters, then put back into circulation and storage in the Library of Congress Capitol Hill complex, at ambient room temperature conditions. The discs were pulled and tested again in 2000, 2002, 2005, and 2010. Over the first six years (1996–2002) the discs showed relatively little change in disc quality (as measured by BLER and other parameters described in ISO/IEC 10149), though 4% did meet the ISO standard definition for end-of-life (i.e., their BLER was measured to be higher than the 220 per second threshold). For most discs, even those that did not reach a BLER > 220/s, the average maximum BLER ($BLER_{Max}$) was observed to slightly increase over time (fig. 3). In addition, discs that began their testing with BLER at or near the limit appear to have degraded faster.

The test discs from this study have remained in the Library's Madison building after the move of the audio collections to the Packard Campus so that they can be maintained in the same room ambient conditions as before. At the time of this publication (2010), data from the 2005 and 2010 rounds of testing are still being interpreted.

ARTIFICIAL AGING OF CD-ROMS

In 1999, a study was conducted using artificial (accelerated) aging to evaluate the effects of applying adhesive security devices to CD-ROM disc (Youket and Olson 2007). A set of 37 pairs of discarded audio compact discs were selected for study. A security device label was applied to one disc of each pair. This device consisted of a clear polyester film circle laminated with a pressure-sensitive adhesive and two magnetic strips that were designed to be detected by the security gates at the exits of library buildings. After aging the pairs side by side for 1000 hours at 80°C and 60%RH, the labeled discs showed a higher increase in BLER compared to their unlabeled mates. As a result of this study, the Library rejected the use of such devices on CDs in the collection.

In 2001, as a complement to the natural aging study, to predict stability further into the lifetime of a disc, the Library initiated an accelerated aging study using a recently developed standard test method, ANSI NAPM IT9.21 Life Expectancy of Compact Discs (CD-ROM)—Method for Estimating, Based on Effects of Temperature and Relative Humidity (now ISO 18921). The standard calls for five groups of discs, totaling 80 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.

A modification was introduced into this study, by including two copies of each disc, totaling 160 discs. 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. The laser engraving was proposed by the Copyright Office as a less invasive way to label collection CDs. The discs were divided into the five groups specified in the standard for exposure in an environmental chamber, at the following conditions: (1) 85%RH, 60°C; (2) 85%RH, 70°C; (3) 85%RH, 80°C; (4) 70%RH, 80°C; and (5) 55%RH, 80°C. Each group was tested to establish a baseline for each quality parameter, then placed in the stress chamber to cycle through the given conditions four times. At the end

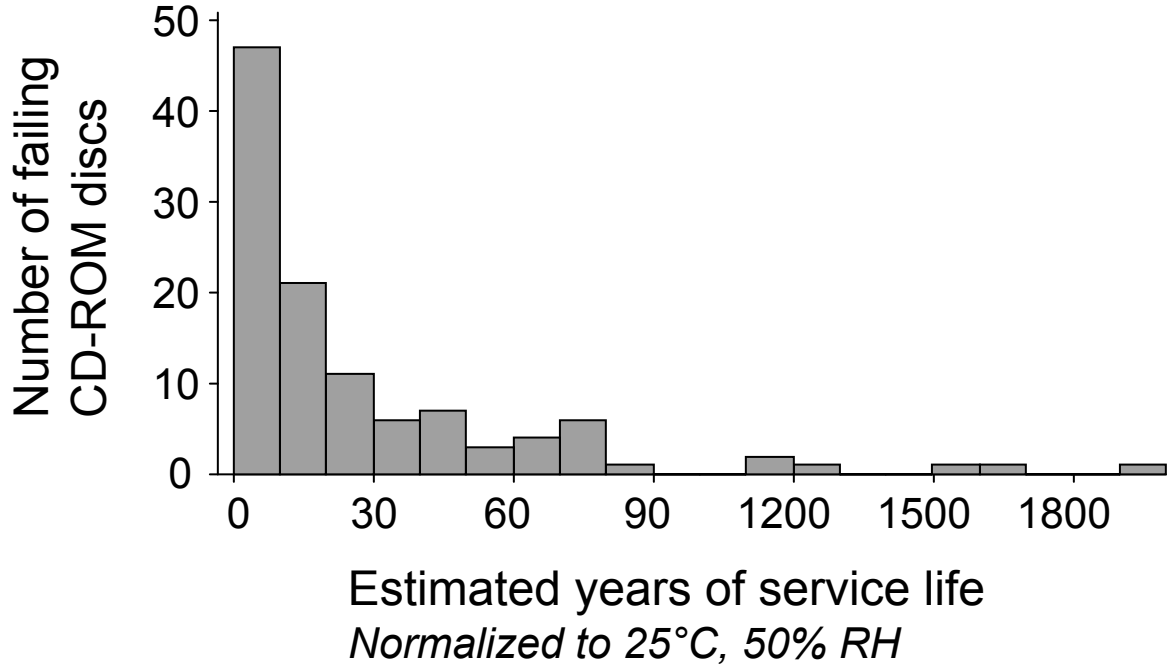

Fig. 4. Number of failed discs versus predicted service life of 160 discs, from the artificial aging study described in Shahani et al. (2009b).

of each exposure cycle the discs were tested again for BLER and other parameters. Both copies of each disc were exposed side by side at the conditions specified for that group. The EOL estimates for the engraved and un-engraved discs were then compared to evaluate differences in predicted longevity (Shahani et al. 2009a). As there was little difference between the EOL for the two sets, the data for all 160 discs were used for calculations of EOL for the total population and reported as a whole (Shahani et al. 2009b).

The results are summarized in figure 4. When normalized to 25°C and 50%RH, only roughly 30% of the discs tested are calculated to have a service life greater than 100 years. Of course, accelerated aging is not a predictive test method, as it has not been shown that these conditions truly mimic natural aging. However, it does give us some idea of the potential for failure within a group of samples. The differences between the EOL estimates for engraved versus un-engraved discs were unremarkable, indicating that laser engraving has little effect on disc stability. Based on this work, the Library proceeded with its plans to laser engrave a property mark on discs in the collection.

RECORDABLE MEDIA: A JOINT STUDY WITH NIST

In 2004, as a complement to the research studies on the longevity of CD-ROM discs, the Library initiated a joint project between the Library of Congress and The National Institute for Standards and Technology (NIST) focused on recordable media, including CD-R, DVD-R, DVD+R, DVD-RW, and DVD+RW. The test method used in the NIST study was based on ISO 18927: Imaging Materials—Recordable Compact Disc Systems—Method for Estimating the Life Expectancy Based on the Effects of Temperature and Relative Humidity. ISO 18927 specifies the same five aging conditions for testing CD-R media as for CD-ROM. The NIST study included a sixth condition (70°C, 70%RH) and reduced the length of time for each exposure. A selection of 100 discs for each disc format was divided into six groups and exposed at the specified conditions for that group for the specified number of hours for each group. The discs were tested after exposure and compared to the baseline values. The discs were cycled through this procedure three more times, for a total of four intervals.

At the end of the study, CD-R discs tested were found to be more stable and, thus, may be better for archival purposes than the recordable DVD formats. The NIST study cited several factors that would account for the differences in expected longevity and stability. Two reasons are the physical differences between CD and DVD media and the maturity of the CD technology. At the most basic level, the larger size of the data pits on a CD reduces the relative effect of material degradation and physical damage on the disc because any defect on a CD physically accounts for a smaller area of data than on the tightly-packed data surface of a DVD. The larger size of the data pits on CD media also means that less sensitive, more stable dye may be used (Zheng and Slattery 2006).

The data reported for this study was used as the basis to develop a new standard test method for DVD media. NIST worked with the Optical Storage Technology Association (OSTA) on the initial draft standard. The method was further developed and finalized by ECMA International Technical Committee 31, and published as ECMA 379 in 2007. The standard was adopted by ISO in 2008 and published as ISO/IEC 10995.

SUMMARY AND FUTURE WORK

In general, work on optical discs at the Library of Congress has shown that CD-ROMs have a range in their quality that is not always predictable by manufacturer. The natural aging study showed that BLER increase over time in CD-ROMs. Accelerated aging predicted that roughly 30% of CD-ROMs in the collection have a service life less than 100 years. However, it should be noted that the sample population was small (relative to the size of the Library of Congress collection) and covered a narrow range of dates of manufacture. Adhesive labels on

discs significantly increase BLER, and therefore are not suitable for use on discs in Library collections. However, the use of a laser to engrave information in the hub of a disc has little effect on disc stability, and is in use today by the Library of Congress as the preferred system for labeling discs. Work on recordable media is ongoing, though a joint study with NIST did demonstrate that, as expected, due to the tighter spacing of data on a DVD, recordable CDs are likely better and more stable than DVDs for archival purposes.

Studies of optical discs in the Preservation Research and Testing Division laboratories at the Library of Congress are still ongoing. The naturally aged discs will be analyzed and monitored for deterioration at regular intervals for years to come. As more material comes into the collection on re-writable media (such as authors' archives, musical compositions, etc.), work will focus even more on those formats. New insights might also be gained through a scientific examination of any visually perceptible defects as well. Initial experiments to analyze the components of discs that have visually detectable physical changes, or high error rates when tested, have shown promise. It is our hope that we will ultimately be able to link compositional characteristics of individual CDs to failure mechanisms in a way that would enable us to flag more vulnerable CDs for replication or backup so as to preserve the data before any of it is lost. Finally, the Library has a future research interest in examination of new material and technologies of optical discs and other digital storage formats.

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