DATA STORAGE TECHNOLOGY ASSESSMENT 2000

STORAGE MEDIA ENVIRONMENTAL DURABILITY AND STABILITY

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ABOUT THE DATA STORAGE TECHNOLOGY ASSESSMENT 2000 REPORT

The Data Storage Technology Assessment 2000 Report has two parts. This document is Part II, which covers storage media environmental durability and stability.

Part I of the Assessment 2000 report covers hardware technology, and is titled, “Current State and Near-Term Projections for Hardware Technology.”

Part I covers the following topics:

• Transition to Digital Domain for Document and Data Production
• Technologies Supporting Continuous Storage Performance Improvements
• Magnetic Recording Overview
• Magnetic Recording—Current Hardware Status and Near/Mid Term Projections
• Floppy Disk and High Capacity Floppy Disk
• Hard Disk Drives
• Magnetic Tape
• Optical Recording
• Write Once Optical Disk Memory
• Magneto Optical Recording
• Continuing Proliferation of Optical Disk Formats and Specifications
• New Optical Storage Possibilities
• Solid State Storage Devices—DRAM
• Future Projections for Semiconductor Technology
• Solid State Storage Device—Flash Memory
• Future Outlook for Data Storage Technology
• Overview of Emerging Data Storage Technologies
ENVIRONMENTAL DURABILITY AND STABILITY OF STORAGE MEDIA

EXECUTIVE SUMMARY

OBJECTIVES

Part II of the Data Storage Technology Assessment 2000 provides information about the life expectancy of electronic data-storage media, based on the degradation of media components and their failure through temperature, humidity, and the presence of corrosive airborne pollutants.

Operational and storage conditions to attain maximum media life are described, as well as life expectancy under practical, i.e., air-conditioned, business office environments.

The storage media addressed in this report include all types of flexible magnetic media manufactured after the mid-1980s and optical disk media produced after the early 1990’s.

BACKGROUND

Earlier data storage media exhibited some physical and chemical weaknesses and instability due to environmental conditions. These media included metal oxide magnetic tape produced prior to about 1970, the first generation of metal particle tape dating back to the 1980’s, and the phase-change optical disk of the 1980’s that entered the market prematurely.

At the time of its market introduction, the first volume-produced optical digital data storage media, the CD family of products, occasionally encountered user problems
ranging from higher than expected error rates on some CD-Audio and CD-ROM disks, to unreliable data retaining capability on CD-R media.

Consequently, users of electronic storage media continue to express concerns about the environmental sensitivity and consequently the durability and extended-term stability of these media.

Environmental durability and stability of storage media

Contemporary magnetic and optical storage media are highly refined products. Some of them have excellent environmental durability and stability that should be capable of delivering high quality outputs after 30 to 50 years of storage under air-conditioned environments designed for human comfort.

Analysis of the material degradation process for each major component of flexible magnetic and optical disk media offers the technical basis on which we can estimate media life expectancy with a reasonable degree of accuracy.

“End of Life” for a data storage medium

The “End of Life” for data storage media is when it no longer can deliver an output signal with a quality high enough to meet user requirements.

The signal quality criteria for a digital data storage system can be defined by the quantity of error bits (bytes or other units of measurement) contained in the output signal. An excess volume of errors within a given period overloads the data reproducer’s Error Detection And Correction (EDAC) system and fails to deliver data of the expected quality.

Flexible magnetic media

Flexible magnetic media, i.e. tape and flexible disks, should have a life expectancy of 30 to 50 years. This life expectancy depends upon the types of magnetic materials used and assumes that the media is stored under conditions prescribed in this report—conditions that are very similar to environments that are comfortable and healthy for human beings.

Optical disk media

Most optical disk media are enclosed products with a protective coating, and are operated without physical contact with the write/read head. Manufacturers generally quote a longer life expectancy for the optical disk media than for flexible magnetic media under identical storage conditions.

The Magneto-Optical (M-O) disk, a magnetic recording medium, relies on an environmentally sensitive recording material, but it should last a minimum of 30 years.
Scheduled transfer to new technology platform

The total active life of a data recorder rarely exceeds 25 years, including the 5 to 7 year product support period offered by most manufacturers after the termination of product manufacture. Since data storage technology improves its volumetric data storage efficiency by a factor of 10 to 50 times every ten years, it is prudent to transfer the stored data to a new technology platform on a regular basis—preferably every ten to fifteen years.

Data storage media typically outlast the active life of the data recorder. Media life is certainly considerably longer than the length of time most users intend to maintain the incumbent technology. However, when production contents with enduring value, high re-issue, or historical value are involved, shorter media life is a threat because it requires migration that may not occur in time or may fail to be financed or may imply undesirable content integrity losses.

Preferred operating and storage environments

With the passage of time, a data storage medium gradually weakens in terms of its physical and chemical properties and its data recovery capability. Its signal output quality also degrades with time. The output level decreases and errors increase. When careful attention is paid to operating and storage conditions, degradation processes will be retarded significantly.

It is prudent, therefore, regardless of the intended storage period for a particular data storage medium, to operate and store it under the best possible environmental conditions, along with the additional precautions described in this report. It assures that the best quality data can be retrieved from the medium throughout its life.

Physical handling of optical disk media

A new generation of optical disk media, the DVD family of recordable disks and higher capacity magneto optical media, are expected to play an important role in building current and future data storage infrastructure. The write-once disk, CD-R and its higher capacity version, the DVD-R, may replace flexible magnetic disk as a work-in-process media, as well as a convenient means for data transfer.

CD-R and DVD-R are also expected to replace the traditional amateur music recording medium, audio cassette tape, in the foreseeable future.

The optical disk is a delicate instrument and the physical sensitivity of its recording surface—immediately underneath the disk label side—to manual handling is often overlooked. Lack of adequate instructions on how to properly handle the disk, including the correct way to write identification on the disk or labeling, has and continues to cause user-induced disk damage. This matter is also addressed in this report.
1. INTRODUCTION

Preservation of the records and information stored by electronic means, and the ability to retrieve them in the future, involves more than the safekeeping of the storage media. Other factors include the availability of reading or playback equipment and data decoding devices and/or software, as well as the knowledge necessary to assemble the recovered material into a human comprehensible form.

In this report only those aspects pertaining to the preservation of the storage media and the maximization of their useful life are addressed.

The production period for a particular type of data storage equipment rarely exceeds ten years. As product acceptance matures and competitive products enter the same targeted sector of the market, manufacturers typically offer derivative products of the originals that are upgraded or are given enhanced capabilities. New products are often designed to have backward compatibility, which means that newer products can read recordings made by the original equipment generation. Even including these upgraded products, the time span for the total production period is typically not more than twenty years.

Most manufacturers continue to offer spare parts and maintain field service operations for five to seven years beyond the time when manufacture of the end-of-life product is terminated. The active and useful life of a particular product, therefore, does not usually extend beyond twenty-five years.

This is one reason why all electronic records that require extended-term life expectancy should be transferred onto new storage media and technology at a regular interval of perhaps 10 to 15 years to assure their continued preservation.

Transfer to new generation recording technology, which may have ten to fifty times higher volumetric storage density as compared to the previous technology-generation used, is likely to help alleviate storage space shortages when the stored data volume increases.

Assuming that the concept of record transfer at 10 to 15 year intervals is acceptable, then media longevity beyond twenty years may seem like a moot point to some users.

The quality of the reproduced information that is retrieved from the storage medium degrades with the passage of time as the medium itself develops physical, chemical, magnetic, and/or optical weaknesses.
The end of media life, as discussed later, is the time when the reproduced information no longer meets the defined minimum quality requirements.

In order to produce high quality signal output during its active life, media life, therefore, should be much longer than the above-mentioned interval to transfer or “migrate” to the new technology.

This report develops the study of the process of media degradation under various environmental surroundings, techniques, and conditions under which the media have the greatest likelihood of achieving the longest possible life.

**THE HUMAN COMFORT ZONE AND STORAGE MEDIA**

Data storage media, such as magnetic tape and optical disk media, etc., are highly complex products. Their basic structure is primarily composed of organic materials. In magnetic tape, inorganic magnetic particles are supported by an organic binder system that forms a thin recording layer, which is then bonded to the organic base film.

Most optical disk substrates consist of organic materials. The recording layer for the recordable optical disk is generally made of a metal alloy, with the exception of WORM recordable optical media, which are based on organic dye compounds. Therefore, it is not unreasonable to define ‘human comfort zone’ conditions as the base line for recording media use and storage environments.

The American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE) defines the Standards of Comfort and has published a Comfort Chart.

The Comfort Chart shows temperature and humidity ranges for human beings to live comfortably in summer and winter. The Comfort Chart, as shown in Fig. 1, also accommodates the fact that individual preferences will vary.
Figure 1. Comfort Chart

Translating the data shown in the Comfort Chart, and using 80% preference as the guideline, a Human Comfort Zone Diagram, shown in Fig. 2, was prepared. This chart shows that most of us are comfortable within a temperature range of 20 to 25 degrees Celsius (68 to 77 degrees F), and a relative humidity boundary of 40 to 60%.

The Comfort Chart is also a useful guideline for office and residential air conditioning system operating ranges. Office air conditioning systems normally provide a temperature range of 21 to 23 degrees Celsius and relative humidity may be controlled between 40 and 50%.

Residential air conditioning operations are a little more tailored for economy, accepting a relative humidity of 60% as the upper limit, and temperatures as high as 25 degrees C. These conditions are also shown in Fig. 2.

Note: Actual measurements indicate the air conditioning system alone is not capable of maintaining the relative humidity to a narrow range. The relative humidity in an air-conditioned room may be as high as 85% in humid summer and as low as 18% in dry winter weather.
Figure 2. Human Comfort Zone

Superimposed on the human comfort zone diagram as shown in Figure 3 are overall temperature/humidity boundaries for storage of both current magnetic and optical data storage media, as recommended by their manufacturers and studies conducted by user organizations.

It is interesting to note that the conditions prescribed by most published studies to be acceptable for recording media use overlaps the normal air conditioned zone.

The lower temperature and lower humidity region of the comfort zone overlaps with the upper temperature (15-23°C) and higher humidity area (30-40%) of the prescribed <10 years medium-term media storage conditions. However, for extended-term magnetic media storage the preferable temperature ranges are between 12-15°C and 30% ±5%, which is considerably colder and drier than would be comfortable for humans. These two areas are indicated as acceptable and ideal zones in the diagram.

When the media is in storage, it is analogous to human sleep. The recording media, as is the case with humans, prefer darkness. All organic materials maintain their physical and chemical integrity best if they are kept in dry and cool environments and away from radiation in the visible, Ultra-Violet (UV) and near InfraRed (IR) spectrum. The organic dye used in some optical recording layers is more susceptible to radiation than other recording materials.
Major airborne pollutants in our living environment include combustion by-products, residues from all forms of manufacturing and cleaning operations, out-gassed materials from building structures, industry and traffic, and other organisms and microorganisms.

Despite filtering, air conditioning, and forced air circulation, they enter offices and homes. Alloys in magnetic pigments and recordable optical media may react with airborne pollutants, especially combustion by-products such as nitrogen dioxide and sulfur dioxide. The presence of water molecules further induces chemical reactions.

All forms of acid, including acetic acid, hydrochloric acid, hydrobromic acid, and nitric acid are also found in the air and potentially react with non-oxidized metal in the magnetic recording layer.
Our normal, clean living environment contains less than one fiftieth of the amount of airborne pollutants described as the upper time-weighted limit of permissible exposure under industrial hygiene conditions during an average eight hour period per day of exposure.

The conditions comfortable and healthy for human beings are acceptable environments for the normal storage and operation of the storage media. For maximum life expectancy, however, most media manufacturers recommend a combination of lower temperature and dryer relative humidity.

2. **DATA STORAGE MEDIA LIFE EXPECTANCY**

**DEFINITION**

A generally accepted concept for the “end-of-life” of a recording medium is that it fails to deliver the required level of quality of signal or data output when it is played on the user’s reproducer.

The required performance level depends on the type of recorded data. In an analog audio or video recorder, the signal-to-noise ratio and the linear and non-linear distortion levels adequately define signal quality.

For the digital recorder, its performance level is solely defined by the raw (uncorrected) error rate of the recovered signal before decoding it to the final output form, which may be text, numerical data, audio, images, or video signals.

On casual observation of a high performance analog system, noise and distortions may not be clearly audible or visible. But they are there.

The presence of errors is common in any form of digital communication, including recording. The output signal from a digital communications system always contains error bits as well as intervals where data is not present.

Noise and distortions in analog signals and errors in digital signals are built-in characteristics of communications technologies.

We will now discuss magnetic recorder/reproducer error sources, as shown in Fig. 4 and Table 1.
**Sources of Single bit Errors**

The presence of noise in, and degradation and interruption of, the data transmission channel cause errors. The data recorder/reproducer combination is a complex form of a data transmission/reception system.

There are three major sources of noise in a data recorder/reproducer system. They are: (1) the medium, (2) the reproducer head, and (3) the signal electronics. In the design of the data reproducer, the system is always so configured that the most prominent of the three sources of noise is the medium itself. By accepting the noise level generated by the recording medium, design engineers try to design the contribution of other noise sources under their control to be at significantly lower noise levels as compared with the noise generated by the medium.

This design concept is known as “Media Noise Limited System Design”. In a contemporary magnetic data recorder, media noise accounts for 60 to 80% of the total system noise. The signal output level is determined by the performance of the read head and media characteristics, including head-to-media physical interface conditions. Providing that the system bandwidth and the channel code are defined, the signal-to-noise ratio directly correlates with the bit error rate.
<table>
<thead>
<tr>
<th>Noise Source</th>
<th>Cause</th>
<th>Type of Errors Generated</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Medium</td>
<td>Finite number of particles per bit volume</td>
<td>Single Bit Error</td>
</tr>
<tr>
<td>2. Reproducer Head</td>
<td>Real part impedance (Ohmic loss)</td>
<td>Single Bit Error</td>
</tr>
<tr>
<td>3. Signal Electronics</td>
<td>Device equivalent Noise resistance</td>
<td>Single Bit Error</td>
</tr>
<tr>
<td>4. Medium surface anomalies</td>
<td>No or insufficient magnetization</td>
<td>Burst Error</td>
</tr>
<tr>
<td>5. Dust Particle</td>
<td>No or insufficient magnetization</td>
<td>Burst Error</td>
</tr>
<tr>
<td>6. Head-to-Media Interface</td>
<td>No or insufficient magnetization</td>
<td>Burst Error</td>
</tr>
</tbody>
</table>

**Figure 4. Magnetic Recorder/Reproducer Noise Sources**
**Magnetic Recorder/Reproducer Error Sources**

<table>
<thead>
<tr>
<th></th>
<th>Single Bit Errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Bit Error</td>
<td>Frequently occurring short duration (1, 2, or 3 bits) errors</td>
</tr>
<tr>
<td>Sources</td>
<td>Electronic Systems Noise (Media Noise, Head Noise, Amplifier Noise)</td>
</tr>
<tr>
<td></td>
<td>Self-healing Micro Head clogging</td>
</tr>
<tr>
<td>Correction</td>
<td>Generally correctable by the EDAC first stage operation.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Burst Errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two Error Types</td>
<td>Hard Error (data not recorded or incorrectly recorded)</td>
</tr>
<tr>
<td></td>
<td>Soft Error (anomaly in playback operation)</td>
</tr>
<tr>
<td>Duration</td>
<td>Up to 10,000 consecutive bits.</td>
</tr>
<tr>
<td>Frequency</td>
<td>As often as several times per second</td>
</tr>
<tr>
<td>Sources</td>
<td>Media surface defects</td>
</tr>
<tr>
<td></td>
<td>Head-to-media separation by dirt and dust particles, smoke residue, oil film, etc.</td>
</tr>
<tr>
<td></td>
<td>Head gap clogging</td>
</tr>
<tr>
<td></td>
<td>Head mistracking due to mechanical system misalignments or media deformation</td>
</tr>
<tr>
<td>Correction</td>
<td>EDAC capability designed to correct errors encountered under normal operations (EDAC capability part of system specifications)</td>
</tr>
</tbody>
</table>

**Table 1. Magnetic Recorder/Reproducer Error Sources**

The three sources of noise mentioned above, however, account only for what is commonly referred to as single bit errors. Since these sources generate low amplitude disturbances throughout the spectrum occupied by the recovered signal, noise coming from these sources is referred to as white or pink noise depending on its amplitude/frequency relationships. Errors generated by these sources are of short duration, lasting only one or a few bits. They do not cause continuous or long duration disruptions of the signal.
Most recording systems accommodate these errors effectively through their built-in error detection and correction system (EDAC).

The uncorrected bit error rate, the error rate at the EDAC system input, varies between $10^{-4}$ to $10^{-6}$, depending upon the recorder design parameters. These error rates are corrected to the level of $10^{-6}$ or better for audio, video, and image recorders and $10^{-12}$ or higher for recorders intended for text and numerical data storage.

The recorder manufacturers specify these figures. The errors that actually drive the EDAC system capability to its limit are not single bit errors, but the errors caused by media defects, and head-to-media interface anomalies.

**SOURCES OF BURST ERRORS**

Small size defects in the recording layer are inevitable. In addition, dust particles, oil film, even airborne pollutants on the media surface, prevent effective magnetization during recording. These elements cause recorded-in errors, generally referred to as ‘hard errors’.

Errors occurring during playback through anomalies in head to media conditions include accidental separations of the head from the medium and head reading gap clogging, which are referred to as soft errors. These errors are of longer duration. A defect of one millimeter in length, at a linear bit density of 100 Kfci causes continuous data loss extending to 4,000 bits.

The EDAC system in contemporary data storage systems is designed to cope with such long duration errors, or burst errors, which could occur several times in succession at regular intervals due to the fact that media defects are often two-dimensional anomalies.

Data recorder manufacturers specify burst error recovery capabilities in terms of the longest continuous burst error, and the maximum number of such occurrences within a given period.

Mistracking of the recorded tracks by the read head is another source of error. Many modern recorders have an automatic tracking servo with a quick reaction time constant. The automatic tracking servo accommodates, to a moderate extent, the physical deformation of tape caused by temperature and humidity variations as well as changes in tension between recording and playback operations.

Deformation and dimensional changes due to normal temperature and humidity variations are reversible and are not permanent. Shrinkage due to exposure to a higher temperature, generally occurring at temperatures above 75 degrees Celsius is, however,
non-reversible. Characteristics of commonly used magnetic media substrates are shown in Figure 5, Figure 6 and Table 2.

Continuous mistracking can cause errors of a long duration that are often beyond the design capability of the EDAC. These errors are uncorrectable.
**Figure 6. Tape Substrate Physical Strength Degradation at Elevated Temperature**

Young's Modulus vs Temperature

![Graph showing Young's Modulus vs Temperature for different materials (PET, PI, PA, PEN) at various temperatures.](image-url)
<table>
<thead>
<tr>
<th>Items</th>
<th>Unit</th>
<th>PET</th>
<th>PEN</th>
<th>Polyimide</th>
<th>Aramid</th>
<th>PBO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>g/cm</td>
<td>1.395</td>
<td>1.355</td>
<td>1,500</td>
<td>1.54</td>
<td></td>
</tr>
<tr>
<td>Melting Temperature</td>
<td>°C</td>
<td>263</td>
<td>272</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Glass Transition Temperature</td>
<td>°C</td>
<td>68</td>
<td>113</td>
<td>None</td>
<td>280</td>
<td>None</td>
</tr>
<tr>
<td>Young’s Modulus</td>
<td>kg/mm</td>
<td>500-850</td>
<td>650-1400</td>
<td>900</td>
<td>1300</td>
<td>4922</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>kg/mm</td>
<td>25</td>
<td>30</td>
<td>50</td>
<td>60</td>
<td>56-63</td>
</tr>
<tr>
<td>Tensile Elongation</td>
<td>%</td>
<td>150</td>
<td>95</td>
<td>30</td>
<td>40</td>
<td>1~2</td>
</tr>
<tr>
<td>Long Term Heat-Stability</td>
<td>°C</td>
<td>120</td>
<td>155</td>
<td>180</td>
<td>300 or &gt;</td>
<td></td>
</tr>
<tr>
<td>Heat Shrinkage (200°C x 5 minutes)</td>
<td>%</td>
<td>5-10</td>
<td>1.5</td>
<td>&lt;0.1</td>
<td>0.3</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Coefficient of Thermal Expansion</td>
<td>10⁶/°C</td>
<td>15</td>
<td>13</td>
<td>2.5</td>
<td>10</td>
<td>~2</td>
</tr>
<tr>
<td>Coefficient of Hygroscopic Expansion</td>
<td>10⁶/%RH</td>
<td>10</td>
<td>10</td>
<td>11</td>
<td>10</td>
<td>0.85</td>
</tr>
<tr>
<td>Moisture Absorption</td>
<td>%@70% RH</td>
<td>0.4</td>
<td>0.4</td>
<td>1.3</td>
<td>1.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 2. Flexible Magnetic Media Substrate Characteristics
ERRORS IN OPTICAL RECORDING

Error distribution patterns for optical recording systems are not unlike the behavior of magnetic recording systems. The contribution made by various sources of noise to single bit errors, however, follows a different pattern.

As the data is written to a rotating disc, such operational anomalies as rotational velocity variations, power fluctuations in the writing laser, media thickness irregularities, and media temperature non-uniformity as recording progresses, generate “Mark” position irregularities and are the source of recorded noise.

On the reading side, unlike magnetic recording, the detector and electronics together generate as high a noise level as is contributed by recording irregularities.

The “media noise limited” design rule, however, does not apply to optical recording technology. In optical systems it is possible to increase the power of the reading laser to a level required to meet the required S/N ratio. This is not applicable to magnetic recording systems.

Both single bit errors and burst errors caused by media defects and read head-to-media interface anomalies are present.

The relationship between the “End of Life” and the criteria for non-acceptable signal out quality are shown in Table 3.

CRITERIA FOR MEDIA “END-OF-LIFE”

Defining the “End-of-Life” due to degradation for a medium at the initial observation of non-correctable error bits (or bytes, symbols, blocks) is unreasonable and not appropriate. Their occurrence is not predictable and the same media may recover the same error on a second try.

A more reasonable and practical approach to define the End of Life, or Life Expectancy, projection in connection with degradation would be to define it in a manner as described below:

1. A group of packaged media (tape cartridges or discs) from a given manufacturer, of a given release date (this could be the manufacturer’s date stamped on the package or the date the user received them) is assembled. A quantity of ten or more should be considered.
2. When a high percentage (80% or higher) of the media generates a number of uncorrected errors after 8 or more tries out of 10 playbacks, the group is considered to be unusable.

3. The End-of-Life is considered to be at 80% of the elapsed time between the release date and the date the group failed by the above criteria.

   The End-of-Life date resulting from degradation thus obtained may be applicable to other media of the same format and from the same manufacturer.

   The error rate of the output signal, the only applicable way to define digital signal quality, requires further explanation. In digital data communication, the smallest unit of transmission is a word, which is represented by a byte. The error rate should be expressed by the number of error bytes per unit of data volume.

   Since one or two error bits in one byte makes the entire byte an error byte, or 8 error bits, the byte error rate is many times larger than the bit error rate for an identical condition.

   This is one of the reasons that the data storage industry still uses the bit-error-rate expression.

   In recent years, however, new terminology that counts the number of errors per certain data volume, e.g., 100 error bytes per 1 GB, is becoming more common. Error data unit terminology includes such data packet expressions as ‘symbol’ or ‘block’.

   Some media manufacturers are also using such an expression as 10 error bytes per cartridge.

   The ISO/IEC-908, CD-R Standard document, defines the maximum allowable error rate to be 220 data blocks per 10 second duration. Since there are an average of 7,350 blocks per second at normal reading speed, the error rate is 220 error blocks per 73,500 data blocks, or \(3 \times 10^{-3}\).
### Media “End of Life” and Unacceptable Signal Quality Criteria

<table>
<thead>
<tr>
<th><strong>End of Life</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Media unable to deliver required quality signal output when played on the User’s reproducer</td>
<td></td>
</tr>
</tbody>
</table>

**Analog System**

- Meeting minimum acceptable S/N ratio
- Meeting maximum acceptable level of Linear and Non-Linear Signal Distortion
- Acceptable level of Frequency and Duration of output signal interruptions compensated and/or concealed by Drop Out compensation, Muting, etc.

**Digital System**

Number of uncorrectable errors exceeding the maximum allowable level per given period

**Allowable Level Examples (Digital System)**

<table>
<thead>
<tr>
<th><strong>Data Type</strong></th>
<th><strong>Error Rate after Correction</strong></th>
<th><strong>Error Rate Prior to Correction</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Audio</td>
<td>$10^{-8}$</td>
<td>$10^{-4} \sim 10^{-6}$</td>
</tr>
<tr>
<td>Video</td>
<td>$10^{-6}$</td>
<td>$10^{-4} \sim 10^{-6}$</td>
</tr>
<tr>
<td>Imagery</td>
<td>$10^{-8}$</td>
<td>$10^{-4} \sim 10^{-6}$</td>
</tr>
<tr>
<td>Text</td>
<td>$10^{-12}$</td>
<td>$10^{-5} \sim 10^{-7}$</td>
</tr>
<tr>
<td>Numerical Data</td>
<td>$10^{-15}$</td>
<td>$10^{-5} \sim 10^{-7}$</td>
</tr>
</tbody>
</table>

* Error rate after correction is governed by the error rate prior to correction and the correction system (EDAC) capability

### Table 3. Media “End of Life” and Unacceptable Signal Quality Criteria
3. FLEXIBLE MAGNETIC MEDIA

MAGNETIC TAPE OVERVIEW

Magnetic recording tape is supplied in widths varying between 2-inches (50.8mm) and 1/8-inch (3.18mm), and its overall thickness has been approximately one thousandth of its width. Commercial availability of higher tensile strength substrates, and the market requirement to pack longer tape lengths inside a given cartridge/cassette volume, have resulted in the recent introduction of thinner tape with a thickness approaching one two-thousandth of the tape width.

The cross section of four representative tape types, two with a particle coated recording layer, and two with an evaporated metal coating, are shown in Fig. 7.

![Figure 7. Magnetic Media Cross Sections](image-url)
**BASE FILM**

The common base film material for particulate-coated tape is PolyEthylene Terephthalate (PET). Because of its weakened physical strength at elevated temperatures, PET must be specially treated before use for evaporated tape base film, which must withstand higher temperatures during its manufacturing process. PolyEthylene Naphthalate (PEN) which maintains a higher level of Young’s modulus at higher temperatures, is a preferred medium for evaporated metal tape, and is now also used for some particle coated tapes because of its generally greater physical strength and reduced tendency to shrink or stretch.

Other base film materials have started to enter the marketplace where their special characteristics outweigh their substantially higher cost. Such materials include Aramid for its superior tensile strength, Polyimide for its high temperature survivability, and Poly Benzo Xazole (PBO) for its superior storage stability.

The base film itself has not been a major problem in media storage operations unless the media was kept under conditions that are uncomfortable to human conditions, such as very high temperatures/high humidity environments. The characteristics of commonly used base film materials are shown in Table 2.
MAGNETIC COATINGS OF PARTICLE MEDIA

In particle coated media, which comprises the majority of data storage tape, the magnetic particles, mixed in with and supported by the binder, are coated onto the base film. Two types of material, metal oxide and pure metal, are used for magnetic particles. Metal oxide, being a fully oxidized material, is generally stable under normal and also harsh storage environments.

Metal oxide materials currently in use for magnetic tape and floppy disks are shown below:

<table>
<thead>
<tr>
<th>Common Name</th>
<th>Chemical Composition</th>
<th>Year of Introduction</th>
<th>Coercivity Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnete</td>
<td>Fe₃O₄</td>
<td>1945/1990 (1)</td>
<td>250 - 750</td>
</tr>
<tr>
<td>Gamma Ferric Iron Oxide</td>
<td>γFe₂O₃</td>
<td>1947</td>
<td>250 - 750</td>
</tr>
<tr>
<td>Cobalt Gamma</td>
<td>CoγFe₂O₃</td>
<td>1975</td>
<td>600 - 1000</td>
</tr>
<tr>
<td>Chrome</td>
<td>CrO₂</td>
<td>1975</td>
<td>200 - 600</td>
</tr>
<tr>
<td>Barium Ferrite</td>
<td>BaO-Fe₂O₃</td>
<td>- - (2)</td>
<td>500 – 1600</td>
</tr>
</tbody>
</table>

Notes
(1) Magnetite was used in the first commercially produced magnetic tape. It was soon withdrawn because of excessive print-through and replaced by gamma Fe₂O₃. It was reintroduced in the 1990’s with much improved characteristics as a lower cost replacement for cobalt gamma tape. The cost of cobalt had increased substantially in the late 1980s.
(2) Barium ferrite media has never been in large-scale commercial production.

Table 4. Metal Oxide Materials Currently in Use

There have rarely been problems associated with magnetic property degradation in recording media based on metal oxide particles.

Gamma ferric oxide magnetic tape was the mainstay of audio, video and data recording through the early 1970’s. After a decade or more of storage in environments that were often uncontrolled, some of these tapes degraded to a state where normal
Playback operations became nearly impossible. They often exhibited excessive levels of dropouts. And under some circumstances, the magnetic coating separated from the base film in the form of powder or debris. In some cases, layers of the tape in a spool were stuck together.

These problems were the result of the physical degradation of the binder material and were not related to the magnetic material, which in most cases maintained its integrity.

The phenomenon described above, however, generated unfortunate public perceptions that magnetic tape is an unreliable recording medium. This generalized opinion toward magnetic tape is only partially correct because all magnetic tapes manufactured after about 1980 are products of a completely different level of quality. Their useful life now extends beyond 50 years if stored under “cooler and dryer than human comfort” conditions.

This matter will be discussed later in concise detail.

Magnetic media based on non-oxidized, pure metal magnetic particles are generally known as MP media, or MP tape. MP technology, because of its higher concentration of magnetic material in a given binder volume, exhibits a larger hysteresis curve and higher coercivity and magnetization, than metal oxide media. This is the reason why MP formula media are more suitable than metal oxide formula tape for high density recording applications.

MP formula currently used in magnetic tape and high-density floppy disks are shown below:

<table>
<thead>
<tr>
<th>Common Name</th>
<th>Chemical Composition</th>
<th>Year of Introduction</th>
<th>Coercivity Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>MP(1)</td>
<td>Fe</td>
<td>1980</td>
<td>1200 – 1400</td>
</tr>
<tr>
<td>MP+, MP++ (2)</td>
<td>Fe</td>
<td>1988</td>
<td>1500 – 1800</td>
</tr>
<tr>
<td>Dual Coat (3)</td>
<td>Fe</td>
<td>1992</td>
<td>2000 +</td>
</tr>
</tbody>
</table>

Notes
(1) Also known as First Generation MP
(2) Known as Second Generation MP
(3) Composed of a thin (less than 0.5µm) main recording layer and a second, non-magnetic, or low coercivity magnetic support layer of substantial thickness

Table 5. MP Formula Currently Used in Magnetic Tape and High Density Floppy Disk
MP tape has been in the marketplace since the late 1960’s, but only on a sample or experimental basis. It was first introduced on a commercial scale in the early 1980’s as the selected recording medium for 8mm VCRs and 4mm (3.81mm) DAT audiotape recorder/reproducers.

As modified versions of both 8mm and 4mm recorders entered the data storage drive market, the first generation MP tape was adopted as a data storage medium.

The first generation MP tape, lacking adequate protection against metal particle oxidation and corrosion from airborne pollutants, suffered gradual degradation of its magnetization under unfavorable storage conditions, i.e. high temperature combined with high humidity.

The observable degradation of its signal output within one or two years under storage conditions similar to those of tropical climates, has caused the loss of irreplaceable data by some users, and also generated unfavorable opinions in the data storage industry towards the MP media.

Indeed the first generation MP media did enter the marketplace without adequate product testing and evaluation to ensure their viability under actual operating and storage conditions.

Manufacturers have subsequently quickly developed several means to guard against particle oxidation and corrosion. This technique involves the encapsulation of each metal particle with a protective coating.

All MP media produced since the mid-1980s incorporate the means for corrosion prevention in one form or another.

Modern MP media exhibit nearly zero degradation of their magnetization level under normal storage conditions.

Standard MP media, because of its higher coercivity and magnetization coupled with smaller particle dimensions, is inherently capable of shorter wavelength recording as compared to metal oxide media.

Dual coat MP media, introduced in the early 1990s, is a further refinement of MP media technology, making it a natural choice for very short wavelength recording applications.

A 1 to 1.5 µm layer of non-magnetic metal or very low coercivity Iron Oxide is first placed on the base film. This layer functions as the compliance and buffer zone between the substrate and the recording layer. It also smoothes the surface of the recording layer (reducing surface roughness, or Ra) by providing a highly refined and level surface platform on which the magnetic layer is placed.
The recording layer of approximately 0.25µm thickness (adjusted to a particular drive format based on its prevailing recording wavelength) reduces the self-demagnetization effects associated with a thicker recording layer. The head-to-media contact, an important factor in short wavelength recording, is better than the single layer media because of the smaller surface Ra, aided by the presence of the compliance layer.

Dual coat MP media has become the mainstay of high-density tape recording and high-capacity floppy disk products.

**EVAPORATED MAGNETIC MEDIA**

The type of recording media referred to as Metal Evaporated (ME) has its magnetic recording layer deposited directly upon the base film.

The recording layer is produced by the controlled deposition of vapor evaporated from the metal target. For deposition of metal alloy, more than one target is used. As the vaporization temperature of metal is quite high (more than 2000 degrees Celsius for cobalt, which is the most commonly used metal) the base film must be able to physically withstand the hot vapor deposition process.

The first generation of ME tape used a mixture of cobalt and nickel as its recording medium. Nickel was used to make the actual recording material, the corrosion prone cobalt more stable against oxidation and corrosion.

Recording layer characteristics can be controlled by the alloy composition and the amount of oxygen or other gaseous material that is present during the deposition operation.

Since the angle of the axis of the deposited metal is slanted with respect to the base film surface, two deposition operations of opposite directions are performed to make the recording characteristics of the medium non-directional.

The recording layer of 0.1 to 0.2 µm thickness is over-coated by an extremely thin layer of carbon, often referred to as Diamond-Like-Carbon (DLC). The DLC coating thickness is kept to a minimum as it is a non-magnetic layer separating the media from the head.

Currently manufactured ME tape, no longer relying on Nickel for its corrosion resistance, is protected against corrosive environments by a DLC layer of 5 to 7.5 nm. Attempts are now being made to reduce its thickness to less than 5 nm. A lubricant layer of approximately 1 nm thickness, placed over the DLC coating, also functions as a means of protecting against corrosion.
The initial ME tape encountered occasional problems with the magnetic layer peeling off the base film when the tape was repeatedly moved at high speed around a small diameter pin or roller. This condition is analogue to a metal plated plastic film being bent sharply, causing the plating to peel off the film.

However, this problem has been resolved completely and is not an issue with current ME tape.

Contemporary ME tape is highly stable in normal conditions, because of its two protection layers.

Advanced Multi-layered ME (AME) tape has recently entered the market place. The first layer on the base film is a cobalt oxide thin film layer that is deposited prior to application of a normal thickness of cobalt deposition. The presence of the nano-crystalline seedbed results in a more compact cobalt recording layer particle of 20 nm diameter rather than 50 nm diameter normally obtained without the under-layer.

Representative ME tape characteristics are shown below:

<table>
<thead>
<tr>
<th>Common Name</th>
<th>Chemical Composition</th>
<th>Year of Introduction</th>
<th>Coercivity Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>ME (1)</td>
<td>Co (80%), Ni (20%)</td>
<td>1981</td>
<td>900 -1100</td>
</tr>
<tr>
<td>ME, AME (2)</td>
<td>Co</td>
<td>1996</td>
<td>1300 - 1500</td>
</tr>
<tr>
<td>NCS ME (3)</td>
<td>Co</td>
<td>1999</td>
<td>1500 +</td>
</tr>
</tbody>
</table>

Notes
(1) For 8mm analog video recording. Later used in first generation 8mm data recorders and 4mm DAT/DDS equipment.
(2) For DVC Camcorders and data recording.
(3) A Nano-scale Crystalline Seedbed (NCS) layer under the recording layer for very short wavelength applications.

Table 6. Representative ME Tape Characteristics
BINDERS

The binder assembles magnetic particles and secures the mixture of particles and binder material firmly on the base film and is a very important component of particle-coated media.

The binder was the weak link of the total tape structure in earlier magnetic tape produced through the early 1970’s. In the earlier days of magnetic tape engineering, the magnetic recording layer was considered to be the equivalent of a coat of paint on a flat surface. The magnetic particle was the color pigment and the binder was the solvent. No serious thought was given to assure that the binder would be chemically and physically resistant to careless usage in harsh environments. Some manufacturers continue to refer to the magnetic particle as the pigment.

Polyester-polyurethane has been the principal component of the magnetic tape binder. During the late 1970’s, polyvinyl chloride-polyurethane was also introduced.

Our present concept of the binder is the formation of a strong organic molecule chain by cross-linking ester compounds. Magnetic particles are held in place by interleaving them within the molecular chain structure, and the three dimensionally cross-linked molecules extend endlessly to form a strong containing body for magnetic particles.

In the presence of water vapor (moisture) in the atmosphere, the esters react with the water molecules and break down to acid and alcohol groups, as shown in Figure 8. Ester was originally formed by a chemical reaction between acids and alcohols.

The Japanese term for this hydrolysis process is “Kasui-Bunkai”. In English Kasui-Bunkai means “breakdown through water addition”, which accurately describes this highly damaging process that is characteristic of polyester polyurethane and polyvinyl chloride polyurethane binders.

With hydrolysis, the magnetic media binder breaks down its cross-links and could disintegrate into smaller molecules, losing its volumetric strength and integrity. The presence of transition metal ion in the binder is known to catalyze the hydrolysis, accelerating polymer degradation. The magnetic media binder, with an abundance of iron oxide or iron particles in it, unfortunately offers a condition suitable for transition metal-induced hydrolysis.
Hydrolysis = Reversible Chemical Reaction
Rate of Reaction = Governed by Absolute Temperature and Atmospheric Water Vapor Content
Equilibrium = Temperature °C % RH

<table>
<thead>
<tr>
<th>Temperature °C</th>
<th>% RH</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>50</td>
</tr>
<tr>
<td>15</td>
<td>40</td>
</tr>
<tr>
<td>25</td>
<td>30</td>
</tr>
</tbody>
</table>

**Figure 8. Polyester Hydrolysis**

Acids, the by-products of hydrolysis, then oxidize the magnetic particles, degrading their magnetic property. This scenario describes what has taken place in binder systems of the earlier magnetic recording media, as shown in Fig.9.

Contemporary magnetic media generally depend on a binder system composed of polyvinyl chloride derivatives and cross-linked polyurethane. This is a significant change from the earlier binder system, which was primarily based on polyester-polyurethane.

The new binder system, used almost universally by major media manufacturers, is less likely to degrade by hydrolysis, and its tensile strength is greater under all conditions. Within the binder system, polyvinyl chloride adsorbs to the magnetic particle surface, preventing transition metal-induced hydrolysis.

The types of polyurethane used in the new binder also prevents the reaction between water molecules and ester, effectively protecting the binder from hydrolysis, except under the most unfavorable conditions.
In reaction with water vapor under higher temperatures, polyvinyl chloride does produce chloric acid, which could be very damaging. This phenomenon is effectively eliminated by the addition of epoxide to the binder, which also prevents acid-catalyzed hydrolysis of the polyurethane.

The modern binder system, although not completely immune from degradation under the most unfavorable conditions, has a far-improved survivability under normal to less favorable storage conditions.

Even if hydrolysis does occur under temporary unfavorable circumstances, the binder structure is not likely to degrade. Since hydrolysis is a reversible chemical reaction, the media maintains its integrity when storage conditions return to normal.

Adsorption of PVC by the magnetic particles also prevents magnetic property degradation by the unlikely occurrence of corrosion from hydrolysis by-products.
The boundary which defines zero hydrolysis for a typical ester compound, where a forward reaction of hydrolysis and reverse hydrolysis cancel each other out, is shown in Fig. 10.

The figure also represents the 15% hydrolysis line. Media manufacturers consider a level of hydrolysis up to approximately this level to be essentially non-damaging to the present media binder system.

It is interesting to note that the human comfort zone, as well as office and residential air-conditioned environments also fall between the zero and 15% hydrolysis boundaries.

Figure 10. Low Hydrolysis Activity Region
LUBRICANTS

An important function of the binder is that it is the reservoir for the lubricant, which reduces the extent of mechanical friction between the media and the write/read head.

During normal head-to-media contact, the lubricant residing on the media surface pores smothers the passage of the head, then it gets back to the surface and is reabsorbed by the media.

Media manufacturers have designed the lubricant to be non-volatile, and its vapor pressure is low, meaning that it is less likely to evaporate under normal conditions. It does evacuate from the media surface when exposed to very high temperatures and/or very low relative humidity conditions or a combination thereof.
4. THE PROCESS OF MAGNETIC MEDIA AGING

Flexible magnetic recording media decays and its usefulness decreases with aging. Degradation of its physical integrity and magnetic performance are the result of changes taking place in all of the media’s components.

Components do not decay synchronously or at an equal rate. But all components decay and the end of life for media comes when one of the components reaches the end of its functionality, or fails to deliver the required performance.

The components of flexible media are:

1. Base film
2. Binders (not used in metal evaporated tape)
3. Magnetic particle and metal evaporated layer and coating
4. Lubricants
5. Protective layer over the evaporated metal layer
6. Back coating

BASE FILM

The extended term physical stability of the base film is important for recorded magnetic media in order to maintain its value, which is the ability to reproduce the recorded data when required.

Three environmental factors influence the physical stability of the base film. They are:

- Temperature
- Relative humidity
- Tension
Dimensional changes due to humidity variations in both directions, the Machine Direction (MD) and transversal direction (TD), are reversible.

The effects of temperature on dimensional changes are also reversible except for those resulting from the impact of higher temperature ranges. Temperatures higher than 50 degrees Celsius for an extended period of time are highly detrimental as the base film shrinks permanently in both directions, and its width changes significantly if the film has been exposed to such conditions. The shrinkage in the machine direction is not significant because the tape is stored under longitudinal tension.

PET-based tape stored at 75 degrees Celsius for a mere 30 minutes shrinks in width 0.5%. In a 200-track linear-scan fixed head drive, this level of tape width shrinkage represents one entire track pitch.

Although narrow track pitch recording media and drives are equipped with embedded servo tracks to guide the read heads on the proper recorded tracks, width shrinkage is a potential source for increased error rates.

In very severe cases of non-reversible width shrinkage, this phenomenon could mean the end of life for the recorded tape.

The tension applied to the tape during recording and playback operations is controllable. The level of tape tension required to exert adequate pressure on the head for assured intimate contact between the head and media has decreased significantly in recent years. This is due to improved media surface roughness. Tension variations during normal operations do not affect base film integrity. An accident involving excessive tape tension, however, could permanently stretch the base film and also damage the recording layer.

Combining all three factors, tape dimensional changes under normal conditions do not exceed plus or minus 0.1%, and do not result in detrimental effects on data recovery.

An example of tape substrate dimensional changes is shown in Table 7.
### Tape Width Change Computation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Shrinkage</td>
<td>_-hour at 75°C</td>
<td>-0.5%</td>
</tr>
<tr>
<td>Temperature Variation</td>
<td>15°C decrease in temperature</td>
<td>-0.01%</td>
</tr>
<tr>
<td>Humidity Variation</td>
<td>40% decrease in RH</td>
<td>-0.02%</td>
</tr>
<tr>
<td>Tension Variation</td>
<td>Tape tension increase of 0.15N in playback as compared to recording condition</td>
<td></td>
</tr>
<tr>
<td>Tape Length Change</td>
<td></td>
<td>+0.03%</td>
</tr>
<tr>
<td>Tape Width Change due to Poisson’s Law (=0.3)</td>
<td></td>
<td>-0.01%</td>
</tr>
<tr>
<td>Total Width Change</td>
<td></td>
<td>-0.54%</td>
</tr>
</tbody>
</table>

**Table 7. Tape Width Change Computation**

The useful life of commonly used (PET or PEN) base film itself, stored under extended-term storage conditions, exceeds hundreds of years.

#### BINDERS

As previously noted, the cause of binder degradation is hydrolysis. Hydrolysis not only weakens but potentially destroys the three dimensional cross-linking of polymers. Its carbolic acid by-products could attack both metal oxide and pure metal magnetic particles and reduce their magnetic remanence.

When and if these events take place, higher levels of dropouts, and partial loss of the level of magnetization will result. Recovered data will contain increasing amounts of both short and long duration errors, which may be beyond the EDAC capability for full data recovery.

In the early 1990’s, the Recording Media Industries Association (of Japan) commissioned a detailed theoretical and empirical study of PolyUrethane (PU)- based...
binder life expectancy. Kobe University carried out the study, and the report was published in the International Journal of Adhesion and Adhesives, Vol. 16, 1995, pp. 277-283. The conclusion of this report is quoted below:

“The lifetime of the PU binder depends on the chemical structure, storage temperature and the presence of cross-linked agents CL and PVC. A small number of ester bonds are directly responsible for polymer degradation. Suitable storage temperatures are required to extend the lifetime of the recording media. Furthermore, addition of PVC and CL (to the binder during manufacture) extends the life (expectancy) of the PU binder. For example, the life (expectancy) of the PU (PCD)/CL/PVC system can be about 200 years at 20° Celsius”.

The tests were all conducted at 95% RH, and the life expectancy is defined as the passage of time required for the binder to lose 50% of its initial tensile strength.

MAGNETIC PARTICLES AND COATING

The function of the magnetic layer is to maintain its recorded magnetic remanence over the expected or required duration under media storage conditions. A gradual reduction of the remanence is expected. But the level of remanence at the end of life must be high enough to ensure complete recovery of data using the EDAC system included with the reproducer.

Under identical storage conditions, the percentage loss of magnetic remanence varies depending on the type of magnetic material used in the recording medium.

The mechanism or mechanisms through which the recording layer maintains or loses its remanent magnetization are described for the types of media currently in use.

**Gamma Ferric Iron Oxide, Fe\textsubscript{2}O\textsubscript{3}**

This material is in use for low coercivity audio and data tape. Because the material is a fully oxidized metal and is non-corrosive, its magnetic characteristics are highly stable.

**Cobalt adsorbed or Cobalt absorbed Gamma Ferric Iron Oxide**

This medium coercivity media is used extensively in audio, video and data recording. The cobalt adsorbed iron-oxide particle has an extremely thin--2 to 3 nanometers--layer of cobalt-iron oxide bonded to the surface of each acicular particle.
It is at least theoretically possible that, over time, the cobalt layer will diffuse into the iron oxide, and will lower the coercivity and remanence of the particle.

The cobalt adsorption process, however, occurs at temperatures above 150 degrees Celsius. Therefore, it is highly unlikely that the diffusion and remanence losses would take place anywhere under normal conditions. It is a highly stable material.

The core of the cobalt absorbed iron-oxide particle is encased by a thin layer of Co-(OH). An advantage of this is that through various combinations of the core and layer material, a very high coercivity--up to 2000 oe--magnetic particle can be produced. This is also an extremely stable material.

**Chromium Dioxide**

With exposure to water vapor, chromium dioxide changes its chemical and magnetic properties. This process takes place at room temperatures and accelerates as the temperature increases.

Studies also indicate that the presence of chromium dioxide catalyzes hydrolysis.

Although manufacturers believe that these phenomena do not shorten media life, measurements show that the rate of remanence degradation is faster than with most other recording layer materials.

**Metal Particle (MP)**

Metal particle tape, when first introduced in the early 1980’s, did suffer remanence degradation through oxidation and corrosion, especially under temperature and humidity conditions that were significantly higher than human comfort conditions.

All MP tapes produced since the mid 1980’s however, have their pure iron particles encased by a protective layer of inert material.

Cross sections of a typical protective layer-covered metal particle are shown in Fig. 11.
Figure 11. Metal Particle Corrosion Protection Technique

MP tape remanence degradation through oxidation and corrosion has essentially been eliminated. Test data shows, however, that during the first one or two years, a small but detectable level of magnetization decrease has been observed. Beyond this initial decrease, magnetic remanence remains as stable as oxidized metal particles.

Critical comparison of the long term durability characteristics of MP tape against oxidized metal media indicates that under all storage conditions—for human comfort as well as at higher temperatures and humidities—modern MP media is nearly equal to low coercivity gamma iron oxide which is the most stable media.

Gradual loss of magnetic remanence through the passage of time for particle coated magnetic media is shown in Fig. 12.

The information shown is a compilation of both actual measured data for the first ten years and estimates for the next twenty years, which are assembled from the results obtained by accelerated aging tests. Storage conditions were at 20 degrees Celsius and 50% relative humidity.

A major media manufacturer conducts long term media stability tests under conditions they refer to as Ordinary Conditions. In ordinary conditions, the temperature is held between 20 and 25 degrees Celsius, and the relative humidity is allowed to vary between 60 and 40%, representing the manufacturer’s office and laboratory environments.
Samples of their first volume produced professional MP tape are kept under these conditions. The tape performance levels have been monitored since 1986, thirteen years ago. The raw measured data, shown in Fig. 13, indicate no measurable loss of signal output level.

![Figure 12. Magnetic Remanence Loss by Extended Period Storage](image-url)
Some other media manufacturers execute long-term media stability tests at 23 degrees Celsius and at uncontrolled relative humidities not exceeding 70%. Data representing the first 10 years of MP media storage do not deviate from the test data representing 20 degrees Celsius and 50% RH.

As mentioned earlier, dual coat MP media is becoming the mainstay of all high-linear density, i.e., short wavelength, recording. Because of its thin magnetic recording layer, e.g. 0.25 to 0.50 micron, some users have expressed concerns regarding its environmental stability.

The magnetization depth in the recording layer is proportional to the recording wavelength, i.e., approximately 1/3. Conventional magnetic media have a recording layer thickness far in excess of the required thickness based on the magnetization depth. Dual coat media provide a recording layer thickness necessary for the recording wavelength and other system requirements.

Its environmental durability and stability are as good as the single layer MP media.
Evaporated Metal Coating

Corrosion of the Cobalt or Cobalt-Nickel layer of ME tape is possible under high temperature and humidity conditions. Presence of airborne pollutants such as HCl, SO₂, and HCHO, combined with the water molecule, may induce other chemical reactions. ME tape recording layer degradation processes are shown in Fig. 14.

ME recording media for data recording applications now use only cobalt deposition. Media for consumer VCRs such as the Hi-8 camcorder, however, were based on a composition of 80% Cobalt and 20% Nickel, which is less corrosive than pure cobalt.

The recording surface of current ME media is protected by a Diamond-Like Carbon (DLC) layer intended to prevent magnetic coating corrosion and a lubricant coating, as shown in Fig. 15.

Since the introduction of DLC coating, Cobalt-Nickel alloy is no longer used for the ME tape recording layer.

![Figure 14. Metal Evaporated Tape Degradation Process—Tape without Protection Layer(s)]](image-url)
Extensive stability studies conducted by manufacturers indicate that the protection of the recording layer against both water vapor and airborne pollutants is highly effective. Accelerated storage tests conducted under high temperature/high relative humidity environments indicate that the life expectancy of ME media protected with the DLC coating protected is nearly as good as that of oxide or MP media.

ME media stability data are included in the previously shown Fig. 12.

**Lubricants**

For particulate-coated media, the binder is the lubricant reservoir. For ME media, a lubricant layer is the outer most layer on top of the DLC coating.

Preservation of lubricant in the binder is important. Extremely low humidity, i.e., below 20% RH, and high temperatures, i.e., above 40 degrees Celsius, are detrimental to the permanent retention of the lubricant.

Under human-comfort level storage conditions, the lubricant retention period is believed to be as long as the binder life. In a strictly technical expression, however, the ideal conditions for lubricant retention do not coincide with the conditions for the longest binder life.

**Back Coating**

In general, the back coat does not present a problem in obtaining maximum media life expectancy. However, PVC, which is the common binder material, produces a very small amount of chloric acid when hydrolysis occurs. The back coat, in intimate contact with the binder of the next tape layer in a tightly packed reel, is known to produce carbonic acid in reaction with chloric acid.
The reaction occurs only rarely and under extreme conditions, and should be of no concern. It is only noted here to assure completeness of the tape component degradation discussion.
5. **MAGNETIC MEDIA HANDLING AND STORAGE FOR MAXIMUM LIFE EXPECTANCY**

**GENERAL CONSIDERATIONS**

Magnetic recording media degrades with aging as its components are subjected to undesirable physical effects and chemical reactions. Examination of each component and its degradation mechanisms clarifies how media life expectancy can be maximized.

One of the most critical factors in preserving metal particle based magnetic media integrity is the preservation of the chemical structure and the physical strength (tensile strength in particular) of the binder system.

Another important concern is how to prevent magnetic particle corrosion from various binder hydrolysis by-products and other corrosive chemicals.

The reduction of magnetic remanence occurring from particle corrosion results in lower signal output, degraded S/N ratio, and higher error rates.

Mistracking due to the base film physical deformation caused by heat shrinkage significantly increases the error rates from the recorded tracks furthest away from the tape guiding edge.

All these undesirable effects are either preventable or retardation of the rate of progress possible by keeping the media under appropriate temperature and humidity environments.

There are no technical reasons to specify separate combinations of temperature and relative humidity for different storage duration requirements. The same criteria apply for operations and transportation environments.

Only economic considerations (lower temperature and lower humidity air conditioning operation is expensive), practical limitations (recorder operators may feel uncomfortable), or uncontrollable circumstances should be the reason or excuse to deviate from the acceptable conditions.

The minimum allowable operating environments are bracketed by the following boundary conditions:

1. Zero or lower hydrolysis area (below 15%)
2. Below 40 degrees Celsius for absolute non-occurrence of base film heat shrinkage

3. Above 20% RH for lubricant evaporation prevention

4. Below 40 degrees Celsius and 80% RH for possible binder separation (head clogging) in operation

5. About 20% RH for prevention of excessively high back coat electrical resistivity. High electrical resistivity may cause uncontrolled static electricity discharges.

Figure 16 shows the above-mentioned minimum allowable operating conditions and the environment acceptable for storage operations.
AIRBORNE POLLUTANTS

Various types of airborne pollutants, including toxic gas, do exist in the general environment. They come as combustion (automobile, cooking, etc.) byproducts, from furniture and garment cleaning agents, outgassing from furniture and internal office walls, and other sources. Some of these pollutants are chemically reactive to components of both magnetic and optical storage media.

Chloride, used in many cleaning and bleaching agents, is particularly reactive to magnetic materials used in Metal Evaporated and Metal Particle tape.

Cobalt, used as the main magnetic recording material for metal evaporated tape and magneto optical disk media, reacts with chloride, sulfur dioxide and hydrogen sulfide. High temperature and high humidity accelerate chemical reactions.

Media manufacturers generally test their products against airborne pollutants in accordance with industry standards established for the testing of other electronic components and systems.

The evaluation criteria, i.e., the level of pollutants in the test chamber atmosphere do vary from one National standard to another. The deviations, however, are small, and tests are generally conducted at 75% relative humidity and 25 degree Celsius temperature. Japanese standards call for tests at a higher temperature, normally 40 degrees Celsius, and at a higher humidity level, 85%.
### Table 8. Airborne Pollutant Levels

Test duration is 500 hours or 21 days (504 hours).

Pollutant levels for product testing are several times higher than the permissible exposure limit, PEL, specified by the US Occupational Health and Safety Administration, OSHA, and as much as 1,000 times the level normally encountered in the US business office environments.

As media manufacturers do not specify the highest acceptable pollutant levels for maximization of media life expectancy, definitive pollutant level guidelines are not available. Manufacturers’ test data, however, indicate that an increase of up to 10 times

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Sources</th>
<th>Product Test Conditions 1</th>
<th>OSHA Industrial Hygiene 2</th>
<th>U.S. Business Office 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen Dioxide</td>
<td>Combustion</td>
<td>30</td>
<td>5</td>
<td>0.02</td>
</tr>
<tr>
<td>Sulfur Dioxide</td>
<td>Combustion</td>
<td>30</td>
<td>5</td>
<td>0.05</td>
</tr>
<tr>
<td>Hydrogen Sulfide</td>
<td>Combustion</td>
<td>15</td>
<td>--</td>
<td>0.02</td>
</tr>
<tr>
<td>Hydrogen Chloride</td>
<td>Cleaning Agents</td>
<td>15</td>
<td>5</td>
<td>0.005</td>
</tr>
<tr>
<td>Isopropyl Alcohol</td>
<td>Cleaning Agents</td>
<td>--</td>
<td>400</td>
<td>1</td>
</tr>
<tr>
<td>Formaldehyde</td>
<td>Building and Furniture</td>
<td>--</td>
<td>3</td>
<td>0.1</td>
</tr>
</tbody>
</table>

**Notes:**
1. Japan Electronic Industry Development Association Test Standards--500 hours at 40 degrees C and 85 % RH
2. Permissible Exposure Limit (PEL)--8 hours per day
3. Average of highest levels measured in business offices in major US cities
in error rates have been observed after 500 hours of exposure to pollutants at 40 degrees Celsius temperature and 85% relative humidity.

As the conditions prevailing in the business office area are several orders of magnitude more favorable than the test chamber, it is assumed that currently produced storage media are immune to airborne pollutant levels normally encountered in U.S. business office environments.

It is prudent, however, to monitor, or periodically check the air quality in the storage area used for large collections of electronic data.

Table 8 shows the types of pollutants which may react chemically with magnetic and optical storage media, the pollutant level used for product testing, the OSHA industrial hygiene Permissible Exposure Limit (PEL) specification, and measured levels in U.S. business offices.

**THE NEED FOR ACCLIMATIZATION WHEN CHANGING TO ANOTHER ENVIRONMENT**

It takes time for magnetic recording media, especially tightly wound tape, to acclimatize to new environmental conditions. When tape is removed from a low temperature/low humidity storage area, it must be conditioned before it can be used under higher temperature/higher humidity operating conditions.

The accepted rate of acclimatization is one hour for each 10 degrees Celsius of temperature change and 5% RH change in either direction.

**ORIENTATION OF THE MEDIA PACKAGE IN STORAGE**

Before storing a tape cassette or cartridge, the tape should be fully rewound into the supply spool.

Magnetic tape cassettes or spools filled with tape should be stored vertically, meaning that the spool flanges must be oriented vertically with respect to the horizontal, flat, storage bin surface.

The tape pack must be in between two flange surfaces, not touching either of the inner flange surfaces.

Improperly wound tape packs should be rewound in a more accurately aligned tape transport deck.
RESPOOLING

Tape wound on a spool, especially the innermost portion of it, is under high compression stress. The high stress can cause damage to the magnetic layer, resulting in increased error rates.

It is recommended to respool the tape at regular intervals at least once per year, and preferably twice per year. It should be run forward to the tape end and then rewound to the beginning.

Spooling should occur at the normal record/playback speed, and on a well maintained and accurately aligned tape transport deck.

Respooling has generated the highly misleading notion that it actually damages and shortens tape life. This was and could still be the case when respooling was (is) done by a so called “spare transport”, a tape deck that is not in regular use and is not properly aligned, and when tape is rewound at a high linear tape speed.

Properly executed respooling is highly desirable and extends media life by releasing inner tape tension, as well as the moisture accidentally trapped within the tape pack.
6. **Optical Recording Overview**

As briefly described below and shown schematically in Fig. 17, there are four basic types of optical recording/reproduction technologies in use today.

![Figure 17. Optical Recording Overview](image)

**Mass Replicated Disks**

Here data is in the form of lands and pits, with a wavelength elevation difference between lands and pits. Data reading is done by reflected laser beam intensity reading between two data areas. CD-Audio, CD-ROM, DVD-Video, DVD-Audio, and DVD-ROM belong to this category.
MAGNETO-OPTICAL RECORDING

The recording layer is a magnetic coating not significantly different from that used for the magnetic Hard Disk (HD).

The laser beam heats the recording spot to its near Curie temperature, and the magnetic head placed underneath reverses the polarity of the layer.

Recording occurs when leaving the laser beam continuously on and turning the magnetic head drive current on-off, or when leaving the magnetic head on, and using the laser for on-off operation.

Currently available products employ the latter recording technique. Data reading occurs by detection of the polarization angle rotation (Kerr effect) as the polarized laser beam is reflected off the magnetic layer or off the reflective layer below it.

PHASE CHANGE RECORDING

The state of certain metal alloys can be altered between their crystalline and amorphous phase, by heating and cooling them through prescribed temperature cycles. An alloy based on tellurium, with a small amount of antimony and germanium, exhibits a very reliable and reversible state or phase change.

When this recording medium is in its erased condition, the alloy will be in its crystalline phase. By heating a pit to an above melting point temperature by means of a laser beam, and letting it cool down rapidly as the laser beam is turned off and moved away, the pit goes into an amorphous phase, and this area becomes a Mark, or a recorded pit.

To erase the pit, the area must be heated again to just above the crystallization temperature below the melting point, cooled off naturally and go into a crystalline phase. Since erasure must precede any recording operation, a change must first occur at the recorded pits into a crystalline phase (erased state). The time required for heating and cooling of each pit is the time constant that determines how fast the system can operate as a recording device.

The light reflectivity difference between the amorphous phase (low reflectivity) and crystalline phase (high reflectivity) generates the playback signal. The same laser is used for recording, erasure, and reading by controlling its output energy as required.

This technique is used in an ISO/IEC standard 3-1/2 inch data drive, DVD-RAM, DVD-RW, and other optical disk drives.
POLYMER DYE CONDITIONING

The recording layer is a thin layer of a high-density organic dye polymer, sandwiched between a transparent substrate and a light reflective layer. A laser beam focused on a small spot heats the dye. The heat is trapped between the substrate and the reflective layer, elevating the area to a temperature of approximately 250 ~ 300 degrees Celsius, decomposing the dye’s chemical structure and altering its optical property.

The altered spot reflects less light than the original layer. The playback signal is the reflected laser beam intensity modulated by the reflectivity difference between the altered and non-altered spots.

The process is non-reversible, and this technique is used for write-once read-many (WORM) applications only. CD-R and DVD-R are based on this recording technique.
7. **MAJOR COMPONENTS OF OPTICAL MEDIA**

Although optical recording technology is applicable to both rigid and flexible media, products that are currently available are based on rigid media, e.g. inorganic glass, or polycarbonate disk media, etc. This report addresses the issues related to rigid media only, and the recording media will be referred to as the optical disk.

As shown in Fig. 18, the optical disk comprises two major components, the disk (substrate), and the recording layer. Depending on the type of recording technology, there may be other ancillary layers, some above and some below the recording layer.

![Figure 18. Optical Media Cross Section](image)

The environmental durability and stability of the recorded data against the passage of time, and under variable operating and storage conditions is governed almost exclusively by the physical and chemical characteristics of the substrate and the recording layer materials.
SUBSTRATE

The recording layer and other ancillary layers are coated on the substrate, which provides physical strength and stability to the layers.

The recording and read out laser beam must first penetrate the substrate in order to reach the recording layer, and the return read beam must go through the substrate again to reach the data reading optical system.

One of the most important characteristics of the substrate therefore, is its optical quality, including the light transparency to the laser wavelength--Near Infra Red (NIR) for CD and visible Red for DVD. Constant thickness and surface flatness, uniform light refraction, and an absence of birefringence are other required attributes.

Although optical recording/reading is a non-contact process, surface degradations such as scratches and scars defuse the light beam spot focused on the recording layer, generating detrimental efforts on both recording and read out operations. Therefore, a reasonable degree of surface hardness is necessary.

Because of the high areal density, maintenance of surface flatness is very important for optimum performance. Minute amounts of disk warping, or tilting as it is often referred to, greatly reduce the quality of the laser spot at the recording surface through both defocusing and spherical aberrations.

The dominant cause for disk warping is water vapor absorption. Contrary to a common sense notion, all polymer-based materials are water absorbers. When water molecules are absorbed by the exposed disk surface on the side opposite of the side facing the recording layer, it expands in radial direction, warping the disk in a convex manner as seen from the exposed surface.

The only non-absorbent material, inorganic glass, is expensive and is used only in disks with a diameter larger than 20 cm.

A technique to prevent disk warping is to fabricate the finished disk by sandwiching two substrates of lesser thickness, as done in DVD products. The recording layer or layers is/are located inside the two sandwiched substrates, and the two water absorbing outer surfaces counteract each other to prevent warping.

The 5-inch (130 mm) diameter MO disk is also composed of two substrates sandwiched together. The CD disk, being a single substrate construction, is subject to warping.

In general, disk substrates of less than 130-mm diameter are mass-produced by high-speed injection molding processes. While the material is in a liquid state, at temperatures of 350 ~ 360 degrees Celsius, it is injected into the mold in less than 0.1 sec., then cooled
to its final form in 4 to 5 seconds, and removed from the processing machine. The material must flow smoothly and fluidly into the mold, which has a high length-to-thickness (L/t) aspect ratio. This smooth flow is another characteristic required of the substrate material.

Another important attribute required of an optical disk is its equal radial weight distribution, or its mass balance. The optical disk drive rotates the disk at high speed. Any degree of disk mass unbalance when the disk is rotated at a high speed, as in the case of an optical recorder or reader, will have highly detrimental effects on the optical head and disk interface conditions. It may result in improper recording, and may contain a high level of errors in reading.

In general, the disk as it leaves the manufacturing plant is in a mass balanced condition. Mass unbalance is often caused by a user who puts a sticker, a label, or tape on the disk for identification purposes. As the higher speed write and read drives become common rather than an exception, inadvertent disk mass unbalance must be avoided.

Substrate materials currently used for optical recording disk and their characteristics are shown below:

<table>
<thead>
<tr>
<th></th>
<th>PMMA</th>
<th>PC</th>
<th>Epoxies</th>
<th>Poly Olefins</th>
<th>Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmittance</td>
<td>.92</td>
<td>.88</td>
<td>.92</td>
<td>.90</td>
<td>.90</td>
</tr>
<tr>
<td>Refraction, n</td>
<td>1.49</td>
<td>1.58</td>
<td>1.54</td>
<td>1.53</td>
<td>1.52</td>
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<tr>
<td>Birefringence</td>
<td>20 ~ 30</td>
<td>20</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface Roughness</td>
<td>&lt;5</td>
<td>&lt;5</td>
<td>&lt;5</td>
<td>&lt;5</td>
<td>&lt;2</td>
</tr>
<tr>
<td>Glass Transition Temp.</td>
<td>100</td>
<td>150</td>
<td>115</td>
<td>140</td>
<td>530</td>
</tr>
<tr>
<td>Water Vapor Absorption</td>
<td>.3 ~ .6</td>
<td>.15 ~ .30</td>
<td>.10 ~ .15</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes:
- PMMA = Poly-Methyl-MethAcrylate
- PC = Poly-Carbonate
- Birefringence = Δn at 830 nm
- Surface Roughness = nm
- Glass Transition Temp = Degrees Celsius
- Water Vapor Absorption = Grams/m²/24 hour

Table 9. Optical Disk Substrate Material
Other than optical properties, important characteristics include the water absorption rate and the glass transition temperature. Surface area expansion by water absorption and the resultant warping of the disk has already been discussed.

The glass transition temperature relates to the temperature at which the substrate softens, and begins to distort its shape if an external force is applied to it, or through its own mass/weight.

Poly-Methyl-MethAcrylate (PMMA), with its good optical quality, was used extensively in earlier optical disk products, including Laser Disks (LD), first generation WORM, and magneto-optical (M-O) disks. Its low glass transition temperature and higher rate of water vapor absorption, however, made it more susceptible to degradation when exposed to higher temperatures and humidity.

Polycarbonate (PC) was initially avoided by the optical disk industry because of its relatively poor optical quality, especially its high light refraction index, and poorer light transmission factor. These deficiencies, however, can be overcome by progress in laser capability and signal processing electronics.

The superior environmental stability of polycarbonate was viewed as its important attribute, and at present practically all small diameter optical disk media are based on this material.

The cost differential between PMMA and PC, initially greatly in favor of PMMA, has also diminished as more PC based media are produced.

The Laser Disk (LD) continues to use PMMA, however. Its analog recording signal system requires PMMA’s higher optical quality.

While it is significantly better than PMMA, PC is still subject to degradation by temperature and humidity. The importance of storing optical recording media at lower temperatures and drier humidity conditions, as demonstrated by magnetic recording media, is again amply shown here.

Like all other organic optical media, polycarbonate disks may craze, generating small irreversible surface deformations that can lead to permeability. Some disks may also exhibit higher levels of birefringence, which cause poorer readout signal performance.
8. **Optical Disk General Degradation Process**

As previously shown in Fig 18, the common structure of optical disk memory consists of the recording layer and the light reflective coating placed upon the optically transparent substrate. A layer of continuous organic material covers the entire structure, including the disk circumference, for protection against its surroundings. On the recording layer side, opposite from the substrate, a silk-screened layer is placed over the protective lacquer coating for the manufacturer’s logo and labeling.

The substrate itself is an environmentally stable material, as it is the same material used for aircraft windshields.

Optical disks, however, degrade through the passage of time, often from the imperfect nature of their protective coatings. Microscopic pinholes develop on the protective coating by exposure to high temperature, high humidity, and exposure to high intensity light, and they allow water molecules and airborne pollutants to penetrate onto the recording and reflective layers. Imperfect sealing around the disk circumference is especially damaging.

The corroded reflective layer seriously degrades its functions as an effective light modulator, reducing the readout signal performance.

The recording layer, depending on the recording system technology employed, is also subject to corrosion.

As mentioned earlier, the moisture absorbed by the substrate warps the disk, and produces an improper optical head to disk interface.

Some materials used in the label silk screening process are known to chemically react with the reflective layer, lowering its reflectivity.

Both the materials and the coating process for the protective layer have been improved significantly since the first introduction of CD-Audio disk in the early 1980’s. The protective coating, according to most manufacturers, now provides a highly effective seal for the disk internal components. Some manufacturers are known to place two separate protective layers on the entire disk surface area.

The transition to more corrosion resistant materials for the reflective layer such as Gold, Silver, and Silver Alloy, initiated by disk manufacturers in mid 1990’s, has also alleviated the reflective layer degradation problem.
The polycarbonate substrate is, at least in the laboratory, subject to local hydrolysis, which in turn reduces its optical quality. However, there have never been known field problems based on substrate hydrolysis.

The optical disk degradation processes are shown graphically in Figure 19. Table 10 lists various causes for the disk degradation, including user-induced effects.

Desirable temperature and humidity conditions for optical disk are wider than for PET based magnetic recording media. While an air conditioned, human comfort zone is preferred, the polycarbonate material itself will maintain its required characteristics under conditions as high as 28 degrees Celsius and 85% relative humidity for at least one hundred years.

Considering the excellent environmental durability of the substrate, the life expectancy of the optical storage media depends mainly on the environmental durability of the reflective coating and the respective recording layer characteristics.

Among other substrate materials, some manufacturers now also use Polyolefin as a substrate.

**Figure 19. Optical Disk General Degradation Process**
## Optical Disk General Degradation Process

<table>
<thead>
<tr>
<th>Component</th>
<th>Process</th>
<th>Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disk Structure</td>
<td>Differential Expansion/Contraction between Substrate and Protective Coating by Temperature/Humidity Variations</td>
<td>Loss of Disk Flatness, Warping and Tilting</td>
</tr>
<tr>
<td>Protective Coating</td>
<td>Oxidation</td>
<td>Growth of Microscopic Pinholes and loss of Hermetic Seal</td>
</tr>
<tr>
<td>Silk Screened Label</td>
<td>Chemical Reaction with Reflective Layer</td>
<td>Reflective Layer Corrosion</td>
</tr>
<tr>
<td>Substrate</td>
<td>Local Hydrolysis</td>
<td>Localized Reduced Transparency</td>
</tr>
<tr>
<td></td>
<td>Water Absorption</td>
<td>Loss of Disk Flatness</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cylindrical Warping</td>
</tr>
<tr>
<td>Reflective Layer</td>
<td>(Format Specific)</td>
<td>(Format Specific)</td>
</tr>
</tbody>
</table>

### User Induced Effects

<table>
<thead>
<tr>
<th>Manually Placed Label</th>
<th>Differential Expansion/Contraction between Label and Protective Coating</th>
<th>Loss of Disk Flatness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Protective Coating Peeling</td>
</tr>
<tr>
<td>Writing on Label by Sharp Point Instrument</td>
<td>Physical Damages to Protective Coating, Recording and Reflective Layers</td>
<td>Permanent Loss of Data</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Irregular Disk Rotation</td>
</tr>
</tbody>
</table>

**Table 10. Optical Disk General Degradation Process**
9. **RECORDING LAYERS: ENVIRONMENTAL STABILITY AND FAILURE MECHANISMS--A FORMAT SPECIFIC ISSUE**

The aforementioned description of optical disk substrates indicates that optical recording media durability and storage life expectancy are not determined by the characteristics of the substrates.

Indeed the recording layer materials and their extended term stability under use and storage conditions are the major factors that control overall media stability.

Environmental media stability is, therefore, recording-technology specific.

**READ ONLY MEMORY, CD-ROM, DVD-ROM**

The mechanism for data storage is identical for CD-ROM and DVD-ROM. The length of the optical path from the data storage surface to the reader’s lens optics is offset by _ wavelength for the Mark (One, recorded on a pit) and Space (Zero, unrecorded area on land), generating a near cancellation of the light reflected from the mark area (pit).

Therefore, to maintain high integrity of the readout signal, the optical path difference, or the elevation offset between the Mark area and Space area must be preserved. Any dimensional change due to temperature and humidity does not effect the elevation difference, generated when the disk was replicated by means of injection molding. Therefore, the likelihood of Mark-Space elevation changes due to long term storage is not an issue.

The reflective layer for CD and DVD-ROM is a sputtered metal coating of 50 to 100 nm thickness. Although aluminum alloy is the most commonly used metal, others such as gold or silver have been used. Since the polycarbonate substrate used for CD-ROM and DVD-ROM is less water absorbing, the protection coating against oxidation normally used in PMMA disk substrates, e.g. Laser Disks, has been omitted.

Water transmission through polycarbonate is minimal and is only measurable by means of laboratory instruments. However, the path through the protective layer is vulnerable, especially if the layer is imperfect and/or damaged.

Water molecules can penetrate through the disk edge if the protective layer does not provide an effective seal around the disk circumference.
These problems, however, are not basic to the design of the disk. They are either defects introduced during manufacturing or compromises or damages due to mishandling.

Therefore, even under conditions of relatively high temperatures (28 degrees Celsius) and high humidity (RH = 85%), oxidation of the reflective layer extensive enough to cause a detectable level of signal quality degradation (S/N loss of 3 dB or more) is improbable for 50 years or longer for the better brands of pre-recorded memory.

Under excessively high levels of humidity, the CD front layer (where the read light beam enters) may expand through water absorption with respect to the rear side, warping the disk so that the disk edge sags with respect to the center.

Such physical deformities may increase the error rate for the outer tracks. CD-ROM's have a high-capability two-stage EDAC system that should be able to cope with such circumstances.

All DVD-ROM disks are of double (two)-disk construction so edge sagging from water absorption is unlikely.

Read only memory optical disk degradation possibilities are shown graphically in Fig. 20.

Figure 20. Optical Disk ROM Memory Degradation Process
MAGNETO OPTICAL DISK

The recording layer of the Magneto Optical Disk is a complex, multi-element alloy composition that must meet the following requirements:

- Low Curie temperature for high recording sensitivity
- High Kerr angle rotation for high signal output
- Moderate level of coercivity
- Minimum of 10,000 record/re-record operations

The composition currently used to meet these requirements is a combination of Rare Earth Elements (RE) and Transition Metals (TM).

Commonly employed rare earth elements are terbium (Tb), gadolinium (Gd), neodymium (Nd), and dysprosium (Dy). Iron (Fe) and cobalt (Co) are transition metals used for the recording layer.

The number of reliable record/erase cycles is one of the important characteristics for the complex, sputtered alloy recording layer, and it can be controlled by making the layer more RE or TM rich. In general, increasing TM content yields better read-out signal levels with a constant noise floor over many thousands of record/re-record operations.

The RE-TM layer is corrosive, especially under high temperature/high humidity conditions.

The recording layer also has a tendency to develop pinholes and sometimes encounters de-alloying, meaning a breakdown of the alloy structure. These problems are, of course, known to the developers/manufacturers of the MO media, and effective means to cope with the situation have been developed. Addition of such materials as thulium (Ti), chromium (Cr) and platinum (Pt) prevents pinhole development. De-alloying is considered to be a manufacturing process anomaly, where a number of targets are used concurrently during the sputtering phase.

A cross section of representative magneto-optical memory disks is shown schematically in Fig. 21.
Both three and four layer constructions are used. The four layer disk, where a light reflection layer is placed below the magnetic layer, offers a greater signal output level because the readout beam passes the magnetic layer twice, doubling the Kerr angle rotation.

The RE-TM recording layer is protected from both sides by a layer of non-corrosive materials.
Al-Si-N, Al-Si-ON, and/or a mixture of terbium and SiO$_2$, Tb-SiO$_2$, are used as protective layer compounds. The protection layer not only prevents recording layer corrosion, it often acts as a high refraction index optical element to increase the reflected beam Kerr rotation angle, thus enhancing read out signal output. The processes through which magneto-optical disk performance capability degrades are shown in Table 11.

<table>
<thead>
<tr>
<th>Magneto - Optical Disk Degradation Process</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Recording Layer</strong></td>
</tr>
<tr>
<td><strong>Degradation</strong></td>
</tr>
<tr>
<td>Coercivity Reduction</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Kerr Angle Rotation</td>
</tr>
<tr>
<td>Reflectivity Reduction</td>
</tr>
<tr>
<td><strong>Protection Layer</strong></td>
</tr>
<tr>
<td>Pinhole growth providing Moisture/Pollutant Passage to Recording Layer</td>
</tr>
</tbody>
</table>

Table 11. Magneto-Optical Disk Degradation Process

Because of the known corrosion prone characteristics of Magneto-Optical media, much effort has been exerted to make the media stable against the environment.

The standard test procedure employed by the media manufacturers includes repeated recording/re-recording after 2,000 hour-long storage at 85 degrees Celsius and 85% relative humidity.

The excellent media survivability under these harsh temperature and relative humidity conditions indicates that MO media has a life expectancy of greater than 30 years at 25 degrees Celsius and 50% relative humidity.
PHASE CHANGE DISK

Phase change recording technology uses a reversible crystalline-amorphous phase change alloy as its recording medium and was first developed in the mid 1970’s. All earlier experiments and the first generation of products (for analog video recording applications) were based on an alloy composed of tellurium and tellurium oxide.

When it was first introduced in the early 1980’s, the stability of the first generation alloy was unsatisfactory in both its crystalline (erased state) and amorphous (recorded state) phase. Clearly, phase change recorders entered the marketplace prematurely. This fact unfortunately had generated some negative user opinions towards phase change technology in general. Hence it was concluded that phase change technology was not as reliable as magneto-optical recording.

A new, highly reliable and stable alloy was developed in the late 1980’s. This new alloy, still based on tellurium but also containing antimony (Sb) and germanium (Ge), is often referred to as “GeSbTe” metal.

The material is highly stable in both phases, and to transition it from a crystalline phase to an amorphous phase during recording, it must be heated to approximately 600 degrees Celsius, which is above its material melting temperature, then letting it cool rapidly to its amorphous phase.

Erasure implies a return to the crystalline phase and is accomplished by heating the recorded area (mark area, or pit) to just above its crystallization temperature of approximately 400 degrees Celsius, then letting it cool naturally to form crystals.

The environmental stability of this phase-change medium is a benefit as recording and erasing occur at a temperature range far above normal environmental conditions.

All small format phase-change media are based on polycarbonate substrates. The recording layer is sandwiched between two protective layers in order not to harm the substrate during the high temperature erase/record operations. The protective layer must consist of high melting point dielectric material, and it should be optically transparent. The most commonly used material is ZnS-SiO₂, Zinc Sulfide-Silicon Dioxide. And because it is optically transparent, it does not absorb the laser energy.

Phase change media recording/erasure operations are shown in Fig. 22.
Phase change recording is an attractive data storage technology applicable to the entire spectrum of products, including audio, video, imagery, instrumentation, and text/numerical data recorders.

The phase change recording technology is not completely immune from recording state degradation. After repeated recording and erasing cycles, the material is known to develop a tendency to grow crystals within its amorphous structure, the recorded phase condition. Another undesirable characteristic that develops with the passage of time and repeated re-recording operations is the migration of the amorphous state material to a crystalline state, and a partial decomposition of the alloy lattice structure.
All these effects accelerate in higher temperature environments.

Development of these effects, however, can be slowed down considerably by exercising the material in such a manner as to reverse the phase of each spot on every recording cycle. This is the exact technique employed to extend the number of usable recording cycles to over a 100,000 times.

The phase change recording media degradation processes are listed in Table 12.

Figure 23 shows the life expectancy data for the phase change media, interpreted from accelerated life testing conditions. As shown, a fifty-year life expectancy at a storage temperature of 25 degrees Celsius or lower, is the most conservative estimate.

The medium is relatively insensitive to humidity and maintaining the RH below 70% is considered to be adequate.

<table>
<thead>
<tr>
<th>Degradation</th>
<th>Process</th>
<th>Induced By</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recorded Area Particle</td>
<td>Crystal Growth in Amorphous Phase Region</td>
<td>High Temperature</td>
</tr>
<tr>
<td>Erasure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recorded Area Boundary</td>
<td>Amorphous Material Migration to Crystallized</td>
<td>High Temperature</td>
</tr>
<tr>
<td>Defusion</td>
<td>surroundings</td>
<td></td>
</tr>
<tr>
<td>Reflectivity Modulation Depth</td>
<td>Partial Alloy Decomposition</td>
<td>High Temperature</td>
</tr>
<tr>
<td>Reduction</td>
<td>Alloy Surface Corrosion</td>
<td></td>
</tr>
<tr>
<td>Incomplete Recording Process</td>
<td>Incomplete Transition from Crystalline to Amorphous Phase</td>
<td>Thermal Fatigue due to Repeated Recording Processes</td>
</tr>
<tr>
<td>on Repeated Recording</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 12. Phase Change Disk Degradation Process
Figure 23. Phase Change Media Archival Life Projections
ORGANIC-DIE POLYMER WORM DISK--CD-R, DVD-R

CD-R and DVD-R are the types of recording media that can only be written once. The recording process permanently alters the optical characteristics of the medium, thus the process is irreversible. The disk can be read as many times as injection-molded media. The writing process does not have to be done at one time nor continuously for the entire disk surface.

As with a paper notebook, these disks may be written as required or desired. For this reason, the Write-Once-Read-Many times (WORM) disk is sometimes referred to as an electronic notebook.

The recording layer is composed of a high-density organic-dye polymer, based on such materials as phthalocyanine. The dye layer is sandwiched between the polycarbonate substrate and the light reflective layer of aluminum, silver, or gold.
As shown in Fig. 24, the laser beam focused on the recording layer is used to heat the mark spot (pit). As the dye absorbs laser energy, it heats up to approximately 250 to 300 degrees Celsius. As the substrate is a heat insulator and the reflective layer returns the energy from the heated dye back to the dye itself, dye heating occurs rapidly and as the dye decomposes, its optical characteristics are permanently altered.
The substrate immediately above the mark spot was also melted by heat. As it cools down, a mixture of the substrate and decomposed dye, with much reduced light transparency, is formed.

In order to produce a clearly defined pit (mark), the recording layer is required to trap the heat vertically inside the laser spot diameter circle. Any heat transfer in a radial direction is detrimental to the formation of a pit with its diameter defined only by the laser beam energy profile. To achieve this condition, the dye is chemically formed to make it minimally heat conductive.

The manufacturers currently use three types of organic dye compound: cyanine, phthalo-cyanine, and azo. Cyanine, initially used by some media manufacturers, is known to exhibit a shorter storage life if it is continuously exposed to ambient light.

When it is exposed to UV, visible or near IR radiation, the polymer dye gradually loses its ability to absorb heat, the essential characteristic required for rapid decomposition. Current compositions, however, have proven to be extremely resistant to such radiation. Based on accelerated tests using high intensity light exposure, all three dye formations are immune to degradation from continuous exposure under normal room illumination.

Manufacturers believe that WORM media have life expectancies of 100 years or longer at 25 degrees Celsius or lower temperatures and 70% or drier relative humidity. This life expectancy includes its non-recorded shelf life. Although unrecorded media has now been proven to be insensitive to light, it is nevertheless recommended to store unrecorded, partially or fully recorded media in relative darkness.

Degradation of WORM media takes place in the form of chemical decomposition of the unrecorded area and the gradual loss of the reflective layer performance due to oxidation. This process makes the light reflectivity difference smaller between the recorded and unrecorded areas, causing higher error rates in the read out signal. The growth of pinholes in the media has also been observed. WORM disk degradation processes are shown in Table 13.
### Write Once Optical Disk Degradation Process

#### Recording Layer

<table>
<thead>
<tr>
<th>Degradation</th>
<th>Process</th>
<th>Induced By</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radial Expansion of Recorded Area</td>
<td>Chemical Decomposition of Area Surrounding Recorded Area</td>
<td>• High Temperature</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Exposure to High Intensity UV-Visual-IR Radiation</td>
</tr>
<tr>
<td>Reflectivity Modulation Depth Reduction</td>
<td>Chemical Decomposition of Unrecorded Area</td>
<td>• Exposure to High Intensity UV-Visual-IR Radiation</td>
</tr>
<tr>
<td></td>
<td>Pinhole Growth</td>
<td>• High Temperature</td>
</tr>
<tr>
<td></td>
<td>Loss of reflective layer optical performance</td>
<td>• Airborne Pollutants and Moisture</td>
</tr>
</tbody>
</table>

**Table 13. Write Once Optical Disk Degradation Process—Recording Layer**

As with Read-Only Memory (ROM) disks, the possibility also exists for water molecule seepage through defects in the thin protective coating covering the surface on the non-reading side, as well as along the outer edge of the disk.

These can be caused by disk handling errors, scratches, removal of labels, the use of damaging inks or accidents.

Fig. 25 shows CD-R life expectancy projections of two manufacturers.
Figure 25. CD-R Disk Archival Life Projections
10. **Manual Handling and Labeling of Optical Disk**

Unlike the 3-1/2 inch floppy disk, which is completely enclosed in a protective jacket, most small format optical disk, including the disk for some recordable formats, are not enclosed in a jacket.

Incidences of disk damages and accidental loss of the data contained in a disk are frequent because of the exposed disk. The transparent substrate side of the disk is physically more enduring than the label side and makes the damage due to mishandling more prevalent.

The label side is closer to the physically and chemically sensitive recording layer and the reflective coating. One or two coatings of thin (typically 10~50 µm) and relatively soft organic material protect these sensitive layers.

The manufacturer’s logo and label are silk-screened onto the protective coating(s).

The disk label side should be handled with utmost care.

As the use of recordable disk becomes more common, users wish to place a content identification and description label on the disk itself. This should not be done by placing a self-adhesive label or a piece of tape on the disk. The mass of the manually placed label is significant if compared to the light weight of the disk, and it seriously impairs the delicate mass balance of the disk. In a high speed reader, the disk mass unbalance causes irregular rotation of the disk and poorer interface conditions between the read head and the disk, making the recovered data unusable because of the excessively high error rate.

The content identification and description should be written on the disk label area by using a soft point, water soluble, permanent ink pen. Writing by a sharp point instrument will permanently damage the disk recording layer.

Volume users should use a thermal or ink-jet printer that is designed for disk labeling.

The unknown nature of the adhesive used to place the label is another concern. Damaging chemical reactions between the disk layers and the adhesive are possible. A label, once placed, should not be removed from the disk. The delicate protective layer may be peeled and or damaged.

Specially designed self-adhesive labels which does not degrade the disk mass balance and with a chemically inert adhesive, are also available.
11. SUMMARY AND CONCLUSIONS

DATA STORAGE MEDIA CHARACTERISTICS

The flexible magnetic and optical disk-based data storage media that have been addressed in this report have the following characteristics:

<table>
<thead>
<tr>
<th>Flexible Magnetic Media</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle Media</td>
</tr>
<tr>
<td>An organic substrate coated with an organic</td>
</tr>
<tr>
<td>binder containing metal oxide or pure metal</td>
</tr>
<tr>
<td>particles.</td>
</tr>
<tr>
<td>Evaporated Media</td>
</tr>
<tr>
<td>Evaporated metal directly deposited on an</td>
</tr>
<tr>
<td>organic substrate.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Optical Disk Media</th>
</tr>
</thead>
<tbody>
<tr>
<td>Playback Only Media</td>
</tr>
<tr>
<td>An injection-molded organic substrate with</td>
</tr>
<tr>
<td>pits molded on flat lands, coated by a</td>
</tr>
<tr>
<td>metallic reflective coating.</td>
</tr>
<tr>
<td>Record/Playback</td>
</tr>
<tr>
<td>An organic substrate coated with an alloy</td>
</tr>
<tr>
<td>recording layer with inorganic protection</td>
</tr>
<tr>
<td>layers.</td>
</tr>
<tr>
<td>WORM</td>
</tr>
<tr>
<td>An organic substrate with an organic</td>
</tr>
<tr>
<td>record-once layer with a metallic reflective</td>
</tr>
<tr>
<td>coating.</td>
</tr>
</tbody>
</table>

Table 13. Characteristics of Flexible Magnetic and Optical Disk Storage Media

PREFERRED ENVIRONMENTS FOR DATA STORAGE MEDIA

The major components on which data storage media are based are an organic substrate, tape binders composed of a myriad of organic chemicals, corrosion-prone metal compounds, and various forms of thin metallic and organic coatings.

To preserve their physical, magnetic and chemical integrity, preferred optimum storage conditions are show below.
### Table 14. Preferred Optimum Storage Conditions for Media Components

<table>
<thead>
<tr>
<th>Media Component</th>
<th>Preferred Environment</th>
<th>Benefits/Advantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organic substrate</td>
<td>Cool temperature/low humidity</td>
<td>Deformation prevention</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Water absorption prevention</td>
</tr>
<tr>
<td>Organic binder</td>
<td>Cool temperature/low humidity</td>
<td>Hydrolysis retardation</td>
</tr>
<tr>
<td>Inorganic recording Layer</td>
<td>Low humidity</td>
<td>Corrosion prevention</td>
</tr>
<tr>
<td>Metallic reflective layer</td>
<td>Low humidity</td>
<td>Corrosion prevention</td>
</tr>
</tbody>
</table>

#### The Human Comfort Zone

The American Society of Heating, Refrigeration and Air Conditioning Engineers defines temperature and humidity ranges that are comfortable for human beings in a so-called Human Comfort Zone Chart, as follows:

- A temperature range between 20 to 25 degrees C (68 to 77 degrees F)
- Relative humidity between 40 to 60%

The human comfort zone, thus defined, encompasses the environment where hydrolysis activities for binder compounds in currently produced magnetic media are low, i.e., between equilibrium (zero) to 15% activity. Hydrolysis is the major source of degradation for particle media binder systems.

Lower humidity also prevents or retards the corrosion process of metals, which has a detrimental effect on magnetic media (magnetic retentivity loss) and optical media (recording layer decomposition and lower light reflectivity).

#### Storage Conditions for Magnetic Media

Starting from the human comfort zone and moving towards lower temperatures (12 degrees C) and lower humidity (25% RH), we define this zone as ideal for obtaining a maximum life expectancy from the magnetic media.
By keeping the media at low temperature and low humidity, the life expectancy of currently produced magnetic media, including metal oxide, cobalt modified metal oxide, MP, and ME tape can be 50 years or longer.

Moving towards warmer temperatures and slightly higher humidity while staying within the human comfort zone, life expectancy for the above mentioned recording media types is still in excess of 30 years.

Inside this life span, there are minor but discernible differences among recording media types in terms of maintaining magnetic remanence.

Media types, in order of magnetic remanence loss rate, with the smallest loss rate listed first, are shown below:

- Metal oxide, Barium Ferrite
- Cobalt adsorbed/absorbed Gamma Oxide, MP, Dual layer MP
- DLC protected Cobalt ME, AME
- Chromium Dioxide, Cobalt-Nickel ME

All media, except for the last ones listed, i.e., chromium dioxide and cobalt-nickel ME, meet the aforementioned 50-year/30-year life expectancy projections.

Media listed on the last line may have a shorter life expectancy of 30 years/20 years under the same storage conditions.

Other storage and operational precautions described in the text are prerequisites for safe media storage for an extended duration.

**OPTICAL MEDIA STORAGE CONDITIONS AND LIFE EXPECTANCY**

Some recording and light reflecting layers used in optical disks, e.g., Magneto Optical layer, aluminum and silver reflective coatings, are subject to corrosion and oxidation.

Although these layers are protected against outside environmental conditions, water molecules and airborne pollutants do reach the sensitive area by penetrating through the organic substrate and the protective coating.

Water molecules do reach the sensitive layers of the disk despite the extremely low transmission rate of polycarbonate, the material most commonly used for small diameter (smaller than 130 mm, 5 _ inch) optical disks.

The preferred operating and storage temperature range for optical disk media is essentially the same as for magnetic media.
The preferred relative humidity ranges, however, are more relaxed because optical disk media do not have an exposed moisture-absorbing surface, such as the magnetic binder.

Optical disk media life expectancy at 25 degrees Celsius or lower temperatures and 50% or drier relative humidity is included in Table 15.

AIRBORNE POLLUTANTS

Airborne pollutants, by themselves or in the presence of moisture, react with magnetic and optical storage media, and degrade their performance, leading to lower signal output levels and higher error rates.

The prevailing levels in U.S. business offices and residential environments represent one thousandth of the pollutant levels used by manufacturers for product testing, or 10 to 30 parts per billion for the most common pollutants.

Such pollutant levels are acceptable for operation and storage of the media.

Occasional checks of pollutant levels, as done by public libraries and museums, are recommended.

CONCLUSIONS

Magnetic and optical media life expectancy, when they are used and stored in air-conditioned office conditions, can be considerably longer than the 25-year cycle of production and active use life of the storage devices and systems.

When they are stored in cooler and drier conditions, they are expected to produce an acceptable level of output signal quality well beyond this timeframe.

Data storage media gradually lose their ability to produce acceptable levels of signal quality and eventually reach the point where they are not able to meet the required signal quality, defined as the end of life.

Therefore, it is prudent to use, transport, and maintain the media under the conditions prescribed for maximum life expectancy, regardless of the intended useful life of the media. Thus, the best possible signal quality would be available throughout the life of such media.
It is not necessary to maintain ideal conditions for storage and use of the media to extract a reasonable life. But non-air-conditioned, uncontrolled temperatures, and high humidity conditions should be avoided.

<table>
<thead>
<tr>
<th>Magnetic and Optical Disk Media Life Expectancy Projections¹ (In Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Flexible Magnetic Media (Tape, Floppy Disk)</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Gamma Ferric Iron Oxide</td>
</tr>
<tr>
<td>Barium Ferrite</td>
</tr>
<tr>
<td>Cobalt Adsorbed/Absorbed Iron Oxide</td>
</tr>
<tr>
<td>MP, Dual Coat MP</td>
</tr>
<tr>
<td>DLC Protected Cobalt ME, AME</td>
</tr>
<tr>
<td>Chromium dioxide, Co-Ni ME</td>
</tr>
<tr>
<td><strong>Optical Disk Media</strong></td>
</tr>
<tr>
<td>Read Only</td>
</tr>
<tr>
<td>WORM</td>
</tr>
<tr>
<td>Phase Change Write/Read</td>
</tr>
<tr>
<td>Magneto-Optical Write/Read</td>
</tr>
</tbody>
</table>

Notes:
(1) Number of + marks indicates level of industry confidence exceeding years shown, i.e., + = 10 years

Table 15. Magnetic and Optical Disk Media Life Expectancy Projections in Years
REFERENCES

As shown, a number of references listed are Japanese language documents. They include technical papers, reports prepared by industry organizations, and technical committee documents in the public domain.

Japanese language documents are identified by the mark (J) at the end of description.

In addition to listed references, the author benefited greatly by assistance provided by U.S. and Japanese storage media manufacturers in the form of twenty private written technical letters and correspondence.

Flexible Magnetic Media (Tape, Floppy Disk), General


Society of Motion Picture and Television Engineers, “Care, Storage, Operation, Handling and Shipping of Magnetic Recording Tape for Television, SMPTE, PP-103-95, Revised RP to be published in 2000.


Metal Particulate Media


**Metal Evaporated Media**


**Optical Disk Substrates**


**Magneto Optical Disk**


**Phase Change Optical Disk**


**WORM and ROM Disk**


Optical Industry Technology Advancement Association (Japan), Reports on Write Once Disk Reliability, 1988 (J).