Accelerated Aging of Polyester-Based Legacy Audio Magnetic Tape Stock

A Library of Congress/FUJIFILM Research Collaboration

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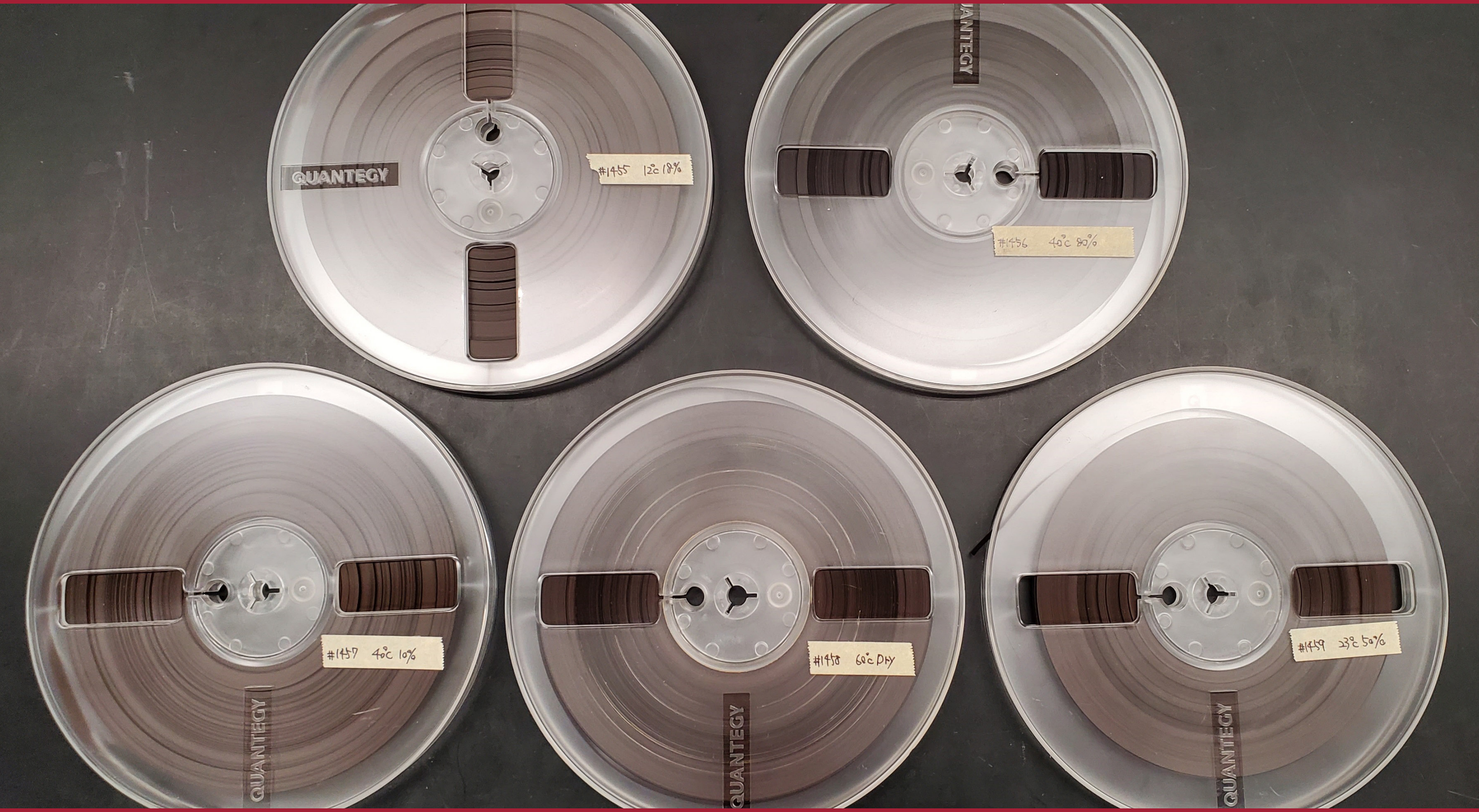

Council on Library and Information Resources

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Contents

Executive Summary

The poor physical playability of some polyester-based magnetic tapes is well known to audiovisual curators and is well documented in the field. These concerns are most frequently constrained to tapes from specific manufacturers over specific manufacturing time frames. Given the challenges that cultural heritage institutions have with safeguarding large collections of seemingly good magnetic tapes, this research explored whether or when currently playable tapes may present stability problems.

A cooperative research agreement between FUJIFILM Recording Media Products Division and the Library of Congress Preservation Research and Testing Division (PRTD) was undertaken to fully characterize changes in magnetic tapes related to ongoing stability during aging under different conditions. This collaborative research focused on two main areas: (1) applying a selection of accelerated temperature and relative humidity ranges, chosen to best predict and assess potential conditions for storage in institutions with and without controlled environmental options; and (2) assessing changes in physical, magnetic, and chemical properties that could impact the tapes' usability (e.g., winding, playback) and hence access to historic sound recordings.

The main research findings were as follows:

- Historic test tapes in playable condition continued to be easily and cleanly windable after accelerated aging across a range of temperature and relative humidity values.
- Physical and magnetic properties remained effectively unchanged after one year of accelerated aging, even at temperatures above common remedial baking temperatures. This magnetic stability suggests that briefly applied baking treatments likely have little detrimental effect on recorded content.
- Certain chemical properties decreased after aging, consistent with hydrolysis and lubricant loss, but these changes occurred only at the most extreme aging conditions and not sufficiently to cause playback problems.
- The observations indicated that under standard room temperature conditions (20-25°C), approximately 100 years would be needed for the tested playable tapes to reach the properties measured in unplayable tapes.
- Estimates for magnetic tape longevity provided confidence that tapes currently in good condition are unlikely to rapidly turn unplayable under standard room temperature conditions of 20-25°C.
- Manufacturing variations appeared more indicative of risk than environmental factors.

Additional reports will be made on material-level research from this work, including lubricant identifications, effects of baking, and back-coat interactions.

Results from this work suggest the need to update institutional knowledge and assumptions. Based on recommendations published 10 to 30 years prior to the time of this writing, the life expectancy for magnetic tapes was predicted to be 10 to 30 years if institutions adhered to published storage guidelines. This study of legacy tapes at the upper end of this age range offers an opportunity to re-evaluate those blanket predictions.

Introduction

In 2014 a cooperative agreement was established between FUJIFILM Corporation and the Library of Congress (LC). The collaboration developed from a meeting between colleagues at Fujifilm and LC's Preservation Research and Testing Division (PRTD) during a storage architecture conference. Subsequently, PRTD was made aware of the extensive accelerated testing that Fujifilm was already undertaking to assess the future stability of new storage media. This led to a discussion of how the testing of modern storage formats could be applied to historic polyester-based sound recordings to see whether magnetic tape degradation could be re-created through a range of accelerated aging conditions.

Motivation for Collaboration

The purpose of the agreement was to allow the partners to share physical materials from the PRTD reference sample collection (Library of Congress n.d.[a]), to degrade samples using age acceleration equipment at Fujifilm, and to gain access to technical expertise that is currently unavailable at LC. All materials tested in this agreement were polyester-based tapes available specifically for scientific testing and were not audio materials within LC's collection. Having access to these tapes allowed PRTD scientists to better observe differences between degraded and non-degraded tapes and to understand the aging behavior of test tapes of known provenance. Being able to access materials treated in Fujifilm's test facilities enabled LC to develop a deeper understanding of the physical mechanisms through which magnetic tape degrades over time. An improved understanding of polyester-based magnetic tape degradation processes, particularly relevant to tapes of controlled vintage, would then allow the PRTD to advise the National Audio-Visual Conservation Center (NAVCC) on planning for the ongoing preservation needs of LC's collections at the NAVCC and specifically how to identify collection materials at the greatest risk of being lost. Ultimately, these efforts could allow NAVCC to focus its preservation efforts and to transfer collection materials that are deemed most critical and subject to the highest risk before loss occurs.

Current Scope of Tapes and Storage

The poor physical playability of some magnetic tapes is well known to audiovisual curators and is already well documented in the literature, with physical degradation frequently assumed to already be present in certain historic tape formulations. While these known troublesome tapes receive the most discussion and attention, there remains uncertainty about the stability of currently playable historic magnetic tape recordings: How vulnerable are seemingly good tapes that fall outside the typical formulations of concern, and how concerned should we be about their longevity? These questions can be pressing for institutions that have large collections of seemingly good magnetic tapes and whose staff need to know whether those tapes will soon prove to be preservation challenges.

Previous publications estimated 10- to 30-year lifetimes for the physical stability of magnetic tape recordings when stored under conditions considered "access storage" (Van Bogart 1995; Canadian Conservation Institute 2020). Given the closure, consolidation, and cessation of many legacy magnetic media manufacturers in the 1990s and 2000s, legacy tapes from those manufacturers are now reaching the top end of the 10- to 30-year lifetime predictions. The timing is now particularly relevant to explore the preservation concerns of any tapes originating from that period. Revisiting these lifetime recommendations and providing additional technical testing might provide refinements to these decades-old recommendations.

Magnetic Media in Archives and Storage

Historically, magnetic tape-based storage media has been one of the most widely adopted technologies for archiving and retrieving audio and video recordings, computer data, and a wide variety of scientific measurements, telemetry, communication, and other electrical signals. For audio recordings, the low overall cost of magnetic tape made the medium a very attractive solution for archives needing to store hours upon hours of recordings. Preservation reformatting of older historic formats to audio tape and the collection of direct-to-

CHARM – A Reference Collection for Scientific Testing

PRTD hosts the Center for Heritage Analytical Reference Materials (CHARM), which was previously called CLASS (Center for the Library's Analytical Scientific Samples). CHARM is an extensive scientific reference collection comprising a range of heritage materials available for destructive testing, with a particular interest in correlating testing with non-invasive analyses available for collection objects. Fenella France began this collection in 2009 with roughly 1,000 test books from the Barrow Collection (ca. 1500–1900). CHARM currently includes more than 100 unique paper types and historical manufacturers' sample books, handmade papers, tree fiber samples (TAPPI), papyrus, multiple parchment types, photographic samples, colorant samples (pre-1800 to modern), paint-outs of historic recipes, Forbes pigments, the Jakes Reference Textile collection, materials used and donated by modern artists, and quality assurance reference materials used in housing and conservation repair.

Relevant to our study involving magnetic tapes, CHARM also includes a wide range of audiovisual materials and modern media. CHARM's collection spans roughly 50 wax cylinders; 350 records in the Thornton Record Collection; 500 open-reel audio tapes; and hundreds of CDs, cassette tapes, DV tapes, and assorted other magnetic videotapes (e.g., VHS, U-matic). Magnetic tapes within this collection include a range of compositions and conditions, including unsealed new-old stock formulations as well as calibration tapes, modern commercially available tapes, and tapes with audio content previously used for personal recordings. To date, these materials have primarily been used for various chemical, material, and aging experiments aimed at understanding topics related to physical preservation concerns.

The CHARM collection can be accessed by contacting PRTD for physical samples including baseline data from multiple instrument characterizations of each sample. The authors encourage researchers to use CHARM for predictive testing, assessment of treatments, development of new analytical techniques, and an understanding of how diverse materials change over time. This collection also includes a digital component, CHARM-D, which is in development as an interactive application with datasets from over 20 instrumental techniques following FAIR (Findability, Accessibility, Interoperability, and Reuse) data principles.

Additional details about this reference collection are available at: **https://loc.gov/preservation/scientists/projects/class.html**.

tape recordings were common during the second half of the twentieth century. The Library of Congress has amassed a collection of over half a million audio recordings on magnetic tape, and countless more recordings exist in studio and home archives worldwide.

Access to the recordings on these media is of vital cultural importance and requires further preservation reformatting to modern digital formats. The sheer volume of recordings would make reformatting a daunting and time-consuming task. The life of primary sources can be protected and preserved for as long as possible through dedicated handling, housing, and storage practices that conform to standards, recommendations, and best practices disseminated among institutions and revised as new studies or practices dictate (Brylawski et al. 2015; AES22-1997 (r2008) 1997; IASA-TC 05 2014; ISO 18923:2000 2000; Library of Congress n.d. [b]; National Archives and Records Administration 2020; Canadian Conservation Institute 2020).

For example, winding is important to the long-term health of a magnetic tape. Tapes often sit for long periods of time in storage, and a proper wind ensures that the tension and pack of the tape is evenly distributed across the surface of the tape. The speed at which a tape is wound can affect the alignment of the pack and distribution of the tension. At a higher speed, the chances that the tape will move up and down slightly during the wind are greater, causing the layers of the wind to not sit evenly with successive layers. This “scatter wind” can eventually cause bends, curls, buckles, and such in the tape that will make uniform contact with the playback head difficult, resulting in decreased audio fidelity. For these reasons, being able to cleanly wind and unwind a tape is critical to its preservation. Ease of clean, smooth winding (or lack thereof) is also a practical criterion for pre-playback evaluation of a tape’s physical condition.

Even with the best efforts, magnetic tapes are not immune to degradation over time. Several degradation symptoms have been observed and described with various terminology over the years. In polyester-based tapes alone, observed symptoms include squealing, dry shedding, and soft binder syndrome, among others, with varying levels of differences and commonalities among them. Richard Hess’s publication remains an unparalleled practical overview of the subtleties of particular symptoms (Hess 2008). Preservation of historic polyester tapes has been complicated by the fact that many of these symptoms have occurred in unpredictable ways, even between seemingly similar tape stocks.

Of note, certain polyester tape formulations manufactured mostly in the latter half of the 1970s through the 1980s have suffered from a physical decomposition ailment commonly referred to as “sticky-shed syndrome.” Many of these tapes are now widely known to the field as problematic models (Hess 2008; 2021).[1] Tapes suffering from sticky-shed syndrome are slightly tacky to extremely sticky and, if played, they can create a buildup of residue on the guides, roller, and tape heads of the deck. If playable at all, the tape will no longer pass

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[1] Note that we will be using the term *models* to refer to tape identifications that other users might call formulations (e.g., the “456” of Ampex 456). This is done to avoid confusion about manufacturing-level material formulations that might have unknown variations over time depending on material sourcing, trade secrets, and such.

smoothly through the deck, which impacts the health of both the deck and the tape as friction causes wear to both. With residue buildup across the playback head, the tape may no longer move at a consistent speed or come into complete contact with the head. This directly affects the quality and accuracy of sound reproduced. In short, attempted playback of a recording with sticky-shed syndrome can cause damage to the playback equipment, the physical tape, and informational content.

Several remedies for treating degraded tapes have been used over the years, and those remedies can often temporarily allow successful playback. Even if a remedy is possible, playability challenges still cause concern as eloquently summarized by Michael Heller: "After all, what good is a tape we cannot hear?" Rarely are syndromes such as sticky shed a death sentence, however, and most tape users are more challenged by lack of time and resources (Heller 2017). Ideally, it would be possible to controllably induce symptoms of sticky-shed syndrome in experimental tapes to better understand its nature and explore more controlled studies of its remedies and predicted occurrences. However, our efforts here, as well as internal efforts by PRTD and by others conveyed informally at technical gatherings, so far have not been able to reliably induce these characteristic degradation symptoms in clean tapes that have not already become sticky. In the meantime, collections staff must continue to make preservation decisions for current collections in both degraded and non-degraded conditions, without reliably knowing the time to failure or further degradation.

Why Polyester Tapes?

Commercial polyester tapes were first introduced in the 1950s and quickly gained widespread acceptance and use, surpassing that of tapes made from other base materials such as acetate or PVC. Unlike acetate tapes, the base polyester film is quite stable over time, but the polyester-urethane binders used in the magnetic layers of these tapes have been found to be susceptible to some degradation symptoms. Polyester-based tapes have also proven to be unpredictable in their batch-to-batch and tape-to-tape degradation severity. Some formulations are known to be widely problematic, but others anecdotally vary from user to user or batch to batch. This uncertainty may pose significant concern for preservation planning in light of the fact that most audiovisual collections are likely to have more polyester-based tapes than tapes made of other materials. Given the large number of polyester-based tapes in historic audiovisual collections and the inherent uncertainties about their stability, institutions would benefit greatly from having a better understanding of the ongoing preservation needs for their audiotape holdings based on up-to-date research findings.

During the 1960s and 70s, magnetic tapes continued gaining commercial popularity in new forms such as enclosed cassette tapes and videotapes. While the precise formulations of these formats differ from those of historic open-reel audiotapes, they are also all polyester-based. Given this commonality in materiality, some aspects of this study's findings on open-reel audiotapes may also be generally applicable to these other more recent polyester-based tape formats which persist in production to this day.

Current State of Storage and Lifetime Recommendations

Aside from reformatting, careful handling and storage environments are controllable ways to encourage tape preservation. Several standards, recommendations, and informal "best practices" have been published on considerations of magnetic tape lifetime and storage. The guidance consensus unanimously suggests long-term storage of open-reel polyester-based audio tapes in cool and dry conditions, which remain sensible recommendations given the known role of chemical hydrolysis as one aspect of the overall degradation process (Cuddihy 1980; Bertram and Cuddihy 1982; Brown, Lowry, and Smith 1982; 1983; 1984; Smith, Brown, and Lowry 1986).

At the same time, it remains difficult to assess the extent and speed at which "normal" building environments, roughly 68-75°F (20-25°C) at 30-60%RH, might affect tapes currently in acceptable condition. For example, a report published jointly by the Commission on Preservation and Access and National Media Laboratory in 1995 (subsequently cited in various recommendations by professional organizations such as the Audio Engineering Society, Association for Recorded Sound Collections, and the Canadian Conservation Institute, among others) cautioned that published lifetime estimates are often based only on chemical kinetics of hydrolysis even though tapes can fail for a variety of reasons including other consequences of friction, magnetic loss, or alternative factors (Van Bogart 1995). The published lifetime estimates are necessarily hindered by the use of fairly extreme temperature and timing constraints in the researchers' informative aging experiments, which are not necessarily applicable to natural aging. More on this topic is provided in the section on aging conditions.

Materials, Methods, and Testing

As with any study of mass-produced objects, our study is most applicable to the specific tapes tested here. It is unknown how much variation exists within the production run of any particular brand or model, and it is difficult to unequivocally account for all environmental, storage, and handling histories of an individual tape. To avoid these unknown historic variables as much as possible, our study aimed to measure variables shared with common types of tape degradation, such as amount of lubricant or binder hydrolysis, by using test tapes of shared provenance.

Since tape playback can be impeded by physical, magnetic, and chemical changes, we performed testing to quantitatively capture information related to these characteristics. No one test was sufficient for describing the subtleties of tape degradation. We chose tests to measure the physical surface roughness and friction of the tapes' oxide layers (atomic force microscopy, optical profilometry, surface toughness, and friction), the magnetic properties of the tapes (coercivity and magnetic saturation), and the chemical changes in concentration of lubricants and the molecular structure of the polymeric binder (gas chromatography-mass spectrometry, size exclusion chromatography, and infrared spectroscopy). Specific details about these methods are described in the section on analytical methods and equipment.

Test Materials

Non-collection reference tapes of known provenance were chosen from the PRTD's Center for Heritage Analytical Reference Materials (CHARM), previously known as CLASS (Library of Congress n.d. [a]). These tapes were physical testing materials that had been acquired specifically for scientific research purposes.

PRTD selected a set of five matching new-old-stock Quantegy 406 1/4-inch tapes (PRTD ID#s 1455, 1456, 1457, 1458, 1459) to use for this study. These tapes were all acquired at the same time from the same collaborator, and they remained sealed in their original

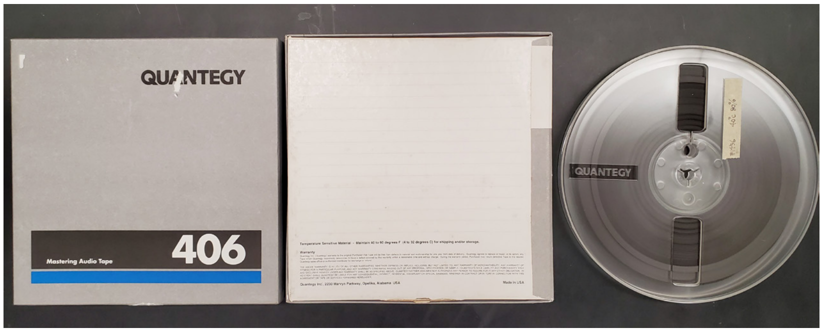

Fig. 1: *Representative image of tape box and tape sample for Quantegy 406 tapes used in this study*

Why Were the Specific Tapes/Years Chosen?

Polyester-based tapes were continually produced from the 1950s onward at a global scale. It would be impossible to test all permutations of tape from all manufacturers across all time. For this reason, having the known provenance of the specific tapes intended for testing was critical to avoid confounding variables of history. The selection of tapes was largely a practical point of experimental design; therefore, a decision was made by identifying tapes that were available for testing from the researchers' reference collection, were known to be from similar time periods, were currently playable, were a formulation that had experienced some reports of playability concerns, and shared a source where we could be confident in their common storage and lifetime histories. Ensuring that the experimentally tested tapes had the most carefully matched provenance enabled us to be sure that findings would be purely the result of our controlled testing variables. In addition, it seemed worthwhile to determine whether the similar tape formulations, which Quantegy acquired from Ampex, should be a preservation concern given Ampex 406's known tendency to demonstrate sticky shed and recent anecdotes and general uncertainty regarding Quantegy tape stability based on online user discussions (Ampex List Digest Vol 114 Issue 4 and Vol 116 Issue 8).

packaging before testing. After opening and before testing, these tapes were confirmed to ride and spool cleanly on a winding deck without any evidence of physical degradation. A representative image of a tape used in this study is shown in Figure 1.

Four additional tapes were used for various control measurements and were not subjected to aging:

- One playable nonsticky Ampex 456 (ID# 1038) as a negative control
- One unplayable Ampex 456 (ID# 1039) showing typical symptoms of sticky shed as a positive control
- Two playable nonsticky Quantegy 406 tapes with known manufacture dates of 2005 (ID# 1123) and 1997 (ID# 1285), which were different from the dates of the Quantegy 406 test tapes chosen for aging

Aging Conditions

Fujifilm completed accelerated aging under five different environmental conditions with a maximum test duration of twelve months. All tapes were aged while wound on their plastic reels.

Aging conditions:

- #1: 23°C, 50%RH
- #2: 12°C, 18%RH
- #3: 40°C, 10%RH
- #4: 40°C, 80%RH
- #5: 60°C, dry (<5%RH)

These aging conditions were chosen to evaluate the effects of varied environments. They served to investigate the effects of a typical storage environment at standard ranges of room temperature (condition #1) (ANSI/ASHRAE 2020), cool and dry storage to prevent degradation (condition #2), different humidity values at elevated temperature (conditions #3 and #4), and very warm but dry conditions (condition #5). The two conditions at 40 °C (conditions #3 and #4) were noteworthy as they spanned entirely plausible uncontrolled storage conditions, such as might exist in tropical climates or uncontrolled warehouses. Table 1 summarizes the tapes described in this study with each of their aging conditions, along with their institutional collection ID numbers.

The combination of conditions #3 (40°C/10%RH) and #4 (40°C/80%RH) served as a comparison to test the impact of low and high humidity at elevated temperature. The combination of conditions #3 (40°C/10%RH) and #5 (60°C/dry) served as a comparison to understand the impact of elevated temperature at low humidity, since these two conditions had comparable amounts of absolute humidity, i.e., the concentration of water vapor in the air. At standard air pressure, condition #3 contained roughly 5.1 g/m^3 of water content. At 60 °C, the same water vapor concentration represented a relative humidity of <4%, which we characterized as “dry.”

Additionally, these aging conditions matched many of Fujifilm’s aging experiments for other magnetic tape studies and allowed for direct comparisons of this study to prior work on longevity of tape formulations (Katayama et al. 2015).

	SAMPLE ID	AGING TEMPERA-TURE °C	AGING RH (%)	COLLECTION ID#	ESTIMATED DATE OF ORIGIN
Experimentally aged samples	23°C/50%RH	23	50	1459	2010
	12°C/18%RH	12	18	1455	2010
	40°C/80%RH	40	80	1456	2010
	40°C/10%RH	40	10	1457	2010
	60°C/dry	60	dry	1458	2010
Control samples	Q406-1997	n/a	n/a	1285	1997
	Q406-2005	n/a	n/a	1123	2005
	A456-nonsticky	n/a	n/a	1038	Unknown
	A456-sticky	n/a	n/a	1039	Unknown

Table 1: *Summary of tapes used in this study*

Finally, the aging condition of 40°C/80%RH was similar to the typical accelerated test conditions described by one legacy tape manufacturer for in-house quality assurance testing of their products when they were being produced. However, their quality assurance tests were typically performed for at least 1,000 hours (41 days) rather than the much longer duration of one year used in this study (personal communication between author Davis and legacy tape manufacturer, 2019).

Most aging studies to date were conducted at ranges that are difficult to extrapolate to long-term natural aging conditions, and they were performed at highly elevated temperatures or for durations shorter than the experiments of this study (Cuddihy 1980; Bertram and Cuddihy 1982; Smith, Brown, and Lowry 1986; Brown, Lowry, and Smith 1982; 1983; 1984; Bowmer, Hull, and Plitz 1989; Edge et al. 1993; Hinterhofer et al. 1998; Weiss 2002; Thiébaut et al. 2007).

A summary of temperature conditions and final aging time points from select publications are shown in Figure 2 (relative humidity and intermediary time points not shown). While convenient for testing, these conditions posed the challenge of "long extrapolation" to usage environments, as described by Smith and coworkers (Smith, Brown, and Lowry 1986). Worse, some of these conditions applied elevated temperatures above critical thermal transitions inherent to the materials comprising magnetic media (e.g., above the glass transition temperature of PET or at temperatures that cause fully catastrophic polymer breakdown). These variables have made predictions of natural aging behavior effectively impossible.

The aging conditions of this study, even at their most extreme, were more conservative than those used by most published studies on magnetic tape aging. However, we applied aging conditions considerably longer than those used throughout most of the cited works. This avoided the "long extrapolation" from reasonable-use temperature and humidity ranges to those used in testing. As far as we are aware, the conditions studied here are the closest to natural aging published yet, both due to the use of lower overall temperatures for longer times and the intention of staying below critical thermal transitions such

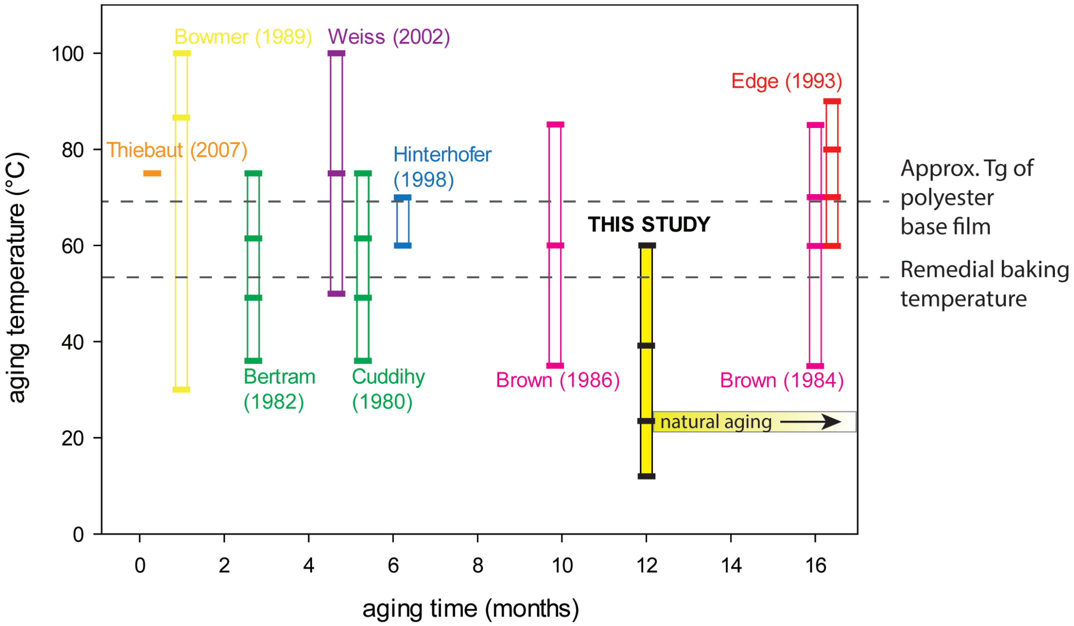

Fig. 2: Summary of accelerated aging conditions (specific temperatures shown in bold lines) and final time points previously applied in select studies investigating the aging behavior of polyester-based magnetic tape

as the glass transition temperature of PET. We also chose most aging temperatures in this study to be below common remedial "baking" temperatures to ensure that any aging-induced effects would not be confounded by possible restorative effects from elevated temperatures.

Analytical Methods and Equipment

Tapes in this study were characterized using a range of physical, magnetic, and chemical measurements.

Physical playability and inspection. All tapes in this study were evaluated for physical playability and winding before and after aging, using a Scully 280 deck with methods described by Cassidy and coworkers (Cassidy et al. 2015). Tapes were loaded onto the deck and threaded to be in contact with a number of static and rolling guideposts, capstans, pinch rollers, etc., similar to a playback or winding machine. Tapes were then wound for a few minutes at 15 IPS and 30 IPS, and intermittent rewind and fast-forward operations were applied. Observations were made for any slowdown, shedding, or audible squealing. Since these were blank tapes, no audio content was evaluated as we were looking for changes in the substrate/physical tape layers that could ultimately lead to deterioration and hence loss of audio content.

Physical measurements: overview of physical measurement methods. Atomic force microscopy (AFM) uses a fine probe to scan a sample surface and monitor changes in the X, Y, and Z directions to provide nanoscale information about any changes in surface topography and roughness. The surface roughness (Ra) quantifies the average value of surface height deviations from the mean line across the measured area. Optical interference profilometry provides similar topographic and roughness information as AFM, but instead of a physical probe, this technique uses interference microscopy to probe the surface and identify height variations by monitoring the change in optical properties as the sample is scanned.

Coefficient of friction (COF) is a quantification of the friction a material experiences as it slides across a surface.

Surface toughness is a measurement of how resistant a surface is to abrasion or deformation, and it is evaluated by inspecting for visible damages after repeated exposure of a sample to physical contact against another material.

Physical measurements: experimental details. AFM measurements were made using a Nanoscope IV AFM in contact mode with scan areas of 40x40 or 90x90 μm^2. COF of the magnetic oxide layer was measured using a custom in-house friction tester at Fujifilm, and the COF was measured for 100 reciprocal motions with a 180-degree wrap around a 4-mm diameter SUS420J stainless steel rod. The value was then averaged over the 100 passes. Toughness of the magnetic oxide layer was measured using a "shoe-shine" surface abrasion test with a Triboster Friction Abrasion Analyzer TS-501. In this test, surface condition of the tape sample was visually assessed for damage after 100 repeated reciprocal passes of a 3-mm spherical steel ball probe against the tape oxide surface in a shoe-shine style. Pressure from the abrasion probe was applied with a 5-g weight, and the abrasive cycling occurred across 1 cm length at 3 mm/sec. In both friction and toughness tests, tape samples were unwound from the experimental reels and left to equilibrate in atmosphere for 60 minutes before testing.

Magnetic measurements: overview of magnetic measurement methods. Both magnetic coercivity and magnetic saturation describe the strength and stability of the magnetic properties in a material. Loss of magnetic information and retrievability would be indicated by a reduction in either value. Coercivity measures the magnetic force necessary to reduce the magnetism of a material to zero and is indicative of a material's magnetic strength and resistance to demagnetization. Coercive force is influenced by particle shape, size, and composition. The coercivity measurement is commonly performed on raw materials of magnetic particles, as well as final products of the magnetic tapes. The magnetic saturation measures the point at which an increase in the applied external magnetic field can no longer increase the magnetization of the material.

Magnetic measurements: experimental details. Magnetic coercivity and saturation were measured using a vibrating sample magnetometer (VSM) with a maximum external magnetic field of 1194 kA/m (15 kOe). Tolerances for coercivity were reported at about 10%.

Chemical measurements: overview of chemical measurement methods. Measurements of the various chemical compositions and concentrations provide information about the stability of the various composite materials and small molecules that make up magnetic tape. Degradation can be indicated by a relative loss or reaction of lubricant molecules, indicated by changes in their relative concentrations within the tape. Degradation can also be indicated by changes in the molecular weight of the polyester-urethane binder polymers (where hydrolysis causes reduction in binder molecular weight and an increase in the total number of binder molecules as long polymer chains are broken into numerous smaller ones by hydrolytic scission). Fourier transform infrared (FTIR) spectroscopy is a nondestructive chemical analysis tool that can identify changes in functional chemical groups between samples, such as those caused by degradation or by entirely different chemical compositions or reactions.

Chemical measurements: experimental details. Concentrations of lubricants and tape degradation products were measured by gas chromatography, following their extraction by soaking tape samples in methanol. Binder molecular weight was measured by size exclusion chromatography (SEC) in acetone with an ultraviolet (UV) detection system. Binder material was first mechanically removed from the base film of the tapes, immersed in acetone, and the dissolved polymer was then directly analyzed. FTIR measurements were collected in attenuated total reflectance mode (ATR) using 32 scans from 4000 – 650 cm^{-1}.

Results and Discussion

After aging, quantified measurements were made of the physical, magnetic, and chemical changes that occurred in the tapes. Figure 3 summarizes the tested properties that were measurably different after aging (yellow) and those that were not (green).

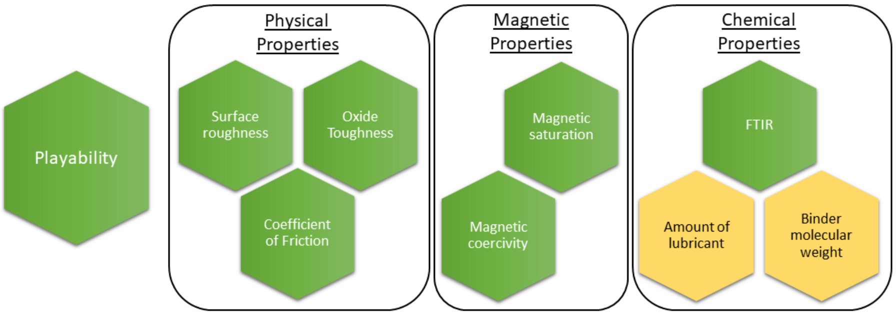

Fig. 3: *Summary of physical, magnetic, and chemical properties measured in tapes after one year of aging, indicating measurable changes (yellow) or no change (green)*

After one year under accelerated aging conditions, all test tapes were first checked for the most critical criteria: physical playability. All tapes were in good and playable condition and continued to be easily and cleanly windable after one year of accelerated aging across all the tested temperature and relative humidity values. None of the common symptoms of sticky shed were observed during playability testing, and all tapes spooled cleanly and easily across the deck (Figure 4).

Fig. 4: *Clip of tapes winding*

We were also interested in any observable changes in the physical tape pack or winding of tapes after aging, for reasons described previously about the importance of winding and storage.

A few non-critical changes in tape winding ability were observed after aging. The tape pack for the 60°C/dry sample had loosened, such that initial winding first retightened the entire tape pack as it was pulled into tension, and tension problems occasionally recurred during the first few minutes of winding. A small amount of dry powdery shedding was observed from the edges of the 12°C/18%RH, 40°C/10%RH, and 40°C/80%RH tapes during winding. Some minor flaking of oxide was also observed from the edges of the 40°C/80%RH and 60°C/dry tapes. However, other than the changes noted at 60°C/dry, these tapes did not leave characteristic sticky shed residues on the playback equipment or experience any other slowdowns or audible squealing. These minor residues were comparable to the small amounts of dry shedding occasionally observed during playback of archived tapes, which do not pose meaningful playability problems, and so the test tapes were deemed to be in playable condition. Much of the shedding we observed likely occurred because the loosened tape pack resulted in physical contact with edges of the hubs during winding and unwinding. PRTD will continue to monitor these tapes to evaluate whether any of these minor dry residues are the start of longer-term degradation.

Figure 5 shows images of the tape reels after aging. Aside from the loosened tape pack and minor dry shedding, no significant visual differences were observed upon initial inspections.

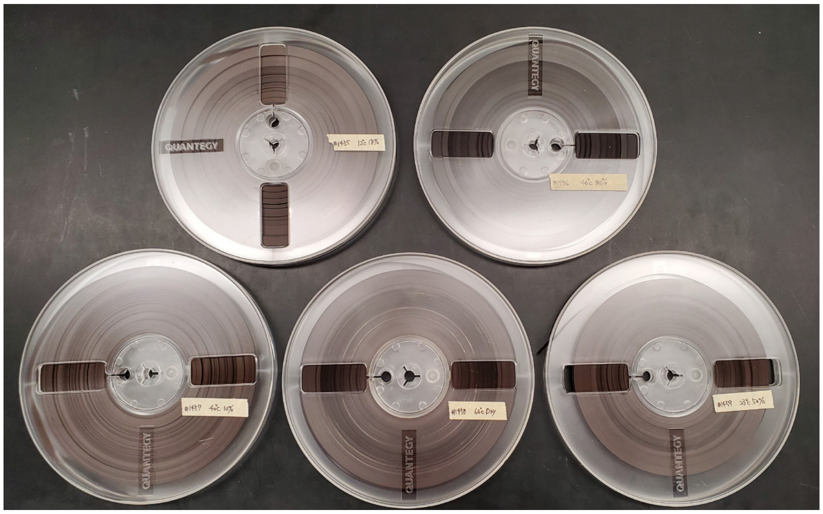

Fig. 5: Test tapes after one year of accelerated aging

In some cases, macroscale curling was seen at the tape ends when they were loosely unspooled as shown in Figure 6. Clearly, some of the aging parameters were causing internal stresses in the tape, and that would be an interesting topic of additional research. These internal stresses and dimensional changes are most likely the underlying cause of the loosened tape pack for the 60°C/dry test tape described above.

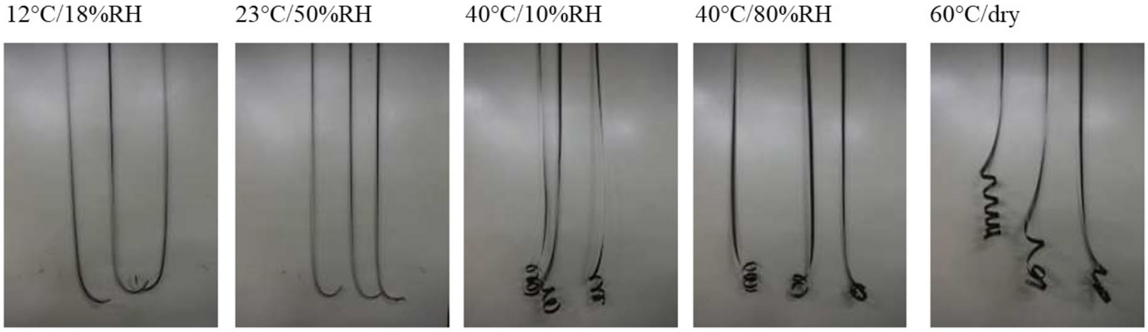

Fig. 6: *Macroscale physical deformations observed in tape ends after aging*

Representative measurements of the experimental tapes' various physical, magnetic, and chemical properties are shown in Figure 7. These results are illustrative of overall trends observed across the wider range of technical tests, with additional results available in the Appendix. While perhaps obvious, that fact that all physical and surface properties (such as surface roughness and coefficient of friction, Figure 7a and 7b) remained unchanged after aging likely explains why the tapes remained physically windable, despite the minor visual changes noted above. These surface properties closely relate to tape transport across points of physical contact on the tape deck, and so their stability matched the overall physical playability of the test tapes. Similarly, magnetic properties remained effectively unchanged.

The only notable quantitative changes caused by aging occurred within the chemical properties at the molecular level of the tapes' lubricants and polymeric binders. These changes were not enough to affect the physical playability of the test tapes, but other possible implications of these chemical changes will be discussed later. Detailed results from these tests are presented later in this section.

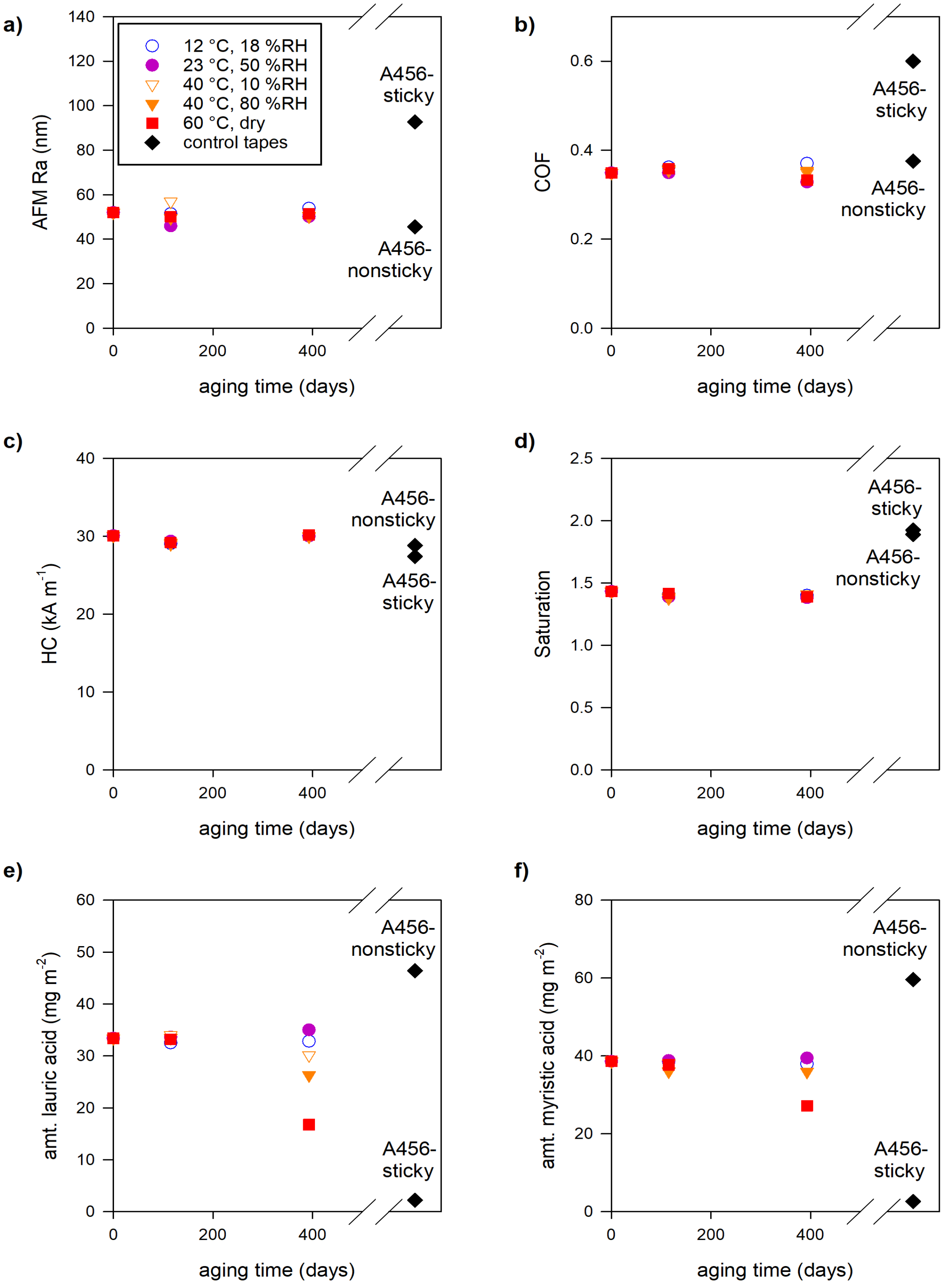

Fig. 7: *Measurements of a range of physical (a, b), magnetic (c, d), and chemical (e, f) properties of the aged tape set. Control measurements from sticky and nonsticky Ampex 456 (A456) samples are shown at the far right of each plot for comparative values.*

Physical and Surface Properties

The experimental tapes' physical properties were investigated by examining surface roughness using atomic force microscopy (AFM) and optical interference profilometry, and by measuring the coefficient of friction (COF) of the tapes' oxide layers. Quantitative results, shown in Figures 7a and 7b respectively, showed no change regardless of the aging conditions.

In addition to the roughness and friction tests, the toughness of magnetic oxide layers was evaluated by shoe-shine abrasion tests. These tests are similar in principle to abrasion tests reported in other studies (Hinterhofer et al. 1998; Bhushan 1996); a schematic illustration is shown in Figure 8. Figure 9 shows microscopic and topographic data from AFM and shoe-shine measurements.

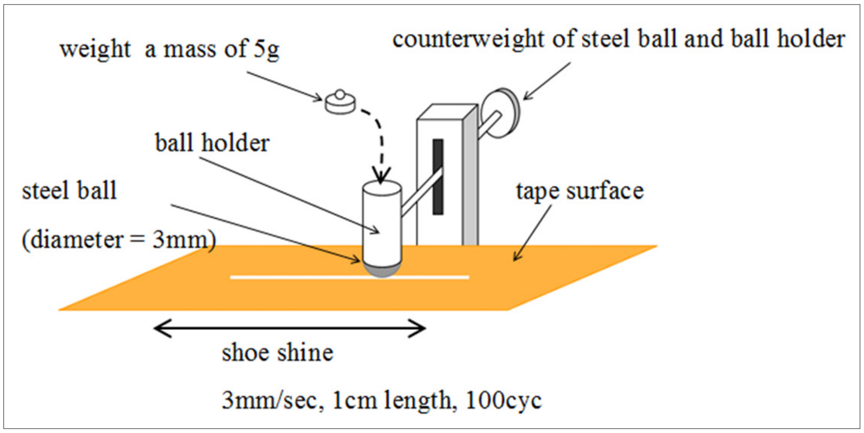

Fig. 8: Schematic illustration of shoe-shine abrasion test to measure surface toughness

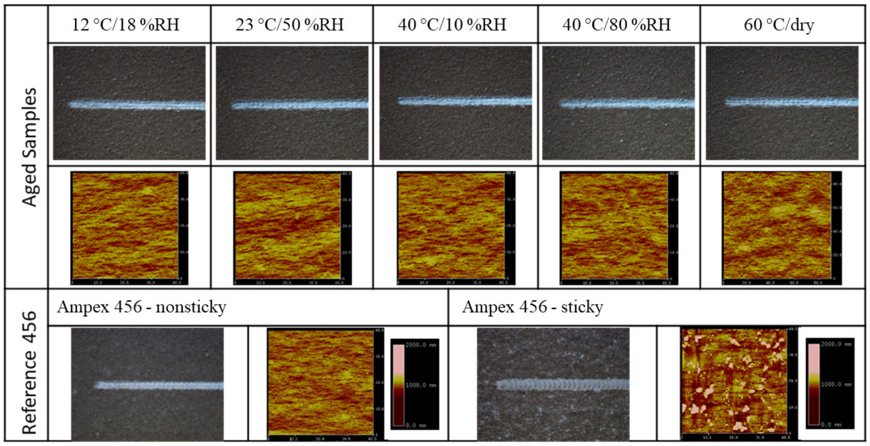

Fig. 9: Surface analysis and testing of aged sample tapes after 393 days (top two rows) and a reference set of Ampex 456 control tapes (bottom row). Results from the toughness test are shown on top for the aged samples, and AFM is shown below. The reference Ampex 456 samples show toughness on the left and AFM on the right.

Surface topography as mapped by AFM (Figure 9) showed little variation induced by aging. Both the surface topography and the calculated roughness values of aged tapes closely matched those from the nonsticky control tape. By contrast, the sticky Ampex 456 control tape was visually distinct and had much higher surface roughness than the aged tapes or nonsticky control sample.

The oxide layer toughness also remained consistent and visibly unchanged regardless of accelerated aging conditions. Again, all aged tapes appeared similar to the nonsticky control tape. In contrast, the sticky Ampex 456 tape appeared visually distinct and unique from all other tapes tested, with a regular oscillating stick-slip style motion. This behavior was not observed in any of the test tapes subjected to artificial aging.

COF values (Figure 7b) did not change over time or with varying aging conditions. A closer look at the dynamics of the COF test is shown in Figure 10. As with surface roughness, COF measurements of aged tapes closely matched those of the nonsticky control tape and were significantly lower and more stable than COF values measured for the sticky control tape.

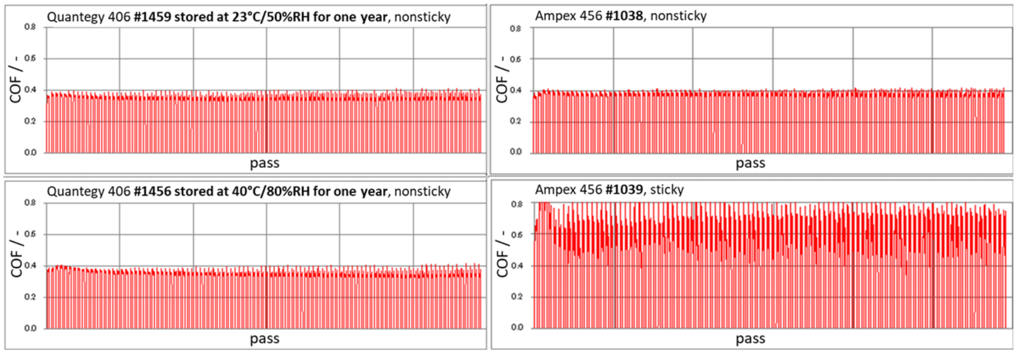

Fig. 10: Coefficient of friction (COF) measurements on representative test tapes, showing two aged tapes on the left (23°C/50%RH and 40°C/80%RH), and control tapes on the right

Magnetic Properties

Magnetic properties of the experimental tapes (coercivity and magnetic saturation) are reported in Figures 7c and 7d. Variation between the coercivity measurements showed little deviation within the sample sets and very little change over the course of aging. The aging conditions had little effect on the coercivity or magnetic saturation of the tapes. Additionally, the sticky and nonsticky control samples showed nearly identical saturation values, suggesting that sticky shed does not affect the inherent magnetic saturation properties. There was some possible evidence showing batch-to-batch or manufacturing-induced variations, which will be discussed later. Since all test tapes were used without any recordings, we cannot say how these tests might correlate to quality of recorded content. As discussed by Smith and coworkers, read failures resulting from aging experiments can depend in complicated ways on physical deterioration symptoms or can occur independently (Smith, Brown, and Lowry 1986). Future experiments using tapes with recorded signals could expand on this topic.

Chemical and Molecular Properties

ATR-FTIR measurements of the artificially aged tapes' oxide layers did not show any appreciable changes in chemical features arising from aging conditions. The spectra for all aged tapes, shown in Figure 11, were effectively indistinguishable from each other regardless of aging conditions. These spectra very closely matched those of the nonsticky control tape, and they did not contain any of the characteristic spectral features observed in the sticky control tape measured in this study or as noted in previously published studies, such as the prominent carbonyl signal around 1725 cm^{-1}, differences in various ester signals around 1200 and 1000 cm^{-1}, and vinyl group signals at 920 cm^{-1} (Edge et al. 1993; Cassidy et al. 2015; Hobaica 2013; Ratnasena et al. 2021).

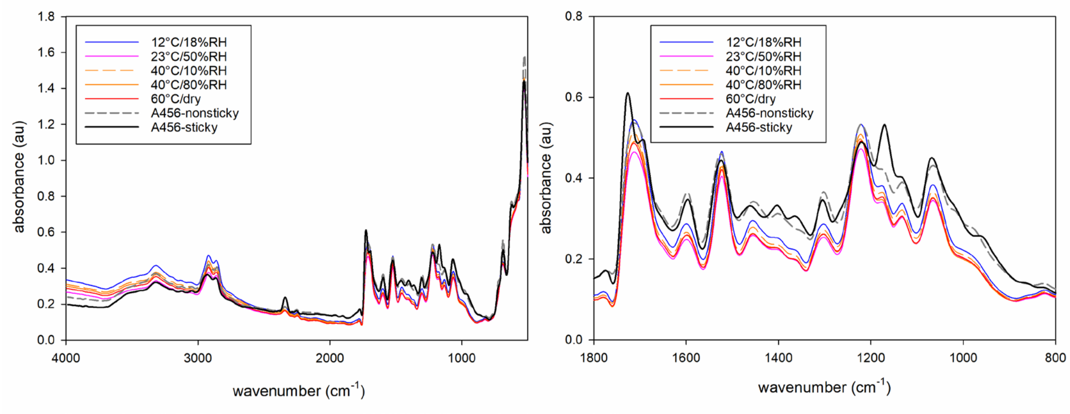

Fig. 11: *ATR-FTIR spectra (left) with zoomed region of 1800–800 cm^{-1} (right) of artificially aged test tapes (colored lines), and control samples of sticky (solid black solid) and nonsticky samples (dashed gray line)*

Chemical stability of the lubricants in the experimental tapes was evaluated by monitoring the concentration of lauric and myristic acid as a function of aging time and condition. Lauric and myristic acid are two common lubricants, among various others, found in many magnetic tape formulations (Vonick 1992; Thiébaut et al. 2007; Hess 2008).

Previous studies have examined the amount of lubricant available as an indicator for the playability and durability of audio tapes and ultimately as a co-factor for degradation and playability challenges (Aoyama and Kishimoto 1991; Bhushan 1996). The lauric acid and myristic acid concentrations measured during aging are shown in Figure 7e and 7f; these lubricant concentrations were stable for all aging conditions tested except for 60°C/dry. The dry, elevated temperature could have led to some evaporation and volatilization of the lubricants in the tape. In addition to lauric and myristic acids, we also identified a branched difunctional ester molecule congruent with features of some variations of lubricants described in literature as well as manufacturer patents (Bhushan 1996; Hartmann et al. 1972). Concentration of this lubricant was also tracked, with results shown in the Appendix. Future reports will discuss additional results we observed regarding specific identities, concentrations, and mixtures of these lubricants.

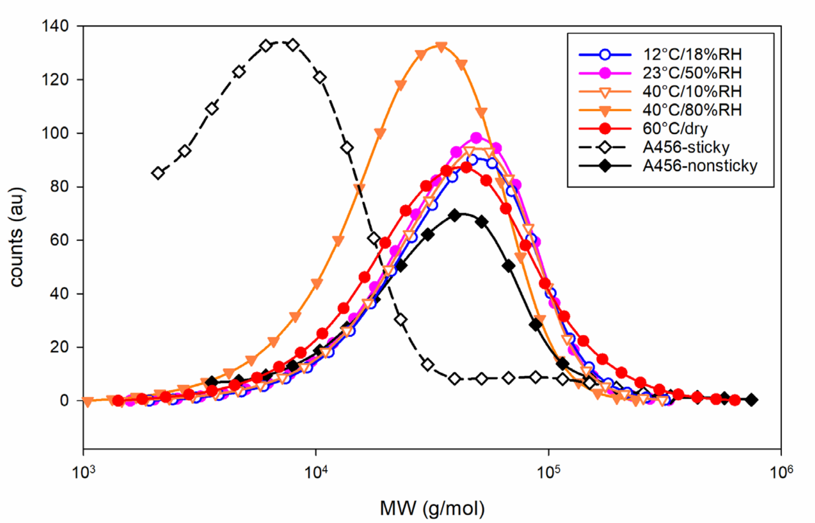

Fig. 12: SEC measurements of binder molecular weight (MW), measured after completion of accelerated aging. Also shown are the distributions for sticky and nonsticky Ampex 456 (A456) control tapes.

Size exclusion chromatography (SEC) measurements revealed changes in the molecular weights in some of the magnetic layers' polyester-urethane binders as shown in Figure 12. Changes occurred in only the two most extreme aging conditions: 40°C/80%RH and 60°C/dry. All other conditions failed to cause any change in the binders' molecular weight.

At 40°C/80%RH, the polymeric binder's molecular weight distribution shifted to lower values, indicative of shorter polymer chains having undergone chain scission. This loss of molecular weight can confidently be attributed to hydrolysis of the urethane-based binders, since conditions with reduced relative humidity at the same temperature (40°C/10%RH) or even higher temperature (60°C/dry) did not cause similar loss of molecular weight.

Aging at 60°C/dry also induced some increase in the breadth of the distribution, with slight increases in both smaller and larger molecular weight polymers. In this case, the increased heat likely caused some polymer breakdown and some mild cross-linking or chain extension via side reactions. However, these effects were not nearly as pronounced as those changes in the binder, which occurred at 40°C/80%RH.

Molecular weight distribution for the sticky control test tape of Ampex 456 is also shown in Figure 12. This sticky tape's binder had dramatically lower molecular weights than even the 40°C/80%RH aged tape. It is possible that if the experimentally aged tapes had continued aging for even longer at 40°C/80%RH, the binder's molecular weight might have been reduced to values closer to those seen in the known sticky tape. However, it is not yet clear whether this reduction in molecular weight alone would have been sufficient to cause macro-scale symptoms of sticky shed.

It should be noted that while these changes in chemical properties were the most detectable consequence of aging (with even more pronounced reductions observed in historically sticky tapes), the toughness and friction of the magnetic coating remained unchanged after aging. This observation agrees with one of the important conclusions from Brown and coworkers, who suggested that the physical strength and adhesion of the oxide layer was more indicative of tape playability than the concentrations of chemical markers and byproducts extracted to solution (Brown, Lowry, and Smith 1984). Even though the macro scale physical and handling properties of the aged tapes remained effectively unchanged, these measurable changes in molecular properties clearly relate to degradation. The SEC molecular weight and lubricant concentration measurements showed quantitative changes caused by our aging experiments, which were trending toward even lower values in known sticky tapes. Indeed, these measurements are the basis of our extrapolated predictions of long-scale degradation times. These measurements also suggest that additional aging, experimental adjustments, and patience might be able to replicate values at a level found only in sticky tapes.

Additional chemical results for specific lubricants and decay rates are shown in Appendix Figures S1–S4.

Predictions of Natural Aging of Nonsticky Open-Reel Audio Tapes

Figure 13 provides an estimate of the time until our currently playable unaged nonsticky tapes would reach chemical properties at a level similar to those observed in the aged experimental tapes and sticky control tapes. Specifically, we used the relative increase in the number of molecules measured by SEC as an indicator of a tendency toward sticky shed and as a reference for extrapolation, since this value was the one that decreased most significantly during aging—moving toward the direction of values measured in the sticky control tape. Although we do not know the precise value where a nonsticky tape begins to show physical symptoms of unplayability, the values measured on the sticky and nonsticky control samples are certainly reasonable places to start.

Previous experiments published by Fujifilm researchers showed that the aging conditions of 40°C/10%RH and 60°C/dry accelerated magnetic tape degradation by factors of roughly 3x and 10x, respectively, compared to ambient conditions (Katayama et al. 2015). Reaction kinetics calculated from tapes tested in this study confirmed that they were comparable to the acceleration rates found in previous research for which results are shown in the Appendix. These 3x and 10x acceleration factors were thus used to project the time points of our aged samples to an equivalent "extrapolated" time of natural degradation. Results from these calculations are shown in Figure 13.

The extrapolation found that these cleanly playable test tapes stored at 25°C/50%RH would reach conditions associated with sticky tape in roughly 100 years (approximately 39,000 days). Conversely, if currently playable tapes were stored at (the very unreasonable) conditions of 60°C/dry, they would be expected to reach unplayability in roughly 10 years. And if stored at 40°C/10%RH, they would not be playable in roughly 30 years. Brown and coworkers cautioned against the challenges of such a "long extrapolation" (Brown, Lowry, and Smith 1982; 1983; 1984; Smith, Brown, and Lowry 1986). Theirs remains a fair and reasonable caution. However, our aging conditions, which were generally applied at lower extremes and for longer times than most studies to date, provide some added confidence in our analysis and additionally avoids Brown's concerns about extrapolation through a physical transition such as the glass transition temperature. Yet these extrapolations are still an estimate at best.

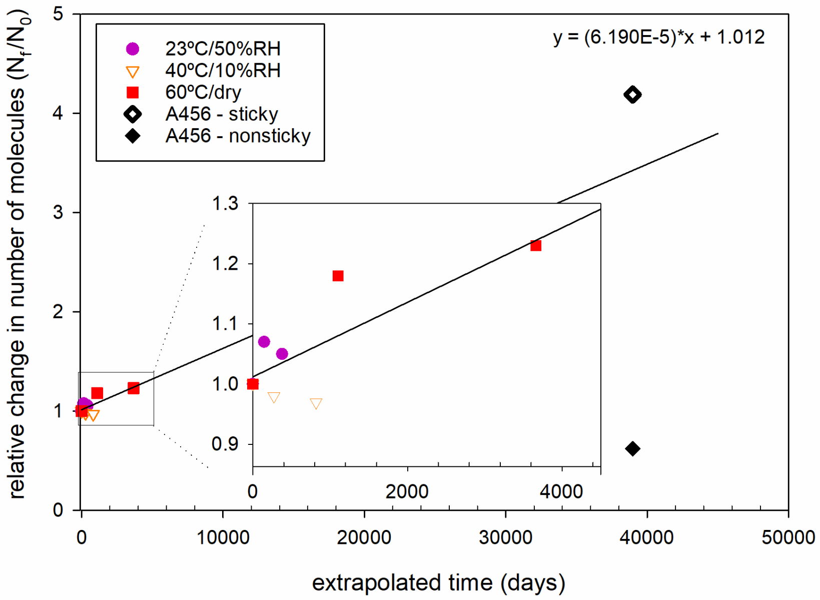

Fig. 13: Prediction of time needed under ambient storage conditions to reach the same relative change in the number of molecules measured from aged experimental samples

Our results suggest that playable polyester-based tapes similar to those in this study are not at imminent risk of deterioration at "normal" building conditions (roughly 20–25 °C at 30–60%RH), but elevated storage temperatures can begin to cause chemical changes. Long-term preservation practices should still be kept in mind for these materials; however, these still-playable tapes do not appear to be at risk for rapid, unexpected deterioration in the short term.

Manufacturing Variations

It is worthwhile to think about possible manufacturer-level variations in these tapes, raised by additional testing observations. Figure 14 shows optical profilometry of the 23°C/50%RH aged test tape and a similar comparison tape Q406-2005. This separate comparison tape showed no playability concerns and was used as a baseline of a similar model of tape made at a different time. The bright white spots seen in all other tapes in Figure 14 are surface protrusions on the oxide layer, and all test tapes looked comparable to each other with no obvious effects from aging. All had some degree of surface protrusions. The notable exception was the comparative non-aged Quantegy 406 tape, which showed significantly fewer surface protrusions than the test tapes. While it is possible that this variation could have been due to sampling location within the tape, it is also possible that the difference in the number of protrusions could be the consequence of a manufacturing-level variation. Additional optical profiles would make those possibilities clearer.

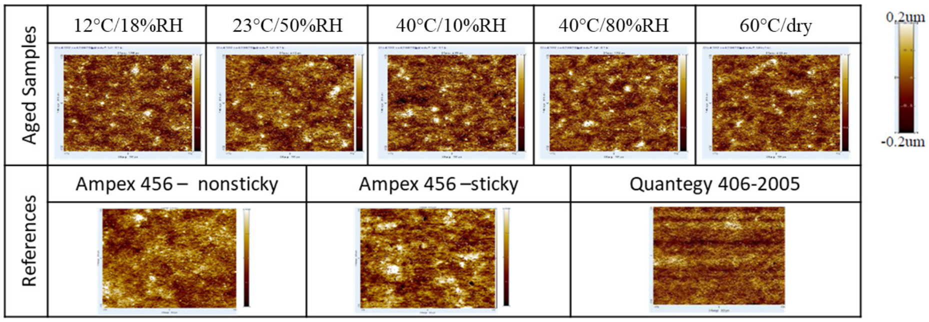

Fig. 14: *Optical profilometry images of aged tapes and control reference tapes, compared to a Quantegy 406 tape of different provenance (Q406-2005)*

This data showed notable physical surface differences between similar tapes of the same tape model from the same manufacturer. This raises questions about overall consistency of tapes, their compositions and uniformity, and their stability even within the same tape model from the same manufacturer. Related results in the SEC data were striking in a similar way. Aside from the harshest aging conditions of 40°C/80%RH, the aged tapes and nonsticky controls all showed nearly identical distributions of their binder's molecular weights (Figure 12). However, the Q406-2005 comparison tape (Figure 14), obtained in 2005 and not subjected to any accelerated aging, had dramatically lower binder molecular weight as shown in Figure 15 alongside a few of the aged and control tapes for comparison. The molecular weight distribution of the comparison tape's binder was most similar to the experimental sample aged at 40°C/80%RH and was much closer to the lower distributions seen in sticky tape. It is impossible to know the precise storage and transport history of this Q406-2005 tape for every prior moment of its life. However, assuming nothing too dramatic occurred in the 15 years until its testing in this study, it is difficult to ascribe this significantly lower binder molecular weight to anything other than manufacturing variation.

We must consider the implication from these combined overall results: The extended artificial aging of identical tapes in this study failed to induce much meaningful material degradation. Yet we observed dramatically different properties in unaged tapes of the same tape model from different manufacture dates, and the variation in

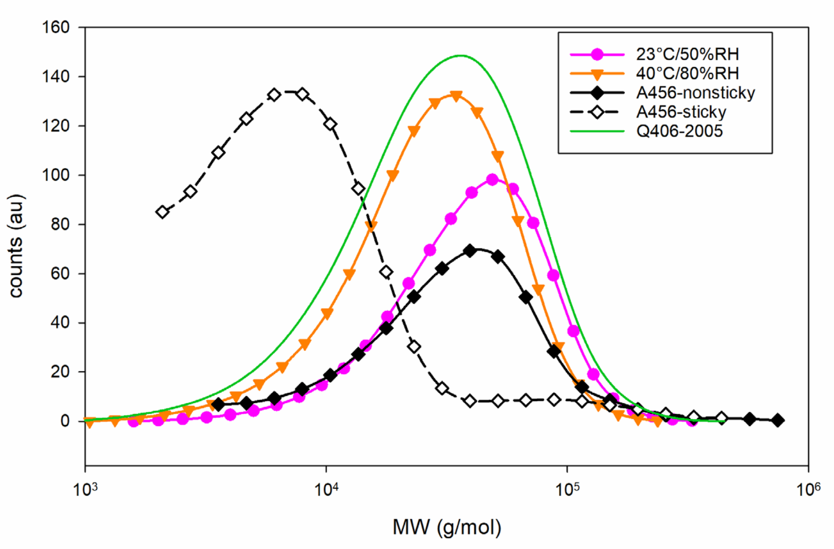

Fig. 15: *SEC binder molecular weight results for unaged Q406-2005 tape (green) compared to select aged tapes as well as sticky and nonsticky control samples*

these properties were well beyond any differences induced by the aging experiments. This implies that manufacturing variations, even within the same tape model, have a more outsized effect on degradation than environmental, storage, or handling conditions. This would agree with hypotheses previously considered and discussed by Schüller, who has suggested that the phenomena of sticky shed and tape degradation are predominantly rooted at the time of manufacturing and that problems with tape playability most typically emerge not long after their production (Schüller 2014). Environmental factors undoubtedly contribute to material longevity, and they should not be ignored. Our work demonstrated such. However, the effects of these environmental factors paled in comparison to the differences observed between similar tapes manufactured even a few years apart. Since formulation and individual tape-to-tape variations seem to be key to their longevity, rapid in-situ assessment tools could assist in identifying individual at-risk tapes, such as those previously demonstrated using IR spectroscopy (Hobaica 2013; Cassidy et al. 2015; Ratnasena et al. 2021) or surface contact angles (Davis 2019).

Conclusions and Recommendations

Historic tapes that are currently playable will likely remain playable for decades.

Historic tapes starting in good and playable condition continued to be easily and cleanly windable after one year of accelerated aging across a range of temperature and relative humidity values without any development of sticky shed or other symptoms of physical unplayability. This is a useful finding since physical winding is often used as an initial indicator of tape condition and is also critical for the long-term storage of magnetic tapes.

Tapes of known problematic vintage are still obviously objects of at-risk concern for archival collections. However, based on this study, existing historic polyester-based tapes that have not yet posed physical preservation problems appear unlikely to start doing so in the short term.

Aging induced little change in physical or magnetic properties although some limited change in chemical properties was observed.

Physical (e.g., friction) and magnetic (e.g., magnetic coercivity) properties remained effectively unchanged at all aging conditions after one year. Considering that one of these aging conditions (60°C/dry) was above common baking temperatures for over one year, it seems unlikely that short-term baking treatments would have a detrimental effect on the magnetic properties of similar tapes.

The harshest aging conditions quantifiably reduced lubricant concentrations and binder molecular weight, but these reductions were not sufficient to impede physical playability even after one year. While these aging conditions demonstrably encouraged hydrolysis, they failed to induce typical symptoms or sticky shed, squealing, or degradation of chemical properties to the extent observed in unplayable tapes. These reductions proved useful as a quantitative way to estimate longevity when compared to values from known degraded tapes.

Roughly 100 years at ambient conditions are estimated for tapes in good condition to reach lubricant and binder conditions observed in unplayable tapes.

Our aging experiments, conducted at lower but longer accelerated aging conditions than those used in studies to date, which are closer to natural aging environments, found that these tapes could likely remain playable for decades if stored in office-like environments.

Extrapolations through other temperature ranges found that elevated temperatures or humidities will, unsurprisingly, reduce the expected time to reach unplayability. For example, the aging conditions using 40°C could reasonably exist within uncontrolled storage spaces such as outdated warehouses or attics; in such environments, our estimates found that tapes in good condition may reach unplayability in roughly 30 years, or possibly more quickly at higher humidity.

These estimates provide confidence that tapes currently in good condition are unlikely to rapidly turn unplayable in "room temperature" storage environments. Even so, careful environmental controls can only further aid preservation.

Manufacturing variations appeared to be more indicative of at-risk tapes than environmental factors.

Reference tapes of the same "model" (in this case Quantegy 406) but known to be of different age or provenance varied dramatically in material properties beyond the extent induced by accelerated aging in the set of aged tapes. This was observed both in properties that measurably changed during aging (e.g., binder molecular weight) and in properties that did not (e.g., surface roughness).

Figure 16 summarizes the experimental conditions that caused noticeable changes to be induced in measured material properties. Also shown in Figure 16 are comparisons for measurements from a matching model of tape manufactured at a different time, but not subject to accelerated aging. The fact that quantitative differences in an unaged tape of different provenance (just a few years older than the experimental tapes) are comparable only to the most extreme aging condition suggests that the most consequential factor for preservation risk is the manufacturing history of any specific tape rather than environmental conditions.

On this note, it is important to emphasize that our results are most applicable to the individual tapes used in this study. Given the myriad factors that can affect a tape's condition, from unknown manufacturer-level variation to careless treatment history by users, it is challenging to extrapolate with certainty from a small sample of test tapes to all collections.

AGING PARAMETERS (1yr.)		MEASURED PROPERTIES			
TEMP. (°C)	REL. HUMIDITY	VISUAL CONDITION / PLAYABILITY	PHYSICAL (e.g., friction)	MAGNETIC (e.g., coercivity)	CHEMICAL (e.g., lubricant concentration)
60	dry	🟩	🟩	🟩	🟨
40	80%	🟩	🟩	🟩	🟨
40	10%	🟩	🟩	🟩	🟩
23	50%	🟩	🟩	🟩	🟩
12	18%	🟩	🟩	🟩	🟩
Different manufacture provenance (naturally aged storage)		🟩	🟨	🟩	🟨

Fig. 16: *Summary of aging conditions and tapes of different manufacturer history, with colors indicating no meaningful changes (green) or measurable differences (yellow) observed for physical, magnetic, and chemical properties*

Given the observed variations at the manufacturing scale of individual tape, it is compelling to consider existing or future tools to enable users to rapidly identify material differences at the level of individual tapes. Some previously published rapid evaluation tools, such as IR spectroscopy or contact angle measurements (Hobaica 2013; Cassidy et al. 2015; Ratnasena et al. 2021; Davis 2019), may prove more beneficial in cases where it is necessary to assess the at-risk possibility of an individual tape. The continual advancement of portable scientific instrumentation can likely support this effort beyond the laboratory.

Environmental considerations remain important.

While the effects of environmental factors paled in comparison to those attributable to manufacturing variations, our results showed the quantitative impact of environment on lubricant and binder properties. Since we have no control over the long-gone details of how a tape was manufactured or used, current storage environments remain one of the few factors actively within institutional control.

That said, quantitative work in this study estimated that it would take on the order of 100 years at ambient temperature and humidity for tapes in good condition to reach levels of lubricant and binder molecular weight measured in sticky tape. If available, careful environmental controls can only help preservation. Yet these estimates provide confidence that tapes currently in good condition are unlikely to rapidly turn unplayable in "room temperature" storage environments.

Revisions to storage and lifetime recommendations are needed.

The magnetic tapes we tested were known to be within the 10- to 30-year lifetime predictions suggested by older reports and recommendations. These tapes were at least midway through that age range and fully playable prior to accelerated aging, and they remained cleanly playable (with predictions of continued playability for decades) after accelerated aging. Findings from this work, paired with additional technical details and scientific measurements, suggest that it would be worthwhile to reassess previously reported lifetime estimates and needs. However, care should still be taken with available environmental controls and handling.

Additional technical research data generated from this collaborative work is planned for publication in a future report, which will include more technical analyses of the chemical identity of lubricants, effects of baking on surface properties, and quantifiable differences between the front and back sides of the test tapes. This complementary paper will consider overall concerns about the physicality of the tape material and how knowledge of composition informs tape playability.

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Appendix

Additional Measurement Data and Calculations

This appendix includes additional scientific measurements regarding details of specific lubricants and their decay rates that support various aspects discussed in the main text and which might be of interest to technical readers. Comparisons to similar lubricants previously measured by Fujifilm researchers are included in these data.

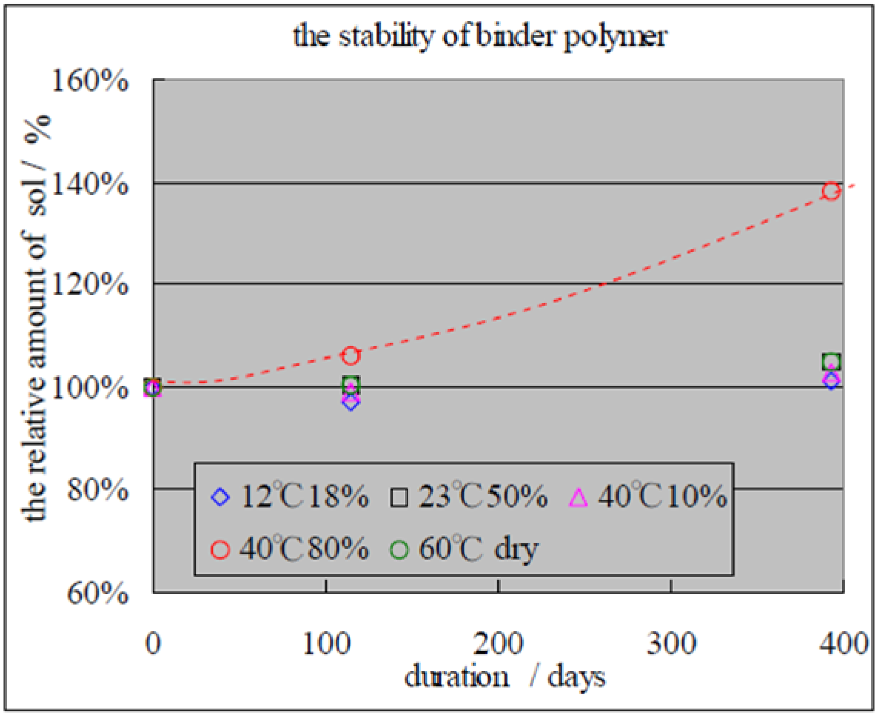


Fig. S1: Measurement of relative amounts of solvent-extracted components (sol %) from aged tapes

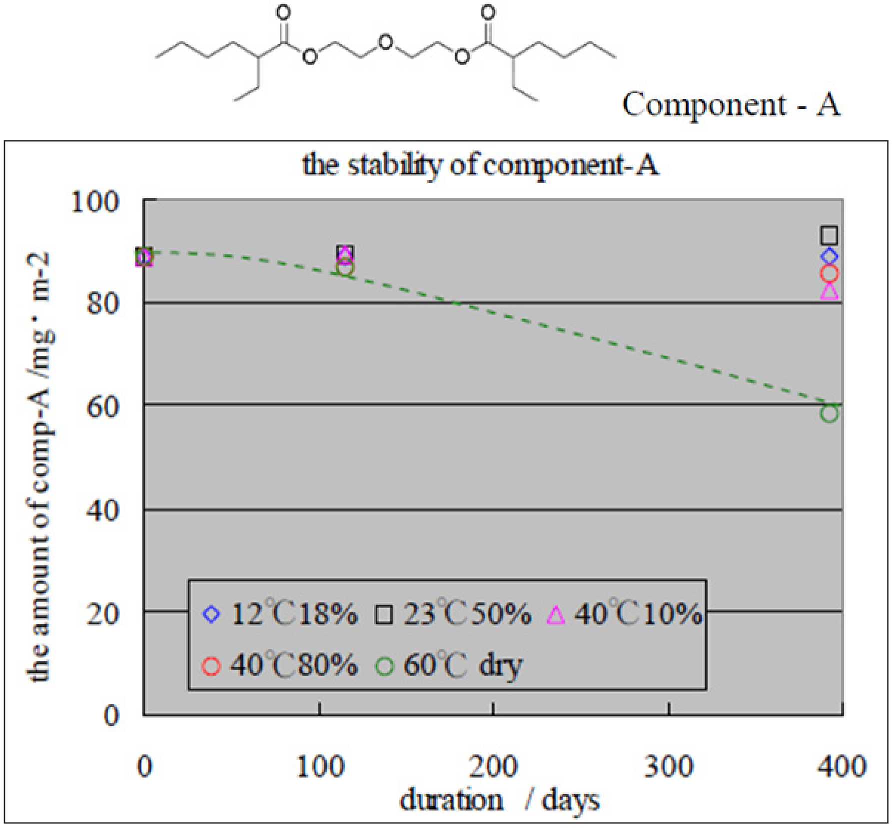


***Fig. S2:** Concentration of possible lubricant "Component-A" (illustrated above) in test tapes during aging*

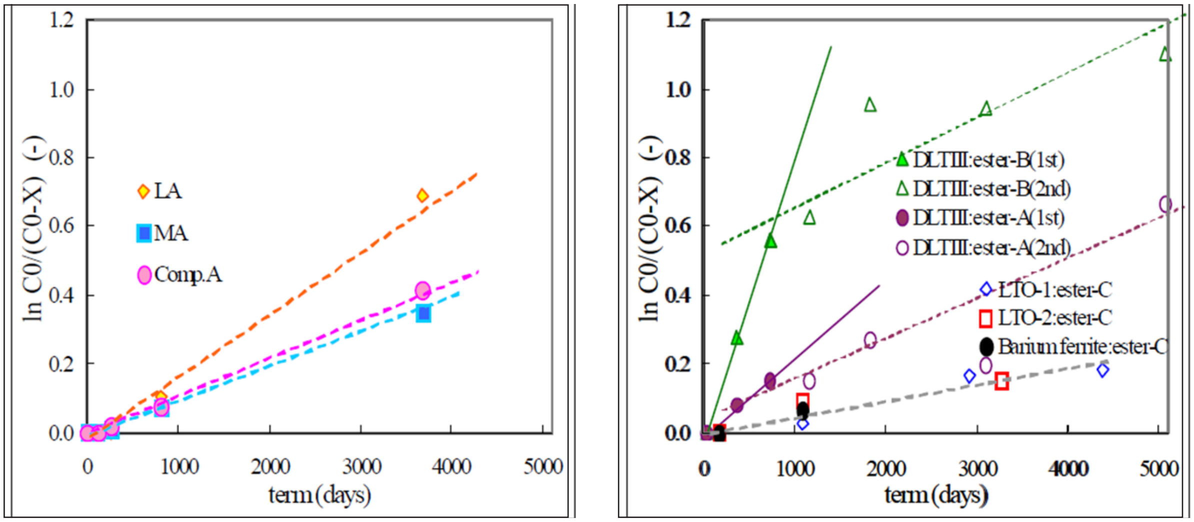
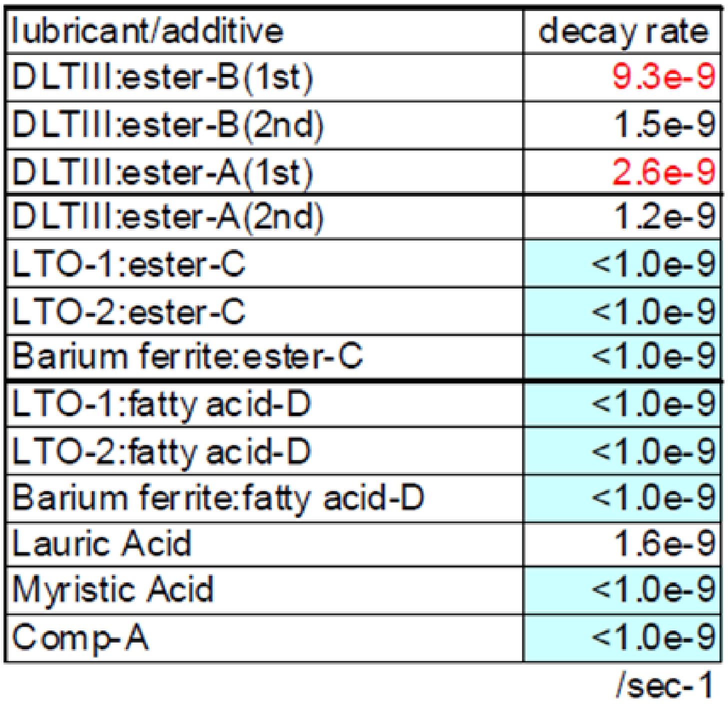


***Fig. S3:** Left: Change in concentration of test tapes' lubricants used to estimate decay rates, with x-axis re-scaled to "natural aging" terms using acceleration factors of 3x and 10x. LA = lauric acid, MA = myristic acid, Comp-A = Component-A. Right: Previous measurements by Fujifilm on polyester tapes as used to calculate acceleration rates.*



lubricant/additive	decay rate
DLTIII:ester-B(1st)	9.3e-9
DLTIII:ester-B(2nd)	1.5e-9
DLTIII:ester-A(1st)	2.6e-9
DLTIII:ester-A(2nd)	1.2e-9
LTO-1:ester-C	<1.0e-9
LTO-2:ester-C	<1.0e-9
Barium ferrite:ester-C	<1.0e-9
LTO-1:fatty acid-D	<1.0e-9
LTO-2:fatty acid-D	<1.0e-9
Barium ferrite:fatty acid-D	<1.0e-9
Lauric Acid	1.6e-9
Myristic Acid	<1.0e-9
Comp-A	<1.0e-9

/sec-1

Fig. S4: *Decay rates calculated in previous research by Fujifilm for lubricants in various polyester-based magnetic media, with lubricant decay rates reported at bottom for lauric acid, myristic acid, and Component-A lubricants as calculated in this report*

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Peter Alyea, preservation science specialist in the PRTD, has been preserving recorded sound collections for over 26 years, serving over 22 of those years at the Library of Congress. He has a bachelor of arts in music composition from Oberlin College and an associate's degree in audio technology from Indiana University. Peter was a principal designer of the Audio Preservation Labs at the Packard Campus of the National Audio-Visual Conservation Center. He has researched fundamental audio preservation issues, including disc cleaning, signal retention on magnetic tape, and the mitigation of sticky shed syndrome, to develop best practices for the field. Peter is a founding member of the IRENE Project, a collaboration between the Lawrence Berkeley National Laboratory and the Library of Congress to develop optical technologies used to rescue historic, fragile, and degrading audio recordings. Using this custom optical metrology equipment, Peter has helped capture sound from and preserve some of the earliest sound recordings ever produced.

Kazutoshi Katayama is a research manager at FUJIFILM Corporation Recording Media Research Laboratories. For more than a decade, he has been researching magnetic tape media with a primary research focus on longevity of tape from a viewpoint of organic materials. He joined Fujifilm in 1994 after graduating from Keio University. For the first six years, he focused on surface analysis of tape by using a photoelectron principle such as ESCA and AES, as well as surface morphology. Later, Kazutoshi started to design various kinds of recording discs such as the floppy disc and the optical disc. In 2008, he designed T10000C tape media, which is known as the first commercial product using BaFe particles in its magnetic tape-recording layer. After this product was released, he began studying media longevity while designing cutting-edge magnetic tape media.

Yuichi Kurihashi, researcher at FUJIFILM Corporation Recording Media Research Laboratories, has considerable experience researching magnetic tape media with a primary research focus on the reliability of tape. He joined Fujifilm in 2009 after graduating from Tohoku University. He began his career working with thermal stability of BaFe tape, which is one of the most important factors needed to achieve high recording density and excellent longevity at the same time. Using this knowledge, he started working with a technical demonstration team to push the limits of recording density one step further by collaborating with IBM Corporation. In 2015, he joined FUJIFILM Recording Media U.S.A., Inc. to support US-based customers. In 2021, he restarted his engineering path as a developer of Linear Tape Open (LTO) media in Japan.

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