# Tape Degradation Factors and Challenges in Predicting Tape Life

*From about 1950 through the 1990s, most of the world's sound was entrusted to analog magnetic recording tape for archival storage. Now that analog magnetic tape has moved into a niche market, audio professionals and archivists worry about the remaining lifetime of existing tapes. This article, based on the author's presentation at the 2007 ARSC Conference at the Ward Irish Music Archive, Milwaukee, WI, defines the basic tape types and the current state of knowledge of their degradation mechanisms. Conflicting prior work is reviewed and correlated with current experience. A new playback method for squealing tapes is described. The challenges in predicting future tape life is discussed. Illustrations of various types of tape degradations and a survey of many of the techniques used for tape restoration are included. Suggestions are made for further research and archival practices.*

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From its introduction in Germany in 1935 and its worldwide rise to the primary medium for audio recording in the late 1940s and 1950s, magnetic tape earned a deserved reputation as a reliable and high-quality storage medium.[1] There are vast archives of magnetic tape that contain information that needs to be preserved. As Dietrich Schuller[2] so aptly stated, "The world's stock of audio recordings is estimated to be more than 50 Mh (million hours) of materials.… None of these recordings are on permanent carriers…" The following claim was found in promotional material for a "Workshop: Audiovisual Preservation for Culture, Heritage and Academic Collection" on the Digitization 101 Blog.

*Seventy percent of all audiovisual material is under immediate threat of deterioration, damage or obsolescence – and seventy percent of collection managers don't know it. Surveys have found serious shortages of trained staff and equipment, and an even more serious shortage of concerted preservation actions. The immediate needs are: awareness – and help.*[3]

The present author became more widely involved with audio preservation and restoration in 2001 while transferring 51 reels of the oldest tapes in the U.S.[4] This work became a full-time career in 2004, and the need for further research into the degradation modalities of magnetic tape became obvious. This paper provides a review of tape types and their degradations and addresses what is known, what is hypothesized, and where more research is required.

 

### *Brief Chronology of Tape Types*

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|---|---|
| 1932 | Magnetic tape development underway at Ludwigshafen, Germany[5] |
| 1935 | Magnetophonband Typ C coated acetate tape |
| 1944 | Magnetophonband Typ L homogeneous PVC tape |
| 1950s | Back coating introduced in Europe |
| 1953 | First PET tape from 3M |
| 1960s | Back coating becomes widespread |
| 1972 | BASF ceases production of PVC tape |
| 1972/73 | 3M/Scotch ceases production of acetate tape |

**Current status**

The use of analog tape declined rapidly at the end of the 20th century, with the major tape manufacturers consolidating and/or spinning off their tape operations and most of them ultimately closing or substantially restructuring. Manufacture of high-end analog audio tape recorders has virtually ceased.[6]

Many musicians and recording engineers prefer the sound of analog for recording, so new material is still being generated, complicating archival strategies.

**Conceptual timeline**

Many factors influence the overall quality of a digital copy of an original analog tape, including (1) the condition of the original tape based on inherent and external degradation factors, (2) the original quality and state of maintenance of the tape reproducer (considering few if any additional quality reproducers will be manufactured), and (3) the quality of the digitization. The overall transfer quality is the product of all of these factors, as conceptually shown in Figure 1.

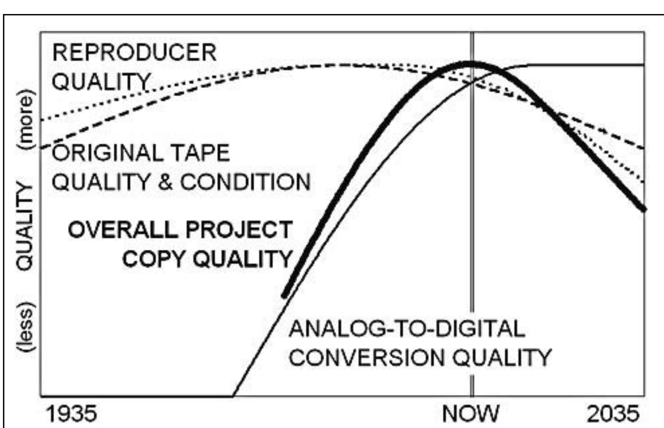



***Figure 1.** Conceptual timeline: Many factors influence the overall quality of a digital copy of an original analog tape. Source: the author.*

While the exact shapes of the curves vary with each tape format and type, the factors remain the same. The "Reproducer Quality" curve includes the availability of technicians skilled in the ability to maximize playback quality as well as to recognize and to treat problems as they are encountered.

Since the publication of the original AES preprint of this paper in 2006-10, there has been discussion as to whether this graph is optimistic or pessimistic. There are, of course, many variables involved, but it should be possible to maintain certain models of at least reel-to-reel players – or perhaps even construct new ones – at least through 2035 and perhaps further into the future. This timeline and comments made under acetate tape are not meant to reduce the pressure to digitize now. Rather, it is meant to show that the time is short considering the amount of digitization that needs to be done. Current best practice is to digitize tapes sooner rather than later and to store these digital files in managed repositories and distribute copies to minimize the effects of catastrophic loss of a single archives. This distributed concept is formalized under the acronym LOCKSS – Lots Of Copies Keep Stuff Safe.

## *Tape Formulations*

In analyzing tapes for aging properties, it is useful to look at the three major components that vary between tapes (Figure 2). The work is presented in the following order because the base film, although in the middle, is the foundation of the tape.

- Base film
- Binder/oxide coating (includes lubrication)
- Back coating (not on all tapes)

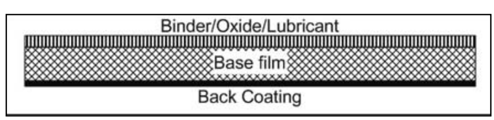



***Figure 2.*** *Tape Formulations: In analyzing tapes for aging properties, it is useful to look at the major components that vary between tapes. Source: the author.*

### Base film

The base film provides structural integrity to the tape. The following base films have been used over time for analog audio tapes:[7, 8, 9, 10]

- Acetate (1935-1972/73)
- PVC (1944-1972) [Polyvinyl chloride], also known as Luvitherm
- Paper (c.1947-1953)[11]
- PET (1953-present) [Polyethylene terephthalate] also known as Mylar, Polyester, Tenzar

**Binder/oxide coating**

The oxide consists of a mix of magnetic particles that retain the magnetism impressed on them by the recording head. The binder is the "glue" or matrix that holds the oxide particles to the base film. A lubricant is added to the binder/oxide mix to reduce friction and wear.[12] In the case of analog audio tapes where little or no air film (or bearing) is developed during normal operation, the solid or liquid lubricant embedded in the tape is the only source of friction reduction in the tape-to-head and tape-to-stationary-guide interfaces.

Multiple binder/oxide formulations have been utilized. The major focus has been on the magnetic performance of the oxide with special regard to increasing the overall dynamic range of the tape. In order to achieve this wide dynamic range, other portions of the binder/oxide/lubricant component were modified to allow a larger percentage of magnetic particle fill. Sometimes these new formulations created both short-term and long-term degradation modalities as evidenced by newer tapes aging more rapidly than older tapes.

On the AES Historical Committee website,[13] the listing of all 3M Audio Open Reel Tapes indicates that 11 different types of binders were used between 1947 and 1980, although this list presents some unanswered questions.[14]

Lists providing manufacturer type designations, years produced, and summary technical information are useful tools. These lists do not report the subtle changes that occurred over time in at least some of the tapes. Running changes were made in tapes without ever being indicated as a revision to the type designation. These running changes came about for many reasons, including the unavailability of a component. In addition to running changes, there were batch-to-batch variations, and sometimes even variations within the same batch.

Benoît Thiébaut, in his presentation to the 2005 AMIA conference, indicated that he had found a range of video cassettes with the same type designation comprised of four clearly different chemical formulations.[15] In discussing this result with Bob Perry[16], he stated that one would never see this much variation in a particular type number during the time he was at Ampex (1969-1992). Scotch/3M was open about the variations in type 111.[17] Bradshaw indicated[18] that aging could possibly create some of the differences found by Thiébaut and that additional analysis would be beneficial. He also indicated the potential for seasonal changes and the difficulties of moving a successful tape line from one climatic location to another. Outsourcing further complicates this analysis, as the box may have one brand on it and the tape may have been manufactured at another facility.

**Back coating**

Tape back coating has been claimed to do several things:

- Provide a smoother wind
- Provide better grip for tape movement
- Provide for electrostatic drain
- Reduce print-through[19]

Back coatings generally contain carbon black and, unlike the binder, add little strength to the overall tape. The presence and chemical composition of back coating requires further analysis for each degradation mode. It appears to accelerate some modes of degradation while retarding others.

**Identifying tapes**

One of the challenges in archives and tape restoration facilities is identifying the open-reel tape type. A few manufacturers marked their name on the back of the tape, and fewer marked the type designation. Short of such marking, there is no guarantee as to the manufacturer or type designation of the product.

In some collections, name-brand tape was purchased and the reels and boxes were always kept together. In other collections, tape was purchased from the lowest bidder and delivered without identification in plain white boxes. In yet other collections, any reel and box was used for any tape. It is not uncommon to find reels of different tape types spliced together. The majority of tapes, therefore, do not have a clear identifier as to their manufacture, which greatly increases the difficulties surrounding proper diagnosis of degradations and their subsequent amelioration.

Even if the tapes were easily identified, we still do not have access to the detailed chemical and physical specifications of the tapes since these have always been considered trade secrets. A detailed survey of that information is likely never to be forthcoming. Reverse engineering the chemical and physical properties from degraded samples is often the best that can be done.

## *Degradation Modes*

The following sections outline each of the major formulation areas and types of degradations which are possible.

**Base film**

The base film forms the structural support for the tape, and if it fails, it is virtually impossible to recover the recording. Each of the three major base film types fails in different ways.

***General***

Base films can degrade in a variety of ways. Poor winding and poor storage conditions can cause most base films to warp. Here are some common degradation effects that involve the mechanics of the physical tape.

1) *Country laning*

Country laning is tape deformation in which the tape does not lie straight but, rather, is wavy (Figure 3). As the tape moves past the heads, it wanders back and forth like an old country lane. This can be caused by a variety of sources, often in combination. It is usually the result of bad slitting during manufacture, but it can also be imparted by a poor wind and/or a defective reel.

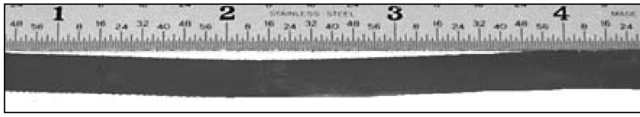
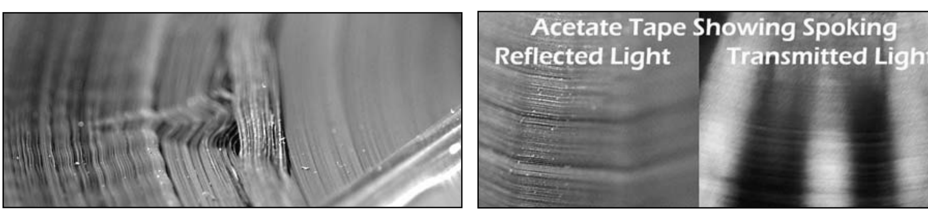


***Figure 3.*** *Country laning is tape deformation in which the tape does not lie straight but, rather, is wavy. Source: the author.*

2) *Winding defects*

In addition to country laning, possibly introduced by sloppy winding, the tape can cinch, have popped strands, have a portion of the pack slip, or be jammed against a flange. All of these can result in sub-optimal tape-to-head contact, which degrades audio quality. Tape-to-head contact suffers either through contamination or through physical deformation. Both result in increased spacing loss, which reduces higher frequencies more than lower frequencies. These effects are usually cyclic through the tape, so are very time consuming to repair after the transfer. Common examples of these defects are shown in Figures 4 & 5.




***Figures 4 & 5.*** *Winding defects: Common examples. Source: the author.*

3) *Edge frilling*

Tapes can frill or lose chips of oxide and/or base film from the edges of the tape. This seems to be caused by mechanical damage or possibly heat damage during storage or playback. It can happen on overly wide tapes if the guides are not widened to accommodate the width. It also seems to be common on paper-based tapes.

### *Acetate*

Acetate was the first widely used base film,[20] with Scotch 111 being in production from 1948[21] through 1972/73, a total of 24-25 years.[22] Acetate tape is generally robust and has the advantage of breaking cleanly rather than stretching substantially prior to breaking when overstressed. Acetate tapes residing in collections are over 30-years-old, with the oldest being over 60-years-old.

1) *Brittleness and drying*

Acetate tapes can become brittle and dry. If that is the case, and severe cupping is visible, a hydration treatment is possible. This treatment is not yet standardized and may weaken the base film, especially if the cupping is caused by vinegar syndrome rather than by dehydration.

2) *Shrinkage*

Acetate shrinks as it degrades. This shrinkage, as has been learned from the film industry, is often non-linear.[23] Steve Smolian[24] indicates that under some conditions, it appears that an acetate tape will lengthen by about 0.6% when humidity is increased 60%. However, since a portion of the tape thickness is added to the capstan diameter when calculating speed,[25] another view of this change is that the effective centre of the tape changes by about a third of the base film thickness, which is also a plausible explanation.

3) *Vinegar syndrome*

Vinegar syndrome occurs as acetate decomposes and forms acetic acid. This is a well-known degradation mode for acetate film.[26, 27, 28] High temperature and humidity levels, the presence of iron oxide, and the lack of ventilation all accelerate the process. Once it has started it can only be slowed down, not reversed. A test that ran for 10 years showed that frozen degrading acetate film “did not display any detectable change in acidity.… [while] the same materials stored at normal room conditions displayed levels of acidity 9 to 13 times higher.”[29] One of the unknowns is when and how vinegar syndrome will attack acetate tapes. There are two current hypotheses for this:

- The differences in structure between film and tape are so great that vinegar syndrome will not be the problem for tape that it is for film.

- The differences in structure between film and tape, while substantial, mean only that the onset of vinegar syndrome and its progress for tape have different rates than for film, but the end result is the same.

This author prefers the second hypothesis and presents the following as support.

Figure 6 shows one of the windows from a reel of Tonschreiber tape. The Tonschreiber was the multi-speed, military version of the Magnetophon, made by AEG during World War II. The tape on this reel appeared to be Magnetophonband Typ C. This tape was manufactured 1939-1943.[30, 31, 32]

While some think that Magnetophonband Typ C is a unique tape and that later acetate tapes will not degrade as dramatically, an alternative perspective is that this tape represents the degradation path for all acetate tape. This particular reel was abused by being stored in a sealed steel can for over 60 years, so its degradation is far ahead of most other reels of acetate tape. Acetate tape is most likely protected by the buffering and acid absorption properties of the cardboard boxes almost universally used to store tapes since 1948. In addition, the cardboard boxes are not sealed, allowing at least some ventilation to remove the build-up of degradation products.

Note how rolled (far more advanced than mere cupping) the loose strands of the tape are and compare to Figure 13 on page 11 of reference,[33] available online. While the amount of shrinkage shown in the IPI document would only marginally affect a full-track tape, it would be devastating to a quarter-track tape. These are the main points to consider about the reel of Magnetophonband Typ C (Figure 6):

- The shrinkage and spoking of the tape
- The tape smelled strongly, although the smell was not specifically vinegar
- The rolled-over loose ends of the tape showing shrinkage of the base film – the roll is inward because this is a B-wind (oxide out) reel – the oxide doesn't shrink, but the base film does
- The corrosion on the aluminum reel surrounding the window
- The corrosion of the steel screw at the top left
- The tape was springy and not as longitudinally stable as one normally expects from acetate tape, and even as other reels of Magnetophonband Typ C restored in 2001[34]
- The tape was analyzed to be cellulose triacetate via a Fourier Transform Infrared (FTIR) analysis spectrum matching[35]
- The tape had been stored in a closed steel can for over 60 years

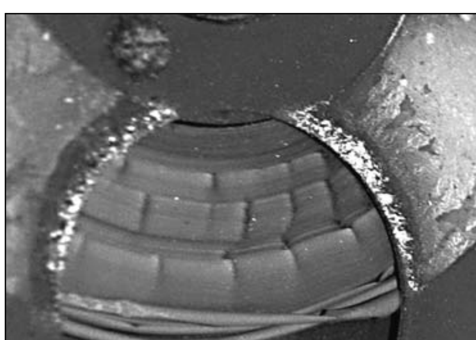


***Figure 6.*** *Vinegar syndrome: One of the windows from a reel of Tonschreiber tape. Source: the author.*

There were two 356 mm reels of Scotch 111B in the same collection as these reels of Magnetophonband Typ C. The "B" refers only to the oxide-out winding of the tape – it is not a different type of tape. Although these were virgin pancakes of tape, there was some shrinkage in the tape, especially in the outer layers, despite their tight packing. These were stored since c.1948-49 in cardboard boxes.

4) *Overheating*

Excessive heat is especially damaging to acetate tape. One recent project was a reel of oral history that had been placed adjacent to a wood stove for several cold winters, and it was unplayable. The tape width had unevenly shrunken about 20%. One side had fused so that it was no longer transparent and the edges had bonded layer to layer.

*Storage strategies for acetate tape*

Freezing acetate film substantially reduces the speed of vinegar syndrome decay.[36] There is a subset of restorers and conservators who are wondering if freezing acetate tape can provide long-term preservation for these aging and deteriorating tapes.

Standards for storage of tape include "DO NOT FREEZE TAPE" as it will damage or remove the fatty acid lubricants that were used in the original tape manufacture.[37, 38, 39] This creates an extremely difficult decision for conservators: store the tapes cool and dry and maybe they will last a few decades, or freeze them and risk destroying them and maybe they will last a few centuries. Of course, digital preservation copies should be made before the freezing, but in some instances there may be more recordings than could be digitized during the remaining life of the tapes at room temperature.

Anecdotal evidence and the experience of a few tape experts was the source of the DO NOT FREEZE rule rather than extended analysis and research. The Canadian Conservation Institute (CCI) is planning a small-scale evaluation of tape freezing. The Scotch 111B from 1948-49 has been donated to be used in the freezing experiments, in addition to other tapes.

The author is not recommending the freezing of acetate tapes, but rather further investigations into this potential preservation method. There are still concerns as to what freezing will do to the binder-base film interface, and whether that will be weakened. The winding tension and profile for tapes to be frozen will need to be investigated to avoid creating situations as shown in Figures 4 & 5.

A further point to consider: some of the fatty acid esters that were commonly used later for tape lubrication freeze at about +21 °C. On cool mornings, vials of these lubricants are frozen, but can be thawed by holding them. Additionally, jojoba oil, which has been considered a close substitute for sperm whale oil, freezes at about +10 °C, which is higher than the lowest temperature (+8 °C) recommended for tape storage.

*Endangered acetate tapes*

While storage conditions play a large role in the risk to any given tape type, the following is an incomplete list of high-risk acetate tapes:

- IG Farben Magnetophonband Typ C
- Kodak acetate tapes
- Any acetate tape that has been stored in metal cans or even in sealed plastic bags
- Any other acetate tape that smells like vinegar[40]

### *Polyvinylchloride (PVC)*

PVC was used from 1943-1972[41] in both homogenous and coated construction. While PVC can degrade in a variety of ways, at least the early Magnetophonband Typ L that was rushed into production after the destruction of the acetate tape production line in 1943 seems to be holding up well. Magnetophonband Typ L is a homogeneous tape and was made 1943-1947 by IG Farben, and BASF made the homogeneous Typ L-extra from 1949–1954. From 1945-1972, BASF made coated PVC tapes, and 3M introduced type 311 in 1960.[42, 43] The "L" in the "Typ L" product name refers to "Luvitherm," the IG Farben trade name for their PVC film. The author has no experience and has heard no reports of degradation of coated PVC tape.

The homogeneous IG Farben Magnetophonband Typ L suffers from a few degradation modes:

- It does not hold up well under continuous use. The iron oxide falls out of the binder matrix, leaving pinholes.[44]
- In some instances, if splices catch the edge of an adjacent layer of tape, the tape can tear diagonally, creating, in some instances, a 600 mm diagonal tear that needs to be carefully spliced together. On any reels that show this tendency, ultra-slow (48 mm/s, 1.88 in/s) unwinding is indicated.
- The outer wrap of tape seems to oxidize and become brittle if left out on display without any protection.
- All of the IG Farben tape is 6.5 mm in width, so the 6.35 mm wide guides of most tape machines will need to be enlarged by 0.15 mm.

*Storage strategies for PVC tape*

All PVC tape is more than 30-years-old, and some of it is more than 60-years-old. Relying on continued long-term storage of this tape is not recommended. However, it seems that the PVC tape, if stored in accordance with good storage practices,[45] should be a lower priority to transfer than acetate tape.

### *Paper*

Paper tape was manufactured c.1947-1953.[46] While it is not very common, it doesn't appear to be degrading rapidly, either. If the original paper was acidic, that might be a degradation factor. Another factor could possibly be damage that the oxide/binder might cause to the paper, but that does not seem to be happening. Paper tapes are likely to frill during playback. Since many paper tapes are recorded in one direction only in the centre of the tape, this would not be a major issue.

*Storage strategies for paper tape*

Since paper tape was manufactured c. 1947-1953,[47] it is all 50-60-years-old. The limited holdings found in most collections should be transferred soon to avoid any future problems.

Paper tape plays well on a gentle transport, but the fidelity may not be great due to the primitive machines used for the early recordings. The track configurations may vary and a careful analysis is required. One paper tape had a 2.5 mm centre track which was reproduced using a 1.1 mm wide head as it was the only centre-aligned track available at the time.

### *Polyethylene terephthalate (PET)*

PET is probably the most widely used base film and the most widely represented in archives, although acetate base film is also widely represented. PET was introduced in approximately 1953, and as of approximately 1972 became the sole base film used in audio tape manufacture. It is most commonly known by the DuPont trade name Mylar. Scotch/3M used the trade name Tenzar to describe their tensilized PET film.

PET does not degrade under normal conditions and is a rather stable base film.[48] It is hygroscopic[49] and it is not well documented how that affects binder degradation; however, if the base film can absorb water, it would seem that it could then transfer that moisture to the back of the oxide coating. This requires further investigation.

PET films are pre-stressed and tensilized during manufacture. The base films come in a variety of thicknesses. Long-play and standard-play open-reel tapes are generally made from "balanced" base films. The base films for double-play and triple-play open-reel tapes as well as for some cassette tapes are made with tensilized film,[50] which can have tremendous shrinkage under the wrong storage conditions.[51]

### *Polyethylene naphthalate (PEN)*

PEN is used in video and data tape and is apparently stronger than PET with no additional negative characteristics.[52] This may be used in some digital audio tapes such as ADAT and DAT in addition to video and data tapes. No PEN-specific degradation modes have been identified to date.

## Binder/oxide coatings

Binder and oxide coatings seem most problematic on PET tapes and somewhat problematic on later acetate tapes. Binder-related degradation modes are rarely seen on PVC, paper, and PEN tapes.

### *Polyester urethane binders: primary recovery methodology*

This section offers a new perspective on degrading polyester urethane tape binders. Prior to this paper, two major binder/oxide coating failure modes have been identified, based in part on data from Ampex:[53]

- Sticky shed syndrome (SSS)
- Loss of lubricant (LoL)

It appears, however, that what has been called "loss of lubricant" over the past decade is not truly loss of lubricant, but merely the failure of the tape to be restored to playability after a normal incubation or baking cycle.

The author would like to suggest that the broad term "soft binder syndrome" (SBS) be applied to all tapes that show stickiness, shedding, and/or squealing, whether they respond to baking or not. Since "sticky shed syndrome" (SSS) is so well known, and is a special case of SBS that responds to baking, the continued use of the term SSS will be a given. We would, however, urge that the use of the term "loss of lubricant" (LoL) be discontinued for tapes that squeal and do not respond to baking, and merely state that these tapes are suffering from SBS of a type that does not respond to incubation. Overall, the adoption of the term "soft binder syndrome" (SBS) to describe all such tapes appears to be warranted.

In the 1960s and 1970s, manufacturers adopted polyester urethane binders for audio tapes while some video tapes utilized polyether urethane binders to better accommodate performance-driven changes in the oxide component. Back coating was often added to the tape design at the same time, resulting in a premium mastering tape.

These tapes have been very successful, but some have shown alarming degradation characterized by large quantities of a gooey residue of binder and back coating being deposited on any stationary surface over which the tape passes. This residue is often difficult to remove. Attempting to play a tape in this condition will usually damage it. Playback is accompanied by squealing and, in some instances, the tape adheres strongly enough to the fixed surfaces that it will stop the tape transport.

In many of these tapes (where this condition is then called Sticky Shed Syndrome) incubating (also called baking) the tape returns the tape to a playable condition for weeks or months after treatment. In current usage, if incubation doesn't help, then the failure mode has been incorrectly defined as "loss of lubricant." The author's current hypothesis is that this degradation is all SBS.

The squeal that accompanies playback of SBS tapes is insidious because it is caused by stick-slip (sometimes referred to as stiction, which is subtly different)[54] of the tape as it passes over fixed elements of the tape reproducer, including the reproduce head. This squeal modulates the audio and is recorded into the digital file along with the desired audio. Since this squeal (created by stick-slip) is a variable frequency modulation of the desired audio, there is no practical method of removing it in post production. A simple, reliable, and acceptable means must be found to eliminate the squeal during playback.

In an informal survey of about a dozen audio tape restorers and one instrumentation tape restorer,[55] only one audio tape restorer had ever encountered a tape that was not back coated that responded to incubation. That one instance involved 15 reels that might have been a special run. The precise nature of the tape and the client were considered confidential. For all practical purposes, it appears that SSS occurs only on back-coated tapes.

In one analysis[56] of Sony PR-150, which is one of the major SBS tapes not made playable by incubation, many components of interest were found. These included:

- Polymer degradation products
- Urethane chemical bond hydrolysis
- Lubricant or product of ester lubricants hydrolysis
- Polyurethane ester manufacturing monomers
- Polyurethane ester manufacturing by-products
- Plasticizers

Most of these components (and the above is merely a summary) are indicative of processes that either did not proceed precisely as expected during manufacture or formulations that degraded for a variety of reasons, including hydrolysis.

Bertram and Cuddihy 1982[57] discuss the hydrolysis of the polyester urethane binder and the measurement thereof by the method of acetone extraction. Bradshaw 1986[58] enhances the acetone extraction method originally used by Bertram and Cuddihy by calibrating the process against the amount of lubricant that is also extracted, providing a more accurate snapshot of the degradation processes. While the interaction of $Cr^{O2}$ with the binder is higher than that of gamma $Fe^{2O3}$, it is only slightly higher.[59] Therefore, studies of $Cr^{O2}$ tape can be generally applicable to gamma $Fe^{2O3}$ tape. Bradshaw shows that the chance of reversing the degradation reactions by simple incubation is slim. Bradshaw looked at the filled matrix and how it is modified, whereas Bertram and Cuddihy reported the individual molecular reactions without considering the action of the filled matrix.

Incubating (baking) a hydrolyzed polyester-polyurethane tape was better understood by Bradshaw and his team after they were able to complete a mechanical analysis. This analysis showed that "the ester end groups (both the hydroxyl and carboxyl groups) during baking displaced water on the oxide pigment surfaces and the effective Tg [glass transition temperature] and modulus of the coating went up, but no real repolymerization resulted."[60]

Below the glass transition temperature (Tg) "polymers deform in the manner of a rigid glass (or elastic solid). A significant increase in reversible strain occurs at temperatures above this, entering the rubbery state. In this range, the elastic modulus changes little with temperature up to the flow temperature, Tf."[61] Brown[62] analyzes the breakdown factors and isolates moisture as the dominant cause.

Brown[63] explains that thermoplastic polyester urethane elastomers are made of both "hard" and "soft" segments. Soft segments are joined to hard segment blocks. The scission of one of the 10-20 ester linkages within the soft segment blocks is enough to cause "severe degradation of mechanical properties." "The degradation accelerates markedly with time. Consequently, the time interval between marginal usefulness and complete failure may be small."

Brown was reviewing high-temperature short-term degradations as found in electronic potting compounds used in aircraft. However, the long-term degradations found in tape appear to have similar mechanisms, only at a different time scale.

Bradshaw's comments[64] for SSS tape are equally applicable here. Bradshaw 1986[65] clearly shows the sharp increase in friction above a threshold temperature. Figure 13b of Bradshaw 1986 shows a steep rise in friction starting at 29°C, with friction doubling by 40°C, and quadrupling by 60°C. In addition to the deposit build-up, this may also explain why tapes squeal more readily when the tape and machine have warmed up. Bradshaw has indicated[66] that tapes with Tg below room temperature have been identified. One additional explanation of the lowering of the Tg could be the failure of the cross-linking in the polymer, as one of the benefits of cross-linking is a higher Tg.[67] Moisture plasticizes coatings, which also lowers their Tg.[68]

Bradshaw was kind enough to look at a sample of 3M 175 and found the Tg to have degraded to about 8°C. This preliminary evaluation was accompanied by the following comments:

*My experience with gamma iron oxide filled, BF Goodrich Estane polyester-polyurethane based formulations from the late 60's and 70's is that they ALL had Tg's at time zero of* *barely 26–30°C, and as they aged and hydrolyzed it dropped to less than 12-15°C. I really believe this is why [cold playback of] many of these tapes improves their runability. For hydrolyzed tapes, an increasing amount of the binder is cleaved and produces greasy, low melting degradation fragments which prefer to migrate to the surface and for back coated media move into the backcoat causing it to be "sticky" at room temperature. Baking tapes with this kind of degradation can force even more migration and ultimately "glue" the two coatings together unless the bake is done with very low wrap tension (interlayer pressure). I think that wiping with a Q-tip or any wipe for that matter is removing some of the degradation fragments (I imagine the wipes get very brown from coating removal as well) and thus improving the unwind and play. The problem with doing this for the length of a tape is that you are also removing what is left of the lubricants and the degraded coatings have lost much of their rubbery (resilient) toughness. It would be better to do a two part wipe, using a damp isopropyl alcohol wipe followed by a butyl stearate (lubricant) (about 5% by volume in hexane) wipe to not delube the magcoat. You have to build a rewind station with two wipe heads in series to do this satisfactorily. We used to have one to handle 3420 reel to reel digital tapes.*[69]

If we view this degradation as lowering the Tg then a different approach to recovering information from degraded tapes suggests itself. Efforts to date have focused on raising the Tg of the tape to make it playable, or adding lubricants in the mistaken view that the failure was loss of lubricant. Instead of the current approach, which attempts to change the physical properties of the tape, this new approach relies on accepting that the Tg has lowered. The playback environment is modified so that the tape is reproduced below its Tg.

To that end, we utilized three tapes that would squeal during normal playback conditions: two separate reels of Sony PR-150 with different storage histories and one reel of 3M 175. We placed a ReVox A-77 tape player in a refrigerator (Figure 7)[70] and allowed the machine and tapes to stabilize at the refrigerator temperature of +4°C. The machine's tape tension setting was set to "large reel," which increased the hold-back and take-up motor torques. This machine also had all three heads and a fixed guide between the capstan and the take-up reel. All three tapes played through from end to end and back to the beginning without squealing unless the refrigerator door was opened and moisture condensed on the tape as it was passing through the machine. The squealing disappeared shortly after the door was closed.

We have had two reports of this technique working on 3M 175, and we look forward to others confirming this technique on a variety of tapes. We anticipate that the temperature will need to vary for different tapes, as the Tg for some badly degraded tapes may have fallen below +4°C. Indeed, one reel of 3M 175 took an entire weekend of cold-soak before it would play without squealing. Our current thinking is that this method will not work in lieu of incubation for SSS tapes and should not be tried due to the risk of layer-to-layer adhesion.

### *Back coating and oxide coating interaction*

There appears to be an interaction between the tape back coating and the oxide layer in back-coated tapes, exacerbating the binder degradation. Richardson patented[71] a process to remove the back coating from tapes, claiming that it was the cause of SSS. This approach

*Figure 7.* *Polyester urethane binders: A ReVox A-77 tape player was placed in a refrigerator. Source: the author.*

seems to risk damage to the oxide surface. The machine described apparently has not been demonstrated. The patent does include cogent observations on the mechanics and chemistry of sticky shed syndrome. Additional preliminary investigations into the back-coating interaction were performed by John Chester and documented on his website.[72] He concluded:

- "The back coating on my samples of Ampex 407 does speed the return of sticky shed.…
- "When the back coating and the oxide coating are not in direct contact with one another, the back coating deteriorates faster than the oxide coating."

The National Film and Sound Archive of Australia has instituted a process of interleaving back-coated tapes with additional material to separate the back coating from the oxide coating.[73]

It has been the author's experience that the back coating creates heavier deposits than the oxide coating in early stages of SSS. This is especially noticeable in tape machines that have non-rotating tension sensors pressing against the back of the tape. With some tapes, there is far more debris left on the tension sensor than on the non-rotating heads and guides. In discussing this issue with Dr. Bradshaw, he suggested the following hypothesis:

*All of the back coatings are far more binder rich than the magnetic coatings and their modulus is half that of the magnetic coatings due to the very poor reinforcement of carbon black. I believe what happens is that the back coating and magnetic coating are compressed into a high pressure contact during storage, and since the binders in both are essentially the same, they intermix and entangle over time such that when you pull them* *apart some of the magnetic coating and some of the back coating are transferred to each other as they separate – pull-outs – and this deposit is above the normal surface and is clipped off onto the head during tape motion. The frictional heating is enough to make the debris "melt" to the head and it can be very difficult to clean off.*[74]

We know from Bertram and Cuddihy[75] that the oxide binder suffers from hydrolytic breakdown. Assuming that the back coating binder is the same chemistry, it will also suffer from hydrolytic breakdown. Combine this with the fact that the PET base film is hygroscopic and the pathways to hydrolytic breakdown and subsequent degradations increase dramatically. This is certainly an excellent reason to use low-humidity storage.

While most back-coated tapes can be made playable by use of incubation as outlined in U.S. Patent 5,236,790,[76] it is only a short-term cure. It was also considered a "last-ditch" effort by one of the inventors.[77]

It is ill-advised to reuse any tape that has degraded to the point of needing incubation other than to recover the recording already entrusted to that tape. In contrast, the incubation of tapes without back coating generally fails, with the exception of one instance reported in our informal survey.

Some restorers are needing longer incubation times to achieve playability. Also, for very large reels of instrumentation tape, re-incubating the inner layers after the outer layers have been unwound has been required. This is predicted by the pressure-related component in Bradshaw's hypothesis, with the increased pressure on the inner layers increasing the SSS reaction. Some restorers prefer to wipe the tapes, and Media Matters LLC is currently developing a high-end audio open-reel tape cleaner based on that premise. Reports from the surveyed instrumentation tape user indicate that he uses both incubation and a tape cleaner.

For those tapes which can be unwound without damage, the advantage of mechanical cleaning such as wiping as opposed to heat treatment is that there is less chance for the base film to revert to its original, as-manufactured geometry, prior to the balancing or tensilizing treatment that was applied before the coatings were applied. However, audio restorers continue to see open-reel audio tapes that cannot be unwound without pull-outs unless the tape is first incubated.

There has been discussion of different tradeoffs between time and temperature for temporarily reversing SSS, but the protocol in U.S. Patent 5,236,790 still appears to be adequate. Some tapes, however, require 24 hour incubation with 24 hour cool-down. Some have even required longer incubation. Subsequent incubation cycles increase risk, so the goal should be obtaining the best possible transfer during the first incubation cycle. Tapes should be incubated shortly before their transfers, because the tapes revert to an SSS condition in weeks or months.

John Chester in his analysis of SSS[78] observed that the two coatings could be removed with approximately the same effort on some tapes, while it required substantially more effort to remove one coating compared to the other on different tapes. The assumption was that if approximately the same effort was required for coating removal with a given solvent (usually isopropyl alcohol), then the two coating chemistries were similar. Further discussions with Chester[79] and the author's own experiments are summarized in Table 1. In the table, JKC refers to John Chester and RLH to the author. Ampex 467 and Sony D-1460 are digital (DASH) tapes, not analog, but are not believed to suffer from SSS.

It is far too early and too rudimentary to draw any conclusions from these data. More accurate analysis comparing oxide coating chemistries to back coating chemistries may be useful as a marker to identify potential SSS tapes.

| Tape type | Similar coating | SSS |
|---|---|---|
| 3M 207 | No (JKC) | No |
| 3M 209 | No (JKC) | No |
| 3M 808 | Yes (RLH) | Yes |
| Ampex 407 | Yes (JKC) | Yes |
| Ampex 456 | Yes (RLH) | Yes |
| Ampex 467 | Yes (RLH) | No |
| BASF 911 | No (JKC) | No |
| Emtec 900 | Yes (RLH) | No |
| Emtec 911 | No (RLH) | No |
| Sony D-1460 | Yes (RLH) | No |

Table 1: Similarities of oxide and backcoatings and whether tape is prone to SSS

*Tapes endangered from soft binder syndrome*

While storage conditions play a huge role in the risk to any given tape type, the following is an incomplete list of tapes that are likely to suffer from SSS:

- Pre-1990 Agfa PEM 468 and PEM 469[80]
- Ampex/Quantegy 406, 407, 456, & 457
- Early 1980s Audiotape/Capitol: Q15[81]
- Scotch/3M: 226, 227, 806, 807, 808, & 809

Since the required incubation times are apparently increasing, collection managers should consider prioritizing the copying of tapes on known SSS carriers. The following is an incomplete list of tapes that appear to be suffering from SBS and do not respond to incubation.

- Scotch / 3M 175
- Sony PR-150
- Melody 169 (3M seconds)
- Pyral tapes (type numbers unknown)[82]
- Any cassette that squeals – the author has yet to find a cassette that responds to incubation

As stated above, 3M 175 and Sony PR-150 respond well to lowering the ambient temperature during playback.

***Polyester urethane binders: alternate approaches***

Multiple restorers have experimented with multiple techniques and have reported mixed results. Many causes for this stick-slip have been hypothesized. The following degradation mechanisms may be present individually or in combination.

*1) True loss of lubricant from the tape*

While hexane or other solvents can remove the manufactured-in lubricant from tape, it is considered highly unlikely that the lubricant has been lost from the tape during normal storage (despite the popular name for this condition). While it is more likely that adverse storage conditions can drive the lubricant out of the tape, analysis of a squealing reel of Sony PR-150 showed that the lubrication was still present.[83]

*2) Degradation of the lubricant and other components*

Lubricant degradation products have shown up in analysis of SBS tape. It is not clear how much of a factor this is in the overall difficulty of properly playing a tape in this condition.

*3) Lubricant caught in the matrix*

This is rather difficult to analyze, but the lubricant is supposed to come to the surface under the pressure of the tape-to-head contact and then return to the spaces in the matrix after the pressure is removed. In this hypothesis, the lubricant stays locked in the matrix and never surfaces to perform its function.

*4) Increased area of contact*

If the binder material softens and the asperities that normally provide contact are compressed or sheared off, then additional surface area is available for contact. Normal contact area is a small percentage of the total surface area.[84] If this increases, then the friction will increase. While the tape is wound on the reel, the oxide layer can be compressed and this will result in an increase in the contact area. This compression can be caused by thermal and humidity cycling. The absorption of moisture from the air can lead to swelling of the binder. Playing the tape above the Tg will result in increased area of contact.

*General comments*

The stick-slip appears to be a situation with positive feedback in the sense that as the friction increases, the tension on the tape past the point of friction increases and the area contacting the head could increase further. In playing SBS tapes, the tension increases dramatically across the heads, indicating a high degree of friction at the tape-head interface.[85]

While these tapes do not exhibit the same build-up of debris on heads and guides that SSS tapes exhibit, when the tapes are stopped, they may attach themselves to the heads, sometimes with small piles of debris that appear to be collected from the passage of the tape. This may be why careful cleaning can permit some playback before the squeal builds up. This leads back to the lowering of the glass transition temperature of the tape coating as the major physical property change. If the oxide coating is rubbery instead of smooth, then, of course, there is an increased area of contact, and the lubricant load is no longer adequate to overcome the friction.

*Relubrication*

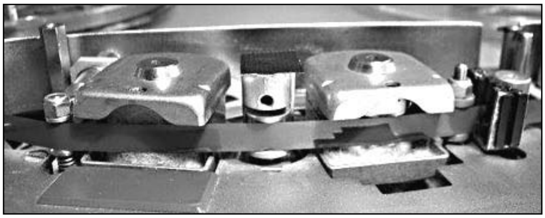
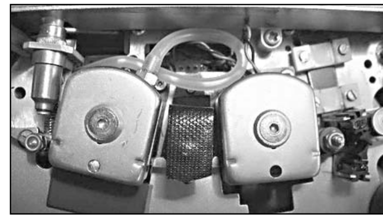
The popular name for the tapes that do not respond to incubation – loss-of-lubricant – has caused much research to be undertaken on tape lubrication and the possibility of relubrication. Since, in fact, it appears that the lubricant is still present in the tape, this is probably a moot point for tapes such as 3M 175 and Sony PR-150.

The literature on tape relubrication is scarce. While investigating methods of reducing head and tape wear, Tobin and Powell[86] suggested the application of Krytox fluorinated lubricants. This has also been suggested by Jim Wheeler[87] and Bob Perry.[88] However, Jean-Marc Fontaine has indicated mixed results when attempting to use Krytox on SBS Pyral tapes.[89]

The best-documented, reasonably large scale treatment of SBS tapes has been by Marie O'Connell in New Zealand.[90] This process involves wetting the tape with isopropyl alcohol prior to the play head and removing the alcohol ahead of the capstan.

In Figures 8 & 9, the record head (on the left) has been replaced with a felt pad fed from an IV drip bag with isopropyl alcohol. Immediately to the left of the capstan is a piece of windshield wiper blade to squeegee off the alcohol ahead of the capstan. This approach was successful and probably over a thousand reels were transferred. However, it requires extensive modification to a machine, which precludes the easy use of multiple track formats. The following is a list of many of the known lubricants:[91]

1. Sperm whale oil – at least according to oral tradition, and probably a long chain fatty acid ester, according to Bob Perry
2. Fatty acids – various formulas, probably directly based on a natural oil, including palmitic and oleic. Bob Perry thought that myristic acid and lauric acid were probably more widely used
3. Esters of fatty acids – various formulas, based on natural or synthetic oil, including butyl, pentyl, isopropyl, iso butyl, etc., and esters from the palmitic, myristic, stearic, etc.
4. Paraffinic oil – various formulas, probably synthetics, including linear alkanes, squalanes, etc.
5. Silicones – 3M advertised this extensively
6. Possibly fluorinated lubricants

***Figures 8 & 9.*** *Relubrication: The record head (left) has been replaced with a felt pad fed from an IV drip bag with isopropyl alcohol. Immediately to the left of the capstan is a piece of wind-shield wiper blade to squeegee off the alcohol ahead of the capstan. Source: Marie O'Connell, used with permission.*

In order to reduce the breadth of analysis, the following categories of lubricants will be considered, based on a variety of recommendations:

- Esters of fatty acids, specifically jojoba oil which is considered one of the closest replacements for sperm whale oil[92]
- Silicones and siloxanes
- Fluorinated lubricants, specifically Krytox

In addition to selecting the proper lubricant, the proper application technique also needs to be developed, and the decision needs to be made as to whether the coating should be applied to the stationary objects in the tape path or to the tape.

The condition of the tape is one of the major challenges in applying a relubrication substance evenly. In the O'Connell method, the tape is fairly well flooded with a constantly replenished stream of alcohol and it only needs to stay wet for a few seconds until it evaporates and is further removed by squeegee. Not shown in the photographs, but mentioned in the referenced article, are drip pans under the heads to collect excess alcohol and avoid damaging the interior of the recorder.

Any of the other mechanisms of lubricating the tape will rely to at least some extent on the surface of the tape to receive and hold the newly applied lubricant, or, if the lubricant is applied to the head, the tape should not rub it off. Sony PR-150 seems to be very difficult to relubricate except through a continuous alcohol film in the O'Connell method. Attempts to relubricate it with several different lubricants have only been marginally effective. In reality, it appears that relubrication attempts are trying to add additional lubrication to the tape, rather than replace lost lubricant, and there is no room for it to be absorbed. The reel of Sony PR-150 that was analyzed appeared to have a reasonable lubricant load still available.[93] Perhaps the alcohol, as it evaporates, is lowering the temperature at the surface of the tape below the Tg of the tape.

*Jojoba oil*

Preliminary investigations applying this in a 10% solution diluted with isopropyl alcohol showed some promise with Sony PR-150, but ensuring that enough stayed on the tape was a challenge. The alcohol may not be an ideal diluting agent as it seemed to swell the binder and make it softer (although this tape does respond somewhat to flooded wet playing with alcohol).

*Silicones and siloxanes*

Decamethylcyclopentasiloxane, also known as cyclomethicone and D5, is a volatile siloxane that completely evaporates.[94] It is widely used in diverse applications including the cosmetic and personal care industries where it is used to add a slippery feel to shampoos and creams. It is also starting to be used as a dry cleaning agent. Applying this to a squealing cassette worked, but one Nakamichi Dragon stopped working for a while as the material penetrated the mechanism. The D5 was over-applied. One attractive feature in this regard is that the Dragon healed itself as the D5 evaporated completely over a few days. It apparently leaves no residue and the evaporation time is, of course, related to the amount used.

While successful with cassettes when heavily applied, it has had mixed results with both 3M 175 and Sony PR-150 in open-reel applications. In both instances, the tapes do not play all the way through without returning to squealing. The problem was made worse when the environment that the 3M 175 was being transferred in became warmer with the advent of summer.

Silicones that are not volatile seem to work better with 3M 175, but application methods still need refinement. These lubricants seem to work best when over-applied, but that increases the risk of higher wow and flutter. Perhaps if a fluid is to be over-applied, the O'Connell alcohol technique may be a better choice as the alcohol is removed and evaporates completely.

*Fluorinated lubricants*

Preliminary results of applying Krytox to heads and guides show that it does not stay in place very long and the squealing returns after 5-10 minutes. While it is working, it works well. There are no known usages where an SBS tape was treated in its entirety. This lubricant is difficult to remove if it gets on the wrong surfaces of the transport, so it needs to be applied sparingly. As mentioned previously, Jean-Marc Fontaine has not had promising results with Krytox and Pyral tape.[95]

*Controlling tape tension*

Since tape tension builds at each fixed surface, the first step to reducing tension is to remove as many fixed surfaces as possible.[96] The next step is to replace fixed guides with rotating guides. A reel of Melody 169 that was recently transferred was done with a modified Studer A810 with the erase and record heads as well as some guides removed (Figure 10). The only fixed surface that the tape passed over was the playback head. This arrangement permitted reliable transfer in 20-30 minute segments. It was necessary to perform a careful cleaning between segments. No relubrication was used.

Further investigations into this method of playing SBS tapes provided encouragement that this process should be seriously considered as an option. The Studer A810 transport was set up with tape tensions reduced by approximately 35%. The tensions were decreased until the dancer arms were less than 5 mm from the shutoff position on both sides. This increased the time until first squealing. It was noted that when squealing began there had been a slight build up of debris on the head. The tape was aggressively cleaned by moving it across a cylindrical Pellon[97] pad at library wind speeds utilizing the peak tensions allowed by the transport. On the first pass, a large amount of debris was removed, mostly along the edges. During the second pass, the cleaning fabric showed far less debris.

***Figure 10.*** *Controlling tape tension: A reel of Melody 169 that was recently transferred was done with a modified Studer A810 with the erase and record heads as well as some guides removed. Source: the author.*

After this tape cleaning and careful head cleaning with naphtha, we were able to play an 18-minute segment of 3M175 (at 95mm/s) twice (once in each direction) with no noticeable squeal. However, the tape was still dragging as the tension increased almost 50% after passing the play head. This method was not as successful with Sony PR-150 tape and the squeal came back in approximately 15 minutes, although the debris on the head seemed less. The author suggests that the stick-slip may be caused by the tape-to-debris interface rather than by the tape-to-head interface.

*Reproducing tapes at higher speeds*

Since stick-slip is often worse at lower speeds, at times the relationship between tape speed and stick-slip can be used to solve the problem. Playing the tape at higher speeds and then slowing it down in the digital domain can work, but it is imperative that all of the details are addressed. One easy way of checking the entire system is to play a native-speed frequency response calibration tape through the high-speed transfer system and evaluate the final result after processing. We have had limited success with this approach for Shamrock 031 (a part number that could be any surplus tape from the Ampex factory as we understand it). This was tried after both incubation and cold-play failed. What was interesting was that the instrumentation recorder used for this playback had a totally different topology.[98]

*The contribution of slitting anomalies to squeal*

While it is unlikely that the squeal is being caused completely by the edges of the tape, we did find that the Melody 169 that squealed was oversize by 25-50µm. Observations indicate that the entire face of the tape (at least with the Sony PR-150) is causing the increased friction, but the edges should not be overlooked.

*Lubricants that have been reviewed and rejected*

The following lubricants were rejected due to risk of excessive spacing loss.

- Graphite – while finer versions of graphite probably exist, and it was used in the harsh automotive 8-track environment, in viewing some lock-grade graphite, pieces up to about 50 x 200µm were found, which would introduce excessive spacing loss. Even the smallest pieces were 5-10µm.

- The average PTFE particle size in dry-film mold-release agents is specified as 3.4 µm, which would still be too large from a spacing loss perspective.

For reference, the reproducing spacing loss equation (in decibels), from Wallace in 1951, is:[99]

$$\text{spacing loss} = 54.6 * \frac{\text{separation}}{\text{recorded wavelength}}$$

This equation, for example, indicates that a 3dB loss at 15 kHz at 95 mm/s (3.75 in/s) occurs with a spacing of 350nm. Films or particles that increase the spacing by 200-300nm are the largest that can be tolerated for general-purpose reproduction. Cassettes are even more critical, with ideal separation increases kept to no more than 100-150nm.

***Blocking or pinning***

Blocking and pinning are two variants on layers adhering to each other with catastrophic results during uncontrolled separation. Blocking is the adhesion of a substantial portion of one layer to another, while pinning applies to small areas of adhesion. Pinning is also referred to as "pull-outs." Figure 11 shows the result of library winding (approximately 1.5-3 m/s or 60-120 in/s) a reel that suffered from pinning. Fortunately, the audio was on the bottom track in this photo, so there was relatively little damage. This tape suffered from poor storage which was certainly a contributing factor to this condition. The white spots in the photograph of the tape are actually clear areas where the binder/oxide layer had been fully removed. It is thought that extremely smooth surfaces may also promote this condition.

There are two approaches to preventing damage in pinned tapes and both are promising.

1. Wind the tape very slowly.[100] This is always a good approach to try when tapes are misbehaving at fast (library) wind speeds and even play speeds. Usually 48 mm/s (1.88 in/s) is adequate.
2. Use the "cold soak" approach, which involves placing the reel in double freezer bags. Place a small silica gel canister inside the inner bag, but not touching the tape. Place the whole assembly in a refrigerator at about +4°C for several weeks.

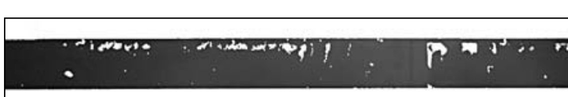


***Figure 11.*** *Blocking or pinning: The result of library winding (approximately 1.5-3 m/s or 60-120 in/s) a reel that suffered from pinning. Source: the author.*

The signs for pinning as a tape is wound off a reel (at library wind speed) are:

- The exit point of the tape from the pack moves away from being precisely tangential to the tape (the exiting strand is being held to the back of the previous layer and is being pulled off)
- A slight "ripping" sound is heard as the tape comes off the reel

If either symptom presents itself, stop the winding immediately to avoid further damage.

In tests run by Bhushan in 1985,[101] a change of winding tension from 1.1 N to 3.3 N and the presence of back-coating increased the likelihood of pinning in the tape pack. One factor in this is that less air is entrapped between the layers of the tape pack in both cases.

*Tapes endangered by blocking or pinning*

While storage conditions play a large role in the risk to any given tape type, the following is an incomplete list of tapes which have shown some incidence of blocking or pinning:

- Scotch/3M 201
- Melody 169 (3M seconds)
- Some other non-back-coated tapes
- Improperly incubated SSS tapes
- Tapes that have been stored in high humidity environments
- Tapes that have been stored in hot environments
- Double- and triple-play tapes

***Binder-base adhesion failure (BBAF)***

It is critical that any tests of storage protocols for tapes evaluate the risk of this failure mode as the current success rate in treating these tapes is variable. Figure 12 shows a dual-layer Ferrochrome Type III cassette with an unknown and presumed-to-be-poor storage history. The two oxide layers are applied one on top of the other on the same side of the tape. It is thought that this dual-layer oxide construction, which only occurs in Type III cassettes, is the formulation most susceptible to BBAF. These were only manufactured for a short time.

Storing the tape in a cold and dry environment (but above freezing), known as "cold soak", has had some success with reducing the extent of the binder-base adhesion failure and permitting one more playing in some cases. (For more details, see the section of this paper titled 'Blocking or pinning.') This Ferrochrome cassette had no adhesion between the base film and the binder for about 10 minutes in the middle of the spool. The balance of the tape played well. We would recommend immediate copying of any Type III cassettes in a collection.

*Figure 12. Binder-base adhesion failure (BBAF): A dual-layer Ferrochrome Type III cassette with an unknown and presumed-to-be-poor storage history. Source: the author.*

**Back coating**

Back coating was added to tape for many reasons. In general, its application was to the high-end "mastering" tapes. In Europe, it was also used as a way to identify tapes as it came in different colours.[102]

The back coating ranges in thickness from 1-3 µm.[103, 104] This coating contains carbon black to provide conductivity, which is important as it drains electrostatic charges from the tape. In some instances, if an arc is drawn from the reel to the tape machine – usually during fast wind operation – this discharge can print as a "click" to the tape. Furthermore, the rough surface of the back coating reduces the chance of the oxide coating laminating to the exposed base film of a non-back-coated tape and suffering from pull-outs or pinning (Figure 11). The back coating also provides superior tape packing as the rough surface allows air to escape.

When sticky shed syndrome became noticed, it was also noticed that it most often appeared on back-coated tapes. At the time, users were told that was simply a coincidence and that there was no interaction between the back coating and the oxide coating. The questions surrounding SSS have been discussed.

## *Challenges in Predicting Tape Life*

It is extremely difficult to predict the lifetime of any given tape. Archivists must assume that all tapes, and the machines to play them, are degrading. While good past performance is not an indicator of good future performance, it does deserve some serious review. It is rare that a tape which has been stable for many years will suddenly become unstable. On the other hand, a degraded tape is likely to continue degrading, possibly at an accelerated rate. In short, the factors influencing tape degradation are:

- Tape formulation / component selection (i.e. what materials are in the tape)
- Component degradation / failure
- Tape characteristics (i.e. base film thickness, etc.)
- Manufacturing defects / tolerances
- Storage conditions (including history, where available)
- Handling (or mis-handling) history
- Playback without proper conditioning
- Playback on defective equipment

As the author continues his dialogue with chemists and chemical engineers he is repeatedly told:

- Tapes are not improving with age
- There will never be a simple test kit for tape degradation classification
- The specific degradations are type- and may be batch-specific
- Tapes which are degrading now cannot be repaired and will continue to degrade
- A tape should be transferred before degradation interferes with playback
- Anything that is important should be copied…now

In addition, the availability of tape machines and machine parts is not to be assumed. In audio, we are lucky in many regards in the continued availability of parts for reel machines. This is less true for cassettes, DATs, minidiscs, and even less so in the video and instrumentation recording fields. Concern extends to the availability of an adequate parts supply and technical expertise to transfer all of the remaining two-inch quadruplex videotape, let alone formats with lesser market penetration. We are even starting to find it difficult to obtain cassette splicing blocks and who knows how much longer high-quality calibration tapes will be available?

In a discussion on prediction of tape life with Dr. Bradshaw in April 2008, he cautioned me that any prediction may provide a false sense of security. This is true as any such prediction must be based on a small sample of tapes and batch-specific variations could easily cause your batch of tapes to fail. When I first started in this business, Jim Wheeler reminded me that any tests I run will only be valid for the reels of tape that I tested. While this advice may seem harsh and perhaps even self-serving to the author, the sooner high-quality digital copies are made the safer the content will be. The key to this point is that while we can make generalizations from collection-wide experience, specific laboratory tests on small samples may be misleading and the most dangerous form of this misleading is to potentially provide a false sense of security.

Initiatives like the PrestoSpace project[105] have identified serial number ranges of certain video tapes which are more likely to fail within a single product type. This, however, is probably not possible within the audio field, at least with open-reel tapes as the only identifying marks supplied with most tapes were discarded when the tape was first used.

Archives can only rely on generalized history and knowledge of different tape types. Accurate analysis is frustrated by the widely variable storage history that may cause or accelerate the degradation. It is imperative that copying[106] be prioritized. Mike Casey of

Indiana University has created the "Field Audio Collection Evaluation Tool" (FACET).[107] It evaluates risk factors based on known degradation modes of different formats and scores the collection. In this way, higher-scoring collections will be addressed first. The tool is designed to work with an importance evaluation as well. The importance relates to non-technical factors such as the research value or intellectual value of the collection, and is generally assigned separately and by a separate group from the technical portion. The FACET score and the importance score are summed, creating an overall score that prioritizes the collection. Factors associated with increased risk to tapes are:

- Base film type (acetate is generally higher risk)
- Base film thickness (thinner has more risk)
- Age
- Known difficulties for a particular tape type such as sticky shed syndrome, soft binder syndrome, loss of lubricant, binder-base adhesion failure, pinning, or blocking
- Evidence of known failure modes
- Poor storage conditions (to the extent they are known for a particular tape or collection)
- Increased areal recording density (higher track density and lower speed both increase risk)

For those wishing to rank various failure modes, FACET would be the tool of choice. There are many factors weighed simultaneously within FACET and it is beyond the scope of this paper to attempt to explain or duplicate the work embodied in FACET. The author of this paper contributed to the FACET criteria and weightings.

While Brown[108] contains an elaborate analytical procedure for predicting life, a substantial amount of chemical analysis would be required for each tape type (and possibly for each batch), and due to unknown storage conditions, this analysis would need to be repeated for each collection.

The anticipated lifetime of tape has been open for debate from the time that the first tapes were manufactured. Perhaps the best anticipated lifetime to use is what was in the minds of some of the designers when they made the tapes. It was common knowledge in the 1970s and 1980s that the vast majority of popular music becomes unpopular in a few years, so a 10-20 year lifetime was considered adequate. As Bob Perry said in a phone interview, "If I wanted to keep it, I'd copy it if the tape was more than 10-15-years-old."[109]

Most tapes are beyond their design life at this point. The previous storage history of the tape, which may adversely affect its future life, is usually unknown and, at this point, most likely unknowable. However, some tapes which are 60-years-old remain easily playable, while some tapes that are 30-years-old require heroics to play properly. No new high-quality analog tape players are being manufactured, and that actually may limit the lifetime of the medium. Studer has committed to providing support for the A807 analog reproducer through the year 2010.

While the details of the degradations can be frightening, if work proceeds at a planned and steady pace, the vast majority of archives can be moved from their traditional shelf-based storage to the new world of virtualized digital storage. It is beyond the scope of this paper to discuss the Information Technology infrastructure and the political/organizational will required to achieve a robust and truly permanent digital repository. Dr. Henry Gladney's website offers discussions of some of the more esoteric issues surrounding long-term digital storage.[110]

Until a tape can be copied to a digital repository, the best course is to optimize the storage environment. Even if the tape looks like some of the photos in this paper, it is generally better not to touch it or wind through it until it is that tape's turn at the high-quality copying station. There are methods to recover data from tapes, even some tapes that are in poor condition. Just because you cannot play the tape, doesn't mean that it is not recoverable. If copies of the tape exist, they should be stored separately from the original to provide geographic diversity.

Bradshaw and Reid[111] further shows the effects of heat and humidity on tape and also provides evidence that regular re-tensioning or rewinding of tapes is not advisable. This is of special concern in audio-video archives as the best machines are rightfully reserved for playing tapes and the rewinding is usually relegated to machines in poorer condition, which will do even more damage. However, winding through the tape in a cleaning pass prior to transfer is recommended in most cases.

Transferring tapes between different environments requires allowing sufficient time for the tapes to reach equilibrium in the new environment. Vos[112] provides analysis of the diffusion of heat and moisture in tape packs. While temperature throughout the pack responds within a few hours for 1" tape, humidity takes far longer. Extrapolating from the curves in Vos, a rule of thumb might be that while temperature equilibrium occurs in 100–200 minutes (depending of course on tape thickness and other factors), moisture equilibrium occurs in 100-200 days. In round numbers, achieving moisture equilibrium takes 1,500 times longer than achieving temperature equilibrium. This helps explain the author's experience of a tape healing itself after several months in a dry environment.

## *Conclusion*

If the content is important and should not be lost, copy it now. Do not rely on old tape. Unlike wine, tape does not improve with age. New data tape is fine as a storage medium, but part of its use involves a plan to refresh the carrier (digitally clone the contents from one tape to another) over time.

Developing a logical plan and sticking with it is an important part of preserving the audio assets in your collection. This plan – and the copying – needs to be started now.

It is important to consider that equipment and related knowledge about how to play older tapes will not survive much longer. It has been suggested that Figure 1 is optimistic. To that end, the archive community has achieved substantial consensus that creating digital audio files and storing them in a managed server system with multiple, geographically diverse copies is the best way to preserve this material.[113]

It is also recognized that many archivists wish to preserve the original recording artifact into the indefinite future. The long term effects of some of the treatments discussed in this paper are unknown and the custodians of the artifacts need to be involved with treatment selection because some treatments may imperil the long-term preservation of the original, even as they enable a good digital copy to be obtained before further tape and reproducer degradation occurs.

Some of the chemicals and techniques discussed in this document may involve health risks if the operator is not adequately protected and if the space is not adequately ventilated. Please research current safety requirements prior to using any technique in this paper.


## *Acknowledgements*

Where trademarks are used in this paper, it is acknowledged that they are the property of their owner and are used to designate specific products. This work was supported by a variety of experts who have graciously helped the author better understand the present subject matter. Any errors or omissions in this paper are strictly the responsibility of the author. The following are due special thanks for their generosity: Sue Bigelow; Jean-Louis Bigourdan; Ric Bradshaw; Peter Brothers; Michael Casey; John Chester; Scott Dorsey; Delos Eilers; Jean-Marc Fontaine; Henry M. Gladney; Marie-Lynn Hammond; Mary Beth Hess; Joe Iraci; Jim Lindner; Jay McKnight; Don Ososke; Bob Perry; Doug Pomeroy; Stuart Rohre; Benoît Thiébaut; Jim Wheeler.



***Richard L. Hess*** *bought his first tape recorder in 1963. Ten years later, he obtained a B.S. degree in communications from St. John's University. In 1974, he joined the engineering department of ABC Television in New York City under Max Berry, John Gable, Ben Greenberg, Joe Maltz, and Hans Schmid. In 1981, he left ABC for McCurdy Radio in Toronto, where he ultimately became director of engineering. In 1983, after George McCurdy sold the company, Mr. Hess joined National TeleConsultants in Glendale, CA, where he worked on a variety of large-scale broadcast facility projects. In 2004, he moved back to the Toronto area to work full-time at audio tape restoration, a second career that began in 1999. His website, www.richardhess.com/tape/, contains substantial information on tape restoration.*


## Endnotes

Note: All web references as of 2006 July unless otherwise noted.


1. Engel, FK. "Magnetic Tape from the Early Days to the Present." *J. Audio Eng. Soc*. 1988;36(July):606-616

2. Schuller, D. "Preserving the Facts for the Future: Principles and Practices for the Transfer of Analog Audio Documents into the Digital Domain." *J. Audio Eng. Soc*. 2001;49(July):618–621

3. From Jill Hurst-Wahl's *Digitization 101* Blog, http://hurstassociates.blogspot.com/2006/07/workshop-audiovisual-preservation-for.html Sponsoring organizations: King's Digital Consultancy Service, King's College London, British Universities Film and Video Council, Training for Audiovisual Preservation in Europe, and PrestoSpace

4. Hess, RL. "The Jack Mullin/Bill Palmer Tape Restoration Project." *J. Audio Eng. Soc*. 2001;49(July):671–674, http://www.aes.org/journal/suppmat/hess_2001_7.pdf

5. See note 1 above.

6. The Studer website (http://www.studer.ch) shows one model multitrack analog recorder and one model multitrack digital recorder available. There are no 1/4" machines listed. Otari (http://www.otari.com) still shows the MX-5050B III 1/4" machine available. While this is a competent machine, it was targeted at the mid-level radio station market in its prime. They also include open reel and cassette players as part of the special-order Digital Archive System. The open-reel recorder appears to be a variant on the late-model mastering MTR-15. Tascam (http://www.tascam.com) no longer lists their last open-reel tape recorder (BR-20) on either their European or their U.S. websites. In fact, the European site lists the DA-98HR high-resolution modular digital multitrack recorder as discontinued, while it is still a current product in the U.S.

7. "3M Audio Open Reel Tapes," http://www.aes.org/aeshc/docs/3mtape/aorprod2.html

8. Personal communication with Delos Eilers, formerly of 3M, indicates 1972/73 as the end of acetate tape production.

9. "Agfa, BASF, and IG Farben Audio Open Reel Tapes," http://www.aes.org/aeshc/docs/basftape/basftapes.html

10. "Ampex Tape List," http://www.recordist.com/ampex/docs/apxtape.txt

11. The information is sketchy on the utilization of paper tape. Some experimental work was done in the early 1930s in Germany, but acetate was selected almost immediately. The 3M tape list shows paper tape being manufactured beginning in 1947, the same year the Brush Soundmirror BK-401 was offered for sale. The author has transferred some 1948 paper tapes from the Saskatchewan Archives and some personal paper tapes from 1953 recorded in Montreal. The Soundmirror date was found in: Clark, Mark, ed., *Magnetic Recording: The Ups and Downs of a Pioneer – The Memoirs of Semi Joseph Begun* (New York: Audio Engineering Society, 2000, ISBN: 0-937-803-42-1)

12. Bhushan, B. *Tribology and Mechanics of Magnetic Storage Devices, Second Edition* .(New York: Springer-Verlag, 1996, ISBN 0-387-94627-6 p.585)

13. See note 6 above.

14. For example, 3M 175, which is known for squealing upon playback, is listed as the same binder type as 201/202/203 which are not known for squealing. In a personal email, Delos Eilers, the author of the list, indicated that 175 is a different binder from the other three tapes. Another example is that while many of the Binder H tapes are known to suffer from sticky shed syndrome (and these are the only 3M tapes widely afflicted with sticky shed), it is not known if all Binder H tapes suffer from sticky shed.

15. Thiébaut, B. "Particulate magnetic tape materials characterisation and degradation study," preprint presented at the Association of Moving Image Archivists (AMIA) Conference in Austin, Texas, USA, 2 December 2005, work sponsored by the Centre de Recherches sur la Conservation des Documents Graphiques in Paris, France, and the PrestoSpace consortium, http://www.prestospace.org

16. Personal communication with Bob Perry, former Director of Advanced Development in the Magnetic Tape Division of Ampex Corporation, 29 July 2006

17. Further confirmation of running changes can be found in the online copies of the Scotch/3M Sound Talk publications: http://www.aes.org/aeshc/docs/3mtape/soundtalk/soundtalkbull13.pdf http://www.aes.org/aeshc/docs/3mtape/soundtalk/soundtalkbull20.pdf http://www.aes.org/aeshc/docs/3mtape/soundtalk/soundtalkbull21.pdf http://www.aes.org/aeshc/docs/3mtape/soundtalk/soundtalkbull22.pdf

18. Personal communication with Dr. Richard

Bradshaw, Tape Development, IBM Tucson, AZ, USA, 31 July 2006 – Note that Bradshaw was the person who finally was able to safely unspool the *Challenger* tape after it was recovered from the ocean floor. He also led the team developing the IBM 3480 and 3490 data tapes, which have (so far) an enviable record of longevity and stability.

19. Kefauver, AP. *The Audio Recording Handbook*. (Middleton, WI: A-R Editions, 2001, ISBN 0-895-79405-5 pp.289–290)

20. Since the focus of this paper is on large collections of audio tape, steel tape and wire, which pre-date acetate tape, will not be discussed.

21. See note 6 above.

22. See note 7 above.

23. Reilly, JM. "IPI Storage Guide for Acetate Film," (Rochester, NY: Image Permanence Institute, 1996, http://www.imagepermanenceinstitute.org/shtml_sub/acetguid.pdf) Note: Downloadable calculator applications are available from IPI at no charge that provides information similar to the wheel mentioned in this publication. http://www.imagepermanenceinstitute.org/shtml_sub/dl_prescalc.shtml http://www.imagepermanenceinstitute.org/shtml_sub/dl_dewpointcalc.shtml

24. Smolian, S. "Preservation, Deterioration and Restoration of Recording Tape." *ARSC J.* 1987;19(2–3,):37–53

25. McKnight, JG. *J. Audio Eng. Soc*. 1968;16(3):266–274

26. See note 19 above.

27. EBU Technical Recommendation R74-2001 "The vinegar syndrome and storage of cinefilm material," http://www.ebu.ch/CMSimages/ en/tec_text_r74-2001_tcm6-4685.pdf

28. Bigourdan, J-L. "Vinegar Syndrome: An Action Plan." (Rochester, NY: Image Permanence Institute, ND, http://www.imagepermanenceinstitute.org/shtml_sub/actionplan.pdf)

29. Bigourdan, JL. "Stability of Acetate Film Base: Accelerated-Aging Data Revisited," *J. Imaging Science and Technology* 2006;50(5), quoted in email from J-L Bigourdan 20070927.

30. The factory that manufactured this tape was destroyed in an industrial (not war-related) fire in 1943 and from that point on, all of the tape made in Germany through 1947 was PVC tape.

31. See note 8 above.

32. See note 1 above.

33. See note 19 above.

34. See note 4 above.

35. Personal communication with Benoît Thiébaut 14 April 2006

36. See notes 22, 19, and 23 above.

37. Van Bogart, JW. C. "Magnetic Storage and Handling: A Guide for Libraries and Archives." National Media Laboratory, June 1995 http://www.clir.org/PUBS/reports/pub54/ Storage at: http://www.clir.org/PUBS/reports/pub54/5premature_degrade.html

38. AES Standard AES22-1997 (r2003) Audio Engineering Society, New York

39. The author's blog contains a chart comparing several tape storage standards, http://richardhess.com/ notes/2006/03/08/tape-and-optical-disc-storage-recommendations/

40. There is some disagreement as to whether the Image Permanence Institute Acid Detection strips properly report the threshold danger lev-

els for tapes as they do for films. Using the A-D strips can provide some idea of the state of the collection. With PVC tapes, positive results may occur, but they appear to be meaningless as far as longevity prediction may be concerned. These positives may be an artifact of co-storage with acetate tapes and/or the acidity of the cardboard boxes.

41. Smaller tape companies, such as Sun-Mark in Connecticut continued to make PVC tape into the middle-to-late 1970s, according to Scott Dorsey.

42. See note 8 above.

43. See note 6 above.

44. The Pavek Museum in Minneapolis and the author had hoped that it would be feasible to use some new old stock (NOS) Magnetophonband Typ L tape to play back the first taped show of "Philco Radio Time with Bing Crosby" from 1 October 1947 as a way of demonstrating this landmark show played on one of the two machines that originally recorded it using the tape type on which it was originally recorded. While it was (barely) possible to calibrate a Sony APR-5000 to record on Magnetophonband Typ L, the day-to-day usage caused pinholes to develop, so the demonstration was discontinued.

45. See note 28 above.

46. See note 10 above.

47. See note 10 above.

48. Edge M, Mohammadian M, Hayes M, Allen NS, Brems K, Jones K. "Aspects of Polyester Degradation: Motion Picture Film and Videotape Materials." *J. of Imaging Science and Technology*, 1992;36(1):13–20

49. http://www.thepetecollective.co.uk/page.php?id=16 accessed 02.04.2008

This statement has caused additional dialog. PET is known for being somewhat permeable as addressed in the citation. PET appears to be far less hygroscopic than acetate base film, but it is hygroscopic nonetheless. It is also permeable to liquids and gasses.

50. "Balanced" base film has similar properties in both the transverse direction (TD) and the machine direction (MD), while "tensilized" base film has substantially different properties in the two directions. http://www.bp.com/liveassets/bp_internet/globalbp/STAGING/global_assets/downloads/pdfs/acetyls_aromatics_pta/N_9_General_Polym_Prop.pdf

51. Personal communication with Bob Perry, 18 May 2006. Perry indicated that the PET films which are only stretched in one direction (tensilized) are much more at risk of losing dimensional stability than the films which are stretched in both directions (balanced) during manufacture. We have recently seen some evidence of this (1 February 2008) in C120 cassette tapes that are very wavy and would not re-spool well on several machines although the initial tape pack appeared smooth. This has not been a common failure mode, but the conditions that caused this are unknowable. From general reading, this may occur if the film is heated above its $T_g$ of approximately 70°C. Standard-play tapes are identified as 1.5 mil (base thickness) or 50 µm (total thickness), long-play as 1 mil (base) or 35 µm (total), double play as 0.5 mil (base) or 26 µm (total), and triple play tapes as 0.5 mil (base) and 18 µm (total). References 5,7 illustrate this dichotomy of usage and the range of variations within the general classifications.

52. http://www.azom.com/details.asp?ArticleID=1933

53. Anglin, D. "Audio Mastering Archive Stability." Ampex Recording Media Corp., N.D. (c.1993), specifically, "Tape stability problems are caused by degradation of the tape polymers or loss of lubricants."

54. According to Bhushan 1996, pp. 231–233, stiction is the increased friction to break an at-rest object free (breakaway force) whereas stick-slip is a sawtooth change in the friction between two already moving objects.

55. Conducted by the author in 2006

56. See note 26 above.

57. Bertram, HN & Cuddihy, EF. "Kinetics of the Humid Aging of Magnetic Recording Tape." *IEEE Transactions on Magnetics*, Vol. MAG-18, NO.5, 1982-09

58. Bradshaw R, Bhushan B, Kalthoff C, Warne, M. "Chemical and mechanical performance of flexible magnetic tape containing chromium dioxide." *IBM J. Res. & Dev.* 1986;30(2):203–216 http://www.research.ibm.com/journal/rd/302/ibmrd3002H.pdf

59. Bhushan, 1996, [12] *op cit*, pp. 652–653

60. Personal communication with Dr. Richard Bradshaw, 28 July 2006

61. Bhushan, 1996, [12] *op. cit.,* p. 157

62. Brown DW, Lowery RE, Smith LE. "Kinetics of Hydrolytic Aging of Polyester Urethane Elastomers." *Macromolecules* 1980;13(2):248–252

63. Brown, 1980, *op. cit.,* p. 251

64. See note 44 above.

65. See note 42 above.

66. See note 44 above.

67. Baghdachi, J., PhD., "Polymer Systems and Film Formation Mechanisms in High Solids, Powder, and UV Cure Systems," 2004, p. 20, http://www.swst.org/meetings/AM04/Baghdachi.pdf

68. Baghdachi, 2004, p. 23

69. Personal communication with Dr. Richard Bradshaw, 20 March 2007

70. In case any reader is wondering, the odd-looking plastic bag in the jug beside the tape recorder is extraneous to this tape-playing method; in Canada, one can buy milk in polyethylene bags. For the environmental rationale, see http://www.cpia.ca/files/files/files_evolution_of_milk_packaging.pdf

71. United States Patent 6,797,072, Charles A. Richardson, Inventor, 28 September 2004

72. Chester, JK., "Sticky-Shed Tape: Investigating the Role of Backcoating," 13 June 2005, http://stuff.jkc-lab.com/sticky-shed/

73. Personal communication with Greg Moss, 25 April 2006

74. Personal communication with Dr. Richard Bradshaw, 6 July 2006

75. See note 41 above.

76. United States Patent 5,236,790, Desmond A. Medeiros, John L.S. Curtis, Robert H. Perry, and Justin D. Underwood, Inventors, 17 August 1993, filed: 31 March 1989

77. Email to a list of restorers from Robert H. (Bob) Perry, 17 April 2006

78. See note 52 above.

79 Personal communication with John K. Chester, 27 July 2006

80. There has been discussion that special microwave incubation treatments may be superior to standard incubation treatments for the Agfa tapes only. The author has no further

information on this and encourages substantial testing prior to treating irreplaceable material. There has been one comment that this only applied to one batch in 1987 and was not polyester-polyurethane binder degradation as PEM is not that chemistry.

81. This tape has not been a main player in the SSS incubation effort, and only a few reels have been reported. Proper treatment of this tape still requires evaluation.

82. See notes 65 and 66 above.

83. See note 26 above.

84. Bhushan, 1996, Chapter 3

85. Author's measurements July 2006

86. Tobin, HG. & Powell C. "Surface Lubrication of Magnetic Tape," presented at the 55th AES Convention, October 1976, Preprint 1189. Note that the Krytox 143AZ mentioned in the paper is certified aero oil and the less-expensive commercial version is Miller-Stephenson's GPL 102 which is a small volume redistribution of the DuPont product.

87. Wheeler, J. "Increasing the Life of Your Audio Tape." *J. Audio Eng. Soc.* 1988;36(April):232–236

88. In various telephone interviews, Bob Perry indicated that applying Krytox had been a useful method of permitting SSS tapes to play, but it was felt that the incubation process would be easier for the end-user.

89. Personal communication with Jean-Marc Fontaine, 27 April 2006

90. O'Connell, M. "Wet playing of reel tapes with Loss of Lubricant – A guest article by Marie O'Connell," published on the author's blog at http://richardhess.com/notes/2006/03/09/wet-playing-of-reel-tapes-with-loss-of-lubricant-a-guest-article-by-marie-oconnell/

91. Bhushan 1996, pp.627–629, additional input from Bob Perry and Benoît Thiébaut

92. Naqvi, HH. & Ting IP. "Jojoba: A unique liquid wax producer from the American desert," 1990, http://www.hort.purdue.edu/newcrop/proceedings1990/v1-247.html

93. See note 26 above.

94. Personal communication with Benjamin Falk, GE Research Chemist, 12 June 2006

95. See note 65 above.

96. Fixed surfaces would include items not immediately needed to reproduce the tape at hand. This would include the erase head, the record head, and generally the time code head. Certain non-rotating guides can usually be removed without degrading performance.

97. http://www.shoppellon.com/

98. For more information see http://richardhess.com/notes/2007/11/08/success-with-squealing-shamrock-031-tape/

99. Camras, M. Magnetic Recording Handbook. (New York: Van Nostrand Reinhold, 1988, ISBN 0 442-26262-0, p.69)

100. This method was pioneered at the British Library National Sound Archive c. 2001 by the late Peter Copeland. Their purpose-built machine unwound the tape at approximately one revolution per minute (3-8 mm/s [0.1-0.3 in/s] with a 178 mm [7in] reel) and provided a current of warm air to dry the tape between supply and take-up reels.

101. Bhushan, B. Mechanics and Reliability of Flexible Magnetic Media, Second Edition. (New York, Springer, 2000, ISBN 0 387 98936 6, p.126)

102. See note 8 above.

103. See note 6 above.

104. See note 8 above.

105. See note 13 above.

106. In the archival world, "copying" is generally referred to as "preservation reformatting," which carries with it certain standards of quality that simple "copying" does not.

107. Casey, M. & Jon Dunn J. "Audio Preservation at Indiana University," 2005, Slide 24, http://www.dlib.indiana.edu/education/brownbags/spring2005/audio/casey.ppt Facet is available (as of 2008-03) at http://www.dlib.indiana.edu/projects/sounddirections/facet/index.shtml

108. See note 46 above.

109. Personal communication with Bob Perry 27 July 2006

110. http://home.pacbell.net/hgladney/ http://home.pacbell.net/hgladney/ddq.htm

111. Bradshaw, RL. & W. Reid TW. "Archival Stability of IBM 3480/3490 Cartridge Tapes." IEEE Transactions on Magnetics 1991;27(5):4388–4395

112. Vos, M, Ashton G, Van Bogart J, Ensminger R. "Heat and Moisture Diffusion in Magnetic Tape Packs." IEEE Transactions on Magnetics 1994;30(2)237–242

113. http://www.dlib.indiana.edu/projects/sounddirections/papersPresent/sd_bp_07.pdf Accessed 2008-02-04