Dimensional Stability of Magnetic Tape

By: Brian L. Weick, Ph.D.
Professor
Mechanical Engineering Department
School of Engineering & Computer Science
University of the Pacific
Stockton, California

Will Tape Survive Archival Storage?

This question has been asked ever since we started to store information on magnetic tape. It continues to be a valid question as more of our valuable digital creations are moved on to tape, which is wrapped in a reel inside a cartridge, and stored on a shelf for long periods of time. Then, many years later, when we want to use our digital information such as documents, music, pictures, or videos, we want it to still be retrievable! To determine if this retrieval is possible, properties of the materials used to make magnetic tape need to be studied and understood. These properties are influenced by temperature and humidity, and can cause the dimensions of magnetic tape to change, which could make the stored information irretrievable. Mathematical models also need to be developed and used to predict stresses in magnetic tape when it is wrapped in a reel. Experimental data can then be gathered and used in the models to predict the dimensional stability of magnetic tape during archival storage.

What is the Answer?

Tape will indeed survive archival storage, but for how long and under what conditions? Well, based on the type of mechanical experiments and conservative analyses summarize herein, dimensional stability goals for 30, 50, even 100 years will be met if magnetic tape cartridges are stored in a room temperature, low humidity environment.

What Happens when we Record information on to an Advanced Magnetic Tape in the 21st Century?

Tape streams under a head that can move or "servo" to multiple positions as information is either written to the tape, or read from the tape. For the Linear Tape Open (LTO) format, the head can move to four positions and servo elements on each end of the head line-up with patterned servo bands on the tape (Figure 1). This unique and scalable timing-based servo (TBS) technology was developed by IBM specifically for linear tape drives,[1] and enables the read/write elements on the head to line-up properly on the tape even if small widthwise dimensional changes to the tape occur. Although this technology works incredibly well, there is a limit to how much the widthwise

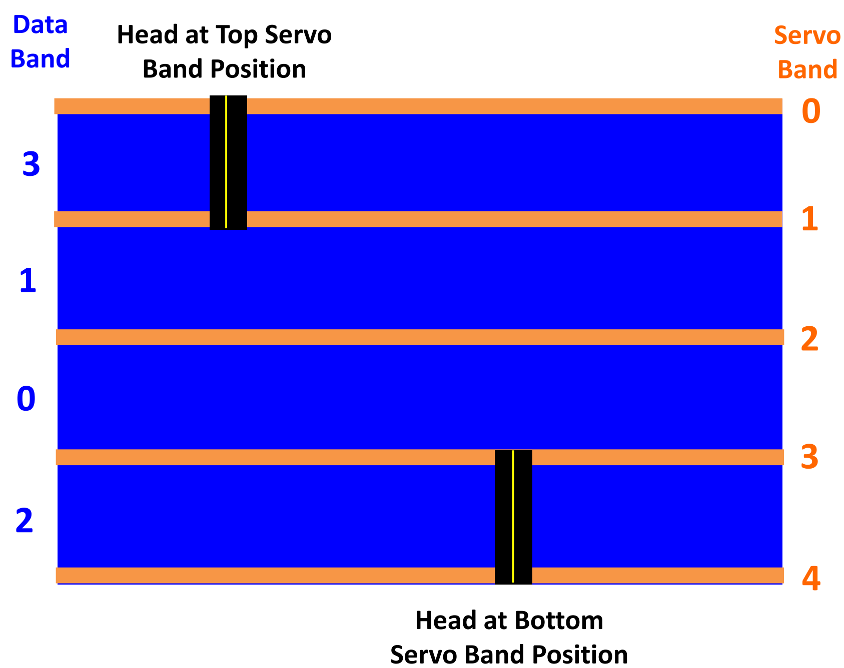


Figure 1. Schematic view of LTO tape showing 4 data bands and 5 servo bands.

dimension of the tape can change. This limit can be referred to as an acceptable maximum lateral strain, where lateral strain is the change-in-width of the tape relative to its original width. It is a measure of dimensional stability.

How Much Lateral Strain can a Tape Tolerate?

Magnetic tapes are made from plastics, which have properties that change with temperature and humidity. They are also stretched when used in a drive, and wrapped in a reel for storage. As a result, information written on a virgin tape might be misread as illustrated in Figure 2. A relatively wide WRITE element can write a track on to a

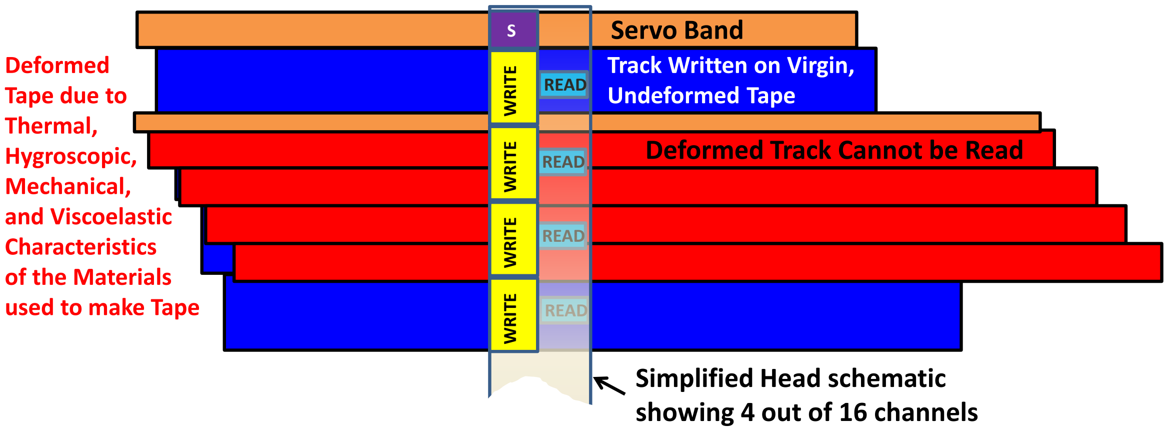


Figure 2. Illustration of tape deformation and how a written track might be misread.

virgin, undeformed tape. Then, the servo element on the head labeled with an "S" in Figure 2 can locate the servo band, and the narrower READ head can read-back the information. However, the tape could deform beyond the ability of the head to read-back the information, even if the head properly locates the servo band. This deformation is due to stresses acting on the tape, and the thermal, hygroscopic, mechanical, and viscoelastic characteristics of the materials used to make the tape. To calculate the maximum acceptable lateral strain, the size of the WRITE and READ elements on the head is used together with the width of the data band. Simplified calculations below use data from the 2012 Tape Roadmap developed by the Information Storage Industry Consortium (INSIC).[2] Note that a "μm" is a micrometer or one millionth of a meter.

In 2012, the typical tape was written with a 3.8 μm wide WRITE element, and read with a 1.6 μm wide READ element. For a 12.7 mm wide tape with a 3000 μm wide data band, the maximum acceptable lateral strain equals (3.8 μm – 1.6 μm)/(3000 μm) = 733 μm/m.	**In 2022**, a tape could be written with a 0.48 μm wide WRITE element, and read with a 0.20 μm READ element. For a 12.7 mm wide tape with a 3000 μm wide data band, the max acceptable lateral strain equals (0.48 μm – 0.20 μm)/(3000 μm) = 93.3 μm/m.

Therefore, in 2012, the maximum acceptable lateral strain for a tape should be about 733 μm/m, but in 2022 this is projected to decrease to about 93 μm/m.

Fundamental Scientific and Engineering Terms

To determine if these acceptable maximum lateral strain levels have been met with current tapes, and can be met in the future, some fundamental scientific and engineering terms need to be defined before experimental and analytical methods and results are described. First, there is the definition of "strain," which we have already learned about with our definition of lateral strain as a measure of dimensional stability. Note that the Greek letter epsilon, ε, is used for strain, and it can be expressed in μm/m. The "Dimension" can be length or width.

$$\varepsilon = \textit{Strain} = \frac{\text{Change-in-Dimension}}{\text{Original Dimension}} \text{ in } \frac{\text{micrometers}}{\text{meter}} \text{ or } \frac{\mu\text{m}}{\text{m}}$$

We also need to understand the concept of "force," which can simply be thought of as a push or a pull. Force can be measured in Newtons or N. For those of you not familiar with this metric unit, a Newton equals 0.2248 pounds, so one Newton is roughly a quarter of a pound. If this force is applied to some object with a known cross-sectional area, then the "stress" on this object can be calculated as follows. Note that the Greek letter sigma, σ, is used for stress, and the units of stress are Newtons per square meter or Pascals abbreviated as Pa.

$$\sigma = \textit{Stress} = \frac{\text{Force}}{\text{Area}} \quad \text{in} \quad \frac{\text{Newtons}}{\text{square meter}} \quad \text{or} \quad \frac{\text{N}}{\text{m}^2} \quad \text{or Pascals or Pa}$$

Since we sometimes have millions of Pascals when a stress is applied, we often use units of MegaPascals or MPa when we refer to stress levels. If billions of Newtons per square meter or GigaPascals are used for units, this is abbreviated as GPa.

Viscoelastic Properties and Characteristics

When a stress is applied to a plastic material, it can "flow" in a manner related to its viscosity, and "stretch" in an elastic manner. This behavior depends on the temperature, humidity, and type of plastic. The toy commonly known as "silly putty" illustrates this so-called viscoelastic behavior. For those of you unfamiliar with the term "viscosity," think of it as the inverse of fluidity. For example, water is less viscous than honey, and therefore flows more easily than honey. One way to measure viscoelasticity using strips of plastic is to apply a constant stress to the plastic, and measure the strain on the plastic as it flows and stretches over a period of time. (Recall that the strain is simply the change-in-length of the plastic relative to its original length.) The engineering term used to describe what happens to the strip of plastic under these conditions is called "creep-compliance," although it is sometimes just referred to as "creep." The letter "D" is used for creep-compliance, and since it depends on time, D(t) can be defined as follows in units of inverse GPa or (1/GPa) or GPa^{-1}.

$$D(t) = \textit{Creep-compliance} = \frac{\varepsilon(t)}{\sigma} = \frac{\text{time-dependent strain}}{\text{constant applied stress}}$$

Custom-built machines are used to measure creep-compliance for strips of tape, substrate materials, and even layers of the tape. This can be done at elevated temperature and/or humidity levels over long periods of time (100 or more hours). Then, analytical methods such as time-temperature superposition can be used with creep-compliance data to predict how a tape will respond over longer time periods of 1, 10, 30, 50, or even 100 years.

Equipment and Methodology for Measuring Creep-compliance

A schematic of the custom creep testers used to measure the viscoelastic characteristics of magnetic tape samples is shown in Figure 3. One of the creep testers is in a temperature-controlled incubator (Figure 4), and the other is in a humidity-controlled chamber (Figure 5). Four specimens can be tested with each creep tester, and each 200 mm long test specimen is fastened to a base plate and load arm. A 7.0 MPa stress is applied to each test specimen using a remotely

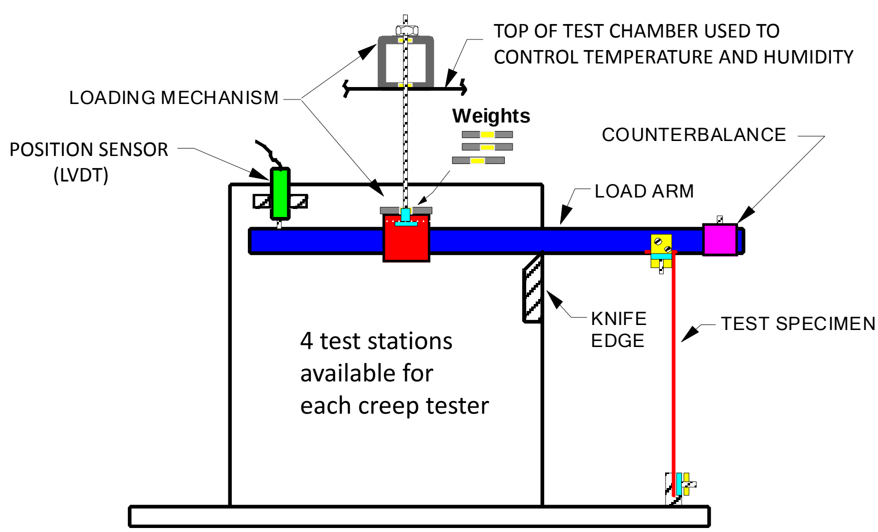


Figure 3. Schematic diagram of creep test apparatus. Adapted from Weick and Bhushan,[3,4] and Weick.[5-7]

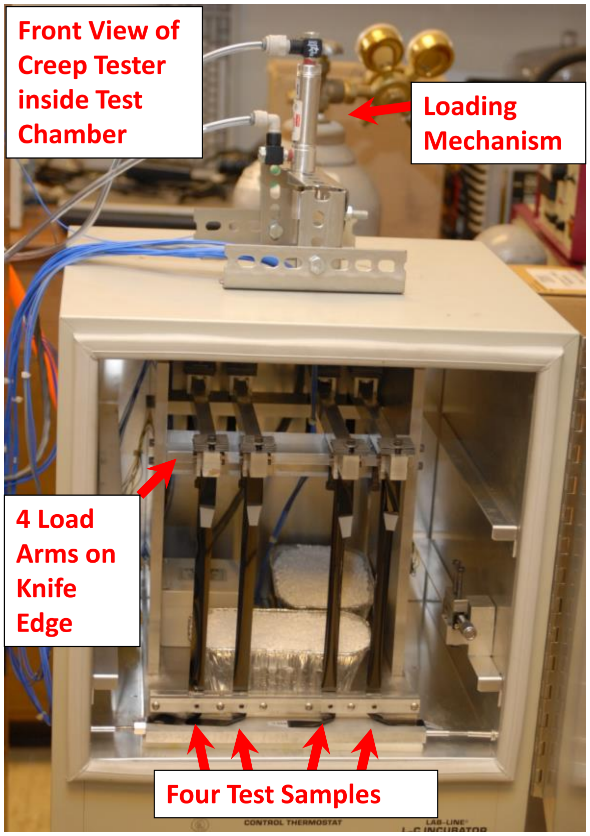


Figure 4. Creep tester in a temperature-controlled incubator.

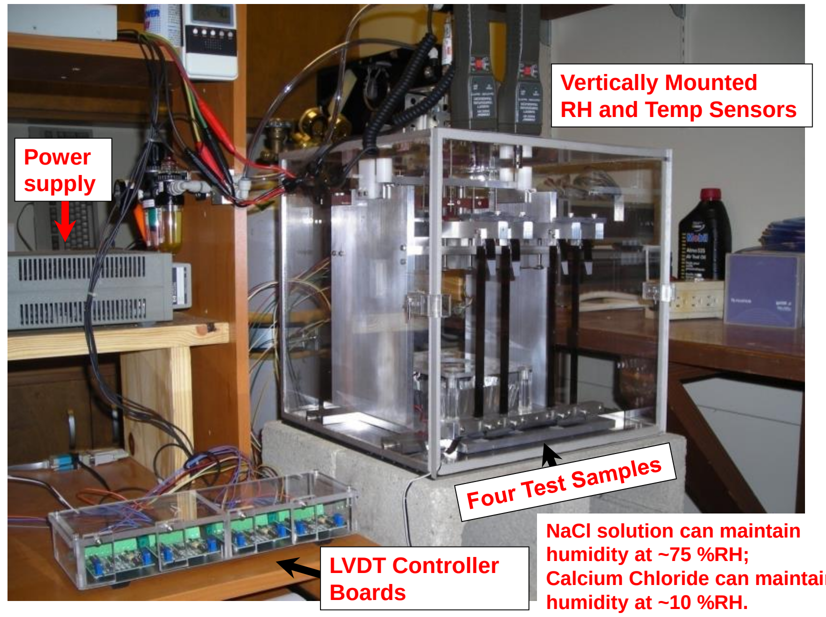
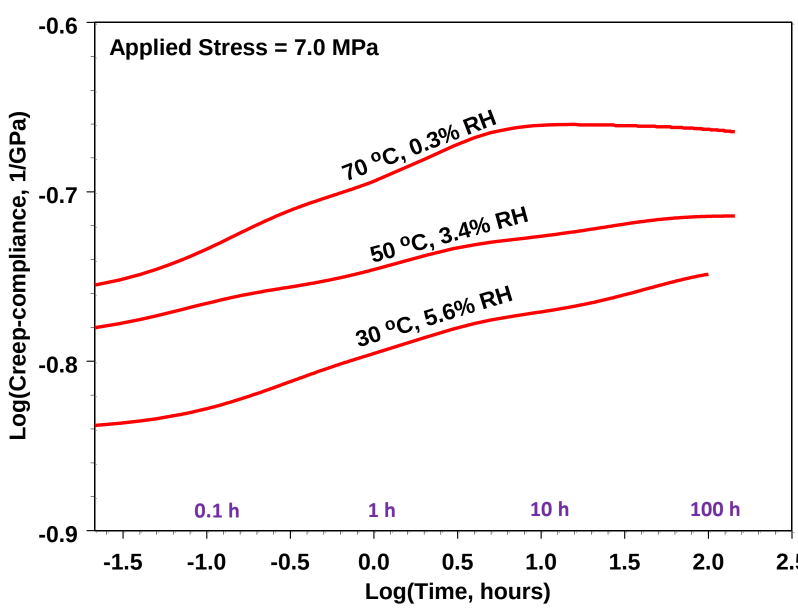


Figure 5. Creep tester in a humidity-controlled chamber.

operated loading mechanism after the temperature and/or humidity reaches the desirable level. Then, the change-in-length of each test specimen is monitored for approximately 100 hours using a position sensor called a linear variable differential transformer (LVDT). Each LVDT is connected through an external control circuit to a computer-controlled data acquisition system.

Creep-compliance Measurements

Experimental results for an LTO-4 tape are shown in Figure 6. The horizontal time axis is on a base 10 log scale, which means that each number on the axis is a power of 10. For instance, the number 2 on the axis means 10^2 or 100 hours. Similarly, the number -1.0 means 10^{-1} hours or 0.1 hours. The vertical axis is also on a base 10 log scale, and the chart to the right of Figure 6 shows how the logs of these numbers can be converted to creep-compliance in 1/GPa. For example, the number -0.60 means $10^{-0.6}$ or a creep-compliance of 0.25 1/GPa. The reason for plotting the base 10 logs of the time and creep-compliance will be discussed shortly, but let's focus on the trend lines in Figure 6 for a moment. Each line represents an average of three experiments performed for 100 or more hours at 30, 50, or 70 ^{o}C. Humidity is kept as low as possible during these experiments using a desiccant in the chamber, and ranges from 5.6, to 3.4, and



D(t) = ε(t) / σ

Log(D, 1/GPa)	D, 1/GPa
-0.60	0.25
-0.70	0.20
-0.80	0.16
-0.90	0.13

Figure 6. Creep measurements for an LTO-4 developmental tape with a metal particle (MP) magnetic layer and PEN or poly(ethylene naphthalate) substrate.

0.3% Relative Humidity for the three temperatures levels. Although not the focus of this white paper, it should be noted that the data sets are fitted to a Kelvin-Voigt mathematical model, which allows the viscous and elastic characteristics of the tape to be studied.[6,7] Lastly, as temperature increases the overall creep-compliance increases due to an increase in the viscous characteristics of the tape. However, at the highest 70 ^{o}C temperature, there is some leveling-out of the trend line due to a thermal transition in the poly(ethylene naphthalate) or PEN substrate used for the tape.[6,7]

Time-temperature Superposition to Predict Long-Term Behavior

Since the semi-crystalline plastic materials used for magnetic tape are viscoelastic, a scientific method developed sixty years ago called time-temperature superposition[8] can be used to connect the 30, 50, and 70 ^{o}C data sets to predict long-term creep behavior. The principle is simple, a viscoelastic material creeps at elevated temperatures over short periods of time in the same manner at lower temperatures over long periods of time. Data sets shown in Figure 6 are plotted on log-scales to enable the use of this time-temperature superposition process. If 30 ^{o}C is established as a reference temperature, the 50 ^{o}C data can be shifted to the right or longer times until it connects with the 30 ^{o}C data set. Similarly, the 70 ^{o}C data set can be shifted farther to the right until it connects with the previously shifted 50 ^{o}C data set. Results from this shifting process are shown in Figure 7, and enable the prediction of creep-compliance for 1, 10, 30, 50, and even 100 years. Furthermore, the lateral strain can be predicted by multiplying the creep-compliance and applied stress together to get the lengthwise strain, then multiplying this by 0.3. This 0.3 factor is an assumption used for the PEN substrate, and is known as the Poisson's Ratio.[5] This prediction of lateral strain is conservative, and is therefore an over-prediction. For the LTO-4 tape, the lateral strain is -434 μm/m for 30 years, and -461 μm/m for 100 years. They are widthwise contractions.

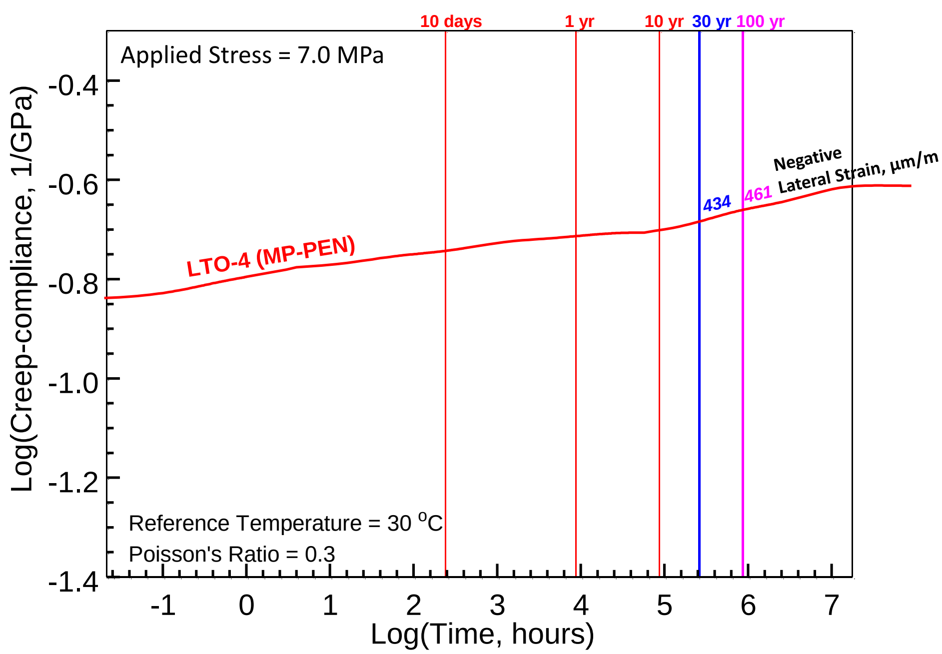
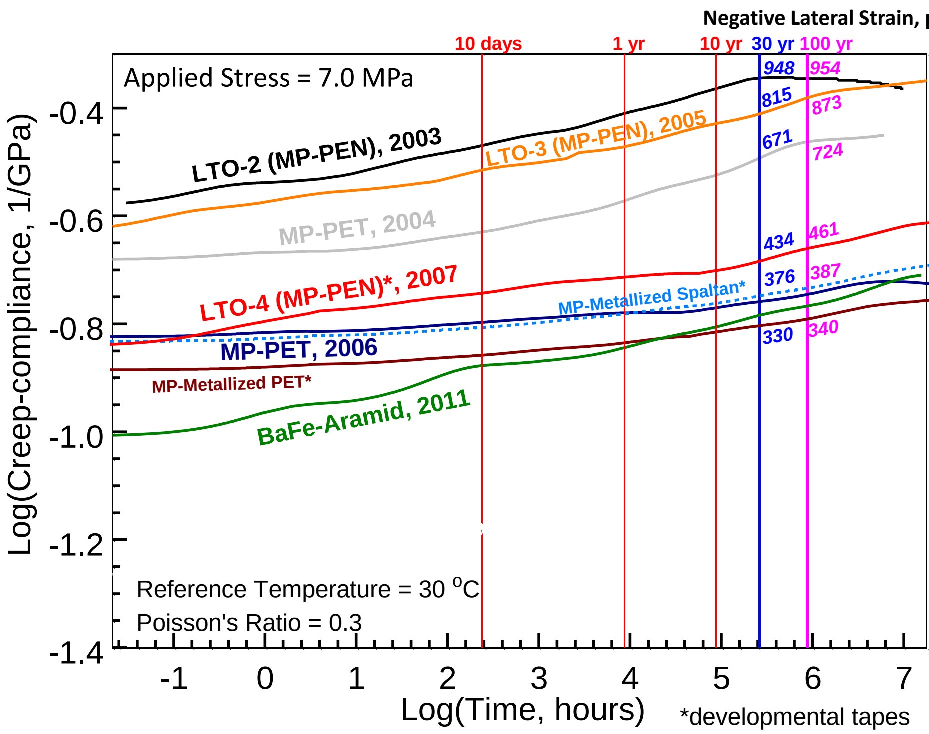


Figure 7. Using data from the 30, 50, and 70 ^{o}C experiments, creep-compliance master curves can be constructed at a 30 ^{o}C reference temperature using a technique called time-temperature superposition to predict creep-compliance for extended time periods. Lateral strains are calculated at 30 and 100 years using the simple equation: Lateral Strain = -(0.3)(D)(σ)

As shown in Figure 8, Creep-compliance characteristics of many other tapes have been measured and used in this time-temperature superposition process to predict long-term behavior out to 100 years. Results for the LTO-4 tape from Figure 7 are included in Figure 8, and can be compared with results for LTO-2 and LTO-3, which are older metal particle (MP) tapes with PEN substrates. The LTO-2 tape has the highest overall creep-compliance, and was released in 2003. Two years later, LTO-3 was released with an improved overall creep-compliance. In addition, the roll-off observed at longer times for LTO-2 was not observed for LTO-3. LTO-4 showed an even lower creep-compliance as well as a lower slope. The slope can be associated with creep velocity or the rate of creep.[6,7] The PEN substrate used for LTO-4 was bi-directionally tensilized to help achieve this lower overall creep-compliance by pulling it in both the machine and transverse directions during



2012 INSIC Roadmap

Stability Goals	
Year	μm/m
2012	-680
2014	-455
2016	-300
2018	-200
2020	-130
2022	-85

Figure 8. Creep-compliance master curves for selected magnetic tapes from time-temperature superposition using 30, 50, and 70 °C data sets. Metal particle (MP) tapes with PET, PEN, and metallized substrates are shown as well as a Barium Ferrite (BaFe) tape with an Aramid substrate. Lateral Strain values for 30 and 100 years are contractions, where Lateral Strain = -(0.3)(D)(σ).

manufacturing.[6,7] Results are also presented for two MP tapes with poly(ethylene terephthalate) or PET substrates, which are also tensilized primarily in the machine direction. The MP-PET tape released in 2004 has an overall creep-compliance between that measured for LTO-3 and LTO-4, and the MP-PET tape released in 2006 has an almost identical creep-compliance to LTO-4 during the initial stages of the experiment, but has a lower creep-velocity resulting in a lower overall creep-compliance at longer time periods. Two developmental MP tapes with Metallized PET and Metalized Spaltan substrates are also included in Figure 8. Spaltan is a proprietary substrate material, and the metalized substrates have an oxidized aluminum coating to improve dimensional stability. The MP-Metallized PET tape has a lower overall compliance than the MP-PET tape released in 2006 with similar creep velocity characteristics, whereas the MP-Metallized Spaltan tape has almost identical creep-compliance characteristics as the 2006 MP-PET tape out to 100 years. A tape with an aromatic poly(amide) or Aramid substrate is also included that uses a Barium Ferrite (BaFe) coating. This tape was released in 2011, and has a lower overall creep-compliance than the other tapes tested for 1 year, and only exceeds the MP-Metallized PET creep-compliance at longer time periods. It does have a slope or creep velocity that is similar to what was measured for the LTO MP tapes that use the PEN substrate.

Lateral strain calculations are included in Figure 8 for 30 and 100 years, and use the same assumption that the Poisson's Ratio is 0.3. Since manufacturer's specifications are proprietary for these tapes, determining whether these lateral strains meet drive specifications is not possible. However, comparisons can be made with stability goals or targets established by INSIC, and a small table from the 2012 INSIC Tape Roadmap is included in Figure 8 for this purpose.[2] Although these goals are for total dimensional stability including free expansion due to thermal and hygroscopic conditions as well as viscoelastic creep behavior under stress, the comparison with calculated lateral strains in Figure 8 is still a conservative approach. In past work the initial creep-compliance or elastic response was even separated-out to make this comparison.[5] Furthermore, the time-frame for the INSIC stability goals is a bit unclear, although 30+ years is stated in the 2012 INSIC Roadmap as the typical use-life for tapes. Therefore, comparisons with 100 year lateral strain calculations in Figure 8 are conservative.

With a -680 μm/m stability goal for 2012, it is interesting to note that LTO-4 is predicted to meet this goal with a lateral strain of -461 μm/m after 100 years, and LTO-4 was released in 2007! Other tapes in Figure 8 released as early as 2006 are also predicted to meet this goal. When the 2014 goal of -455 μm/m is considered, the MP-PET tape released in 2006 still meets this goal as well as the tapes with Metallized substrates and the BaFe-Aramid tape. In 2016 the goal is -300 μm/m with the MP-Metallized PET tape coming the closest with a 100 year lateral strain of -340 μm/m followed by BaFe-Aramid released in 2011 with a slightly more negative lateral strain of about -360 μm/m after 100 years. Based on this trend, tapes released in the last couple of years will likely meet the 2016 goal as well as future dimensional stability goals. Furthermore, the lateral strain calculations in Figure 8 are conservative, but simplistic. A more accurate analysis can be performed as described below.

How do we Account for Stresses on the Tape when it is stored in a Reel?

The lateral strain calculations shown in Figure 8 only consider the applied stress of 7.0 MPa, and do not account for stress variations through the tape pack when it is stored in a reel. Fortunately, many scientists and engineers have developed models for predicting stresses in a tape pack, and these have been summarized and improved upon in recent research.[9,10] The first step is to understand the nature of the stresses in the tape pack using Figure 9. These stresses tend to act in both radial and circumferential directions, and are functions of radial position in the tape pack, r, as well as storage time, t. The radial stress is therefore represented as $\sigma_r(r,t)$, and the circumferential stress as $\sigma_\theta(r,t)$. Both of these stresses can be found using parameters from the Kelvin-Voigt mathematical model used to fit the creep-compliance data sets in Figure 6.[9,10] The model is shown below, and allows for the fundamental compliance terms including D_o and D_k as well as the viscosity terms, η_k, to be extracted from the creep-compliance data and used in the stress equations.[5-7,9,10] They describe the viscoelastic properties of the tape!

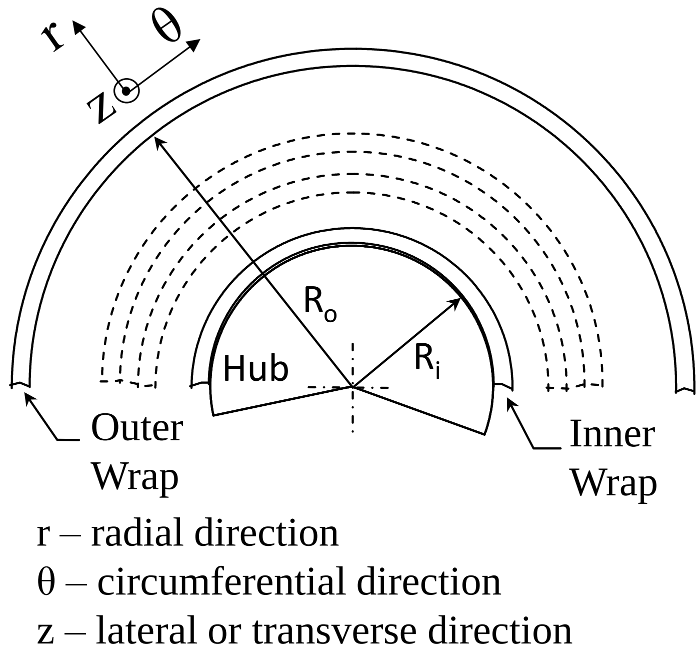


Figure 9. Schematic of a magnetic tape stored in a reel showing inner and outer tape wraps around a hub. Radial, circumferential, and lateral directions are defined. Adapted from Weick and Bhushan.[3,4]

$$D(t) = D_o + \sum_{k=1}^{K} D_k \left[1 - \exp\left(\frac{-t}{\eta_k D_k}\right)\right]$$

Once the stresses $\sigma_r(r,t)$ and $\sigma_\theta(r,t)$ are found, they can be combined with the creep-compliance experimental data, D(t), from time-temperature superposition in Figure 8 to determine the lateral strain in the tape as a function of radial position and time, $\varepsilon_z(r,t)$. An assumed Poisson's Ratio, ν, is used in the equation below, and represents the ratio of the lateral strain to the circumferential strain.[9,10]

$$\underbrace{\varepsilon_z(r,t)}_{\text{Lateral Strain}} = -\underbrace{\nu}_{\text{Poisson's Ratio}} \underbrace{D(t)}_{\text{Creep Compliance Experimental Data}} [\underbrace{\sigma_\theta(r,t)}_{\text{Circumferential Stress}} + \underbrace{\sigma_r(r,t)}_{\text{Radial Stress}}]$$

Calculated using parameters from Kelvin-Voigt model

Figure 10 shows how this advanced stress model can be used to predict lateral strain for an LTO-3 tape. Note that the lateral strain is negative, which means the tape contracts widthwise. The non-dimensional horizontal axis in Figure 10 starts at radial position 1, which is the inner wrap in Figure 9, and ends at radial position 2, which is the outer wrap in Figure 9. The model was run for 250,000 hours, which corresponds with a total of 28.5 years. (Due to computational limitations, the model was not run for longer time periods.[11])The layered color bands show how the lateral strain is becoming more and more negative as time progresses due to the creep-compliance of the tape as well as the radial and circumferential stresses on the tape. Note that strain is more negative at the inner and outer wraps. After 28.5 years of storage, the lateral strain on the inner wrap is -700 µm/m, and the lateral strain on the outer wrap is approximately -800 µm/m. When compared to the 2012 INSIC goal of -680 µm/m, it is interesting to note that the lateral strain on this 2005 era LTO-3 tape is only 20 to 120 µm/m more negative. Therefore, the 2012 stability goal was almost met by LTO-3 in 2005.

Lateral strain predictions for a BaFe-Aramid tape are shown in Figure 11, and are plotted on the same scale as the LTO-3 predictions in Figure 10. Due to the lower creep-compliance of the BaFe-Aramid tape, the lateral strain is significantly reduced, and barely exceeds the -300 µm/m level at the outer wrap after 28.5 years. This is the stability goal for 2016, and is almost met by the 2011 era BaFe-Aramid tape.

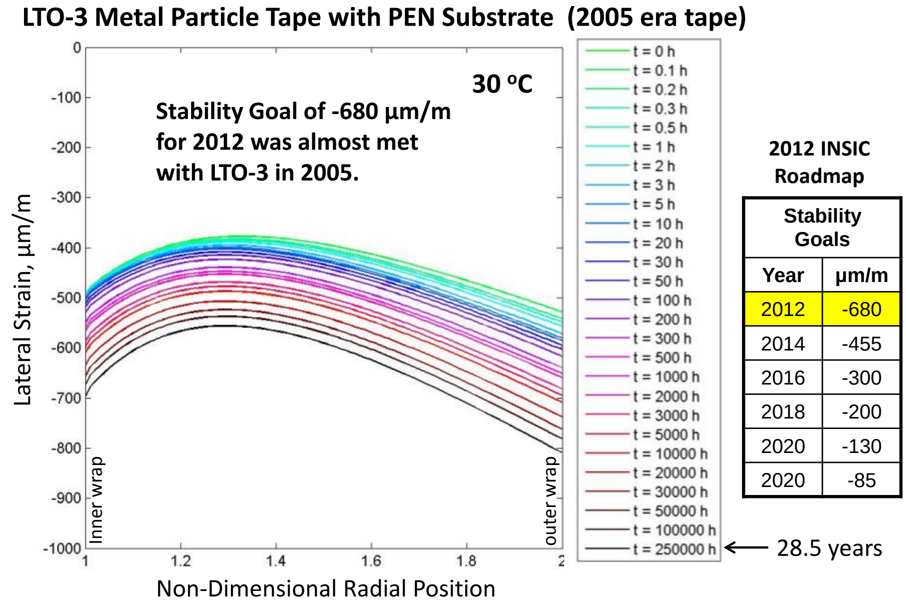


Figure 10. Lateral strain prediction using an advanced stress model for an LTO-3 MP tape with a PEN substrate.[9-11] A 5 parameter Kelvin-Voigt model is used for a winding tensile stress of 7.0 MPa. A "stiff" hub modulus of 10^5 MPa is used, and the orthotropy ratio is 1.

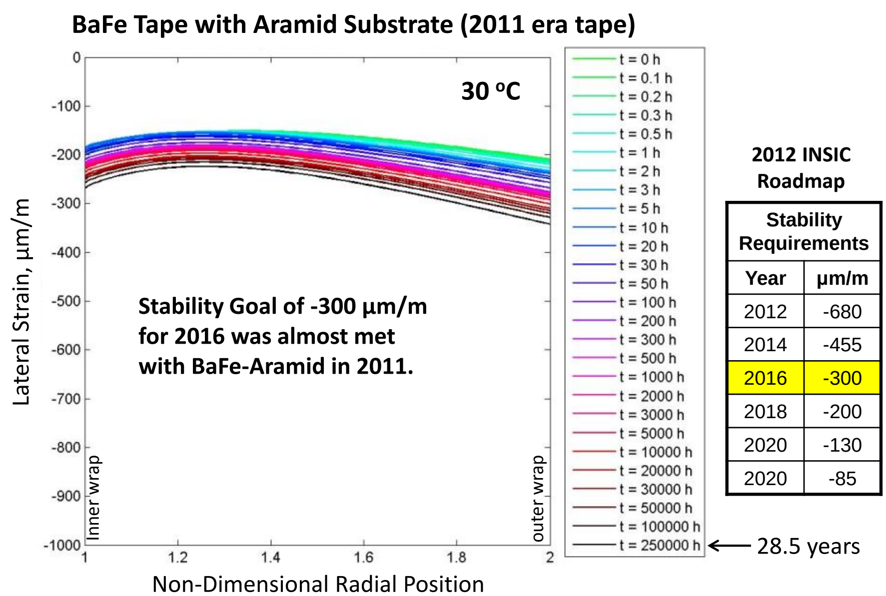


Figure 11. Lateral strain prediction using an advanced stress model for a BaFe tape with an Aramid substrate .[9-11] A 5 parameter Kelvin-Voigt model is used with a winding tensile stress of 7.0 MPa. A "stiff" hub modulus of 10^5 MPa is used, and the orthotropy ratio is 1.

Tapes are Multi-layer Composite Materials that are Designed to meet Dimensional Stability Goals

Magnetic tapes are advanced composite materials comprised of multiple layers with constituents that have been carefully developed to work together to meet dimensional stability goals. Figure 12 shows the layers of a typical LTO-4 (MP-PEN) tape. An advanced polyester substrate that goes by the acronym PEN is sandwiched between a front coat and back coat. The front coat consists of a magnetic layer with the metal particles (MP) held together in an elastomeric or rubber-like binder consisting mainly of poly(ester-urethane) on top of an under-layer. The back

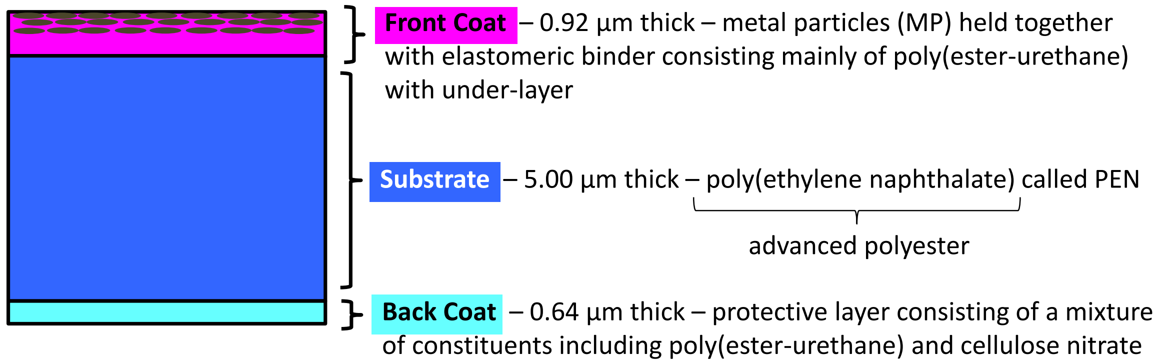
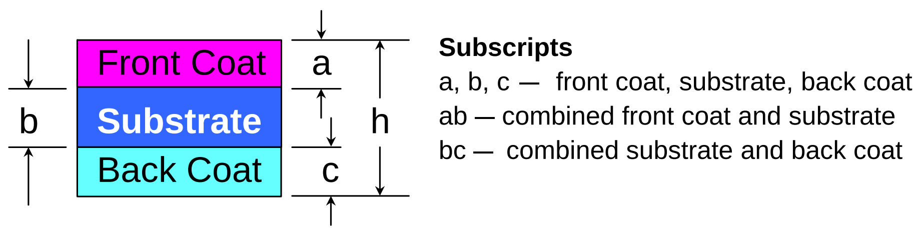


Figure 12. Layers of a typical LTO-4 (MP-PEN) Tape.

coat is a relatively soft, protective layer consisting of a mixture of constituents including poly(ester-urethane) as well cellulose nitrate. To understand how the different layers influence the dimensional stability of the overall tape, a technique has been developed to remove either the front coat or back coat and measure the creep-compliance of dual-layer substrate plus back coat, and front coat plus substrate samples.[3,4,6] (Unfortunately it is not feasible to do experiments with just the very thin front coat or back coat.) In addition, both the front and back coat can be removed to measure the creep-compliance of just the substrate. Using a rule-of-mixtures approach, results from the dual-layer creep-compliance experiments can be combined with results from the substrate experiments to calculate the creep-compliances for just the front coat and back coat.[3,4,6] Equations used for this process are in Figure 13.

Results for an LTO-3 (MP-PEN) tape, substrate, front coat, and back coat are shown in Figure 14. Time-temperature superposition was used to piece together data from 30, 50, and 70 °C experiments. A reference temperature of 30 °C was used, and the tape master curve in Figure 14 is the same one shown in Figure 8 for LTO-3. The substrate curve is just below the tape curve, and follows it



Front Coat: $$D_a(t) = \left\{ \left(\frac{a+b}{a}\right)\left(\frac{1}{D_{ab}(t)}\right) - \left(\frac{b}{a}\right)\left(\frac{1}{D_b(t)}\right) \right\}^{-1}$$

Back Coat: $$D_c(t) = \left\{ \left(\frac{b+c}{c}\right)\left(\frac{1}{D_{bc}(t)}\right) - \left(\frac{b}{c}\right)\left(\frac{1}{D_b(t)}\right) \right\}^{-1}$$

Figure 13. Illustration of rule-of-mixtures method for determining the creep-compliance of the front and back coats of a magnetic tape using experimental data for the substrate as well as data from dual-layer experiments where the front or back coat has been removed.[3,4,6]

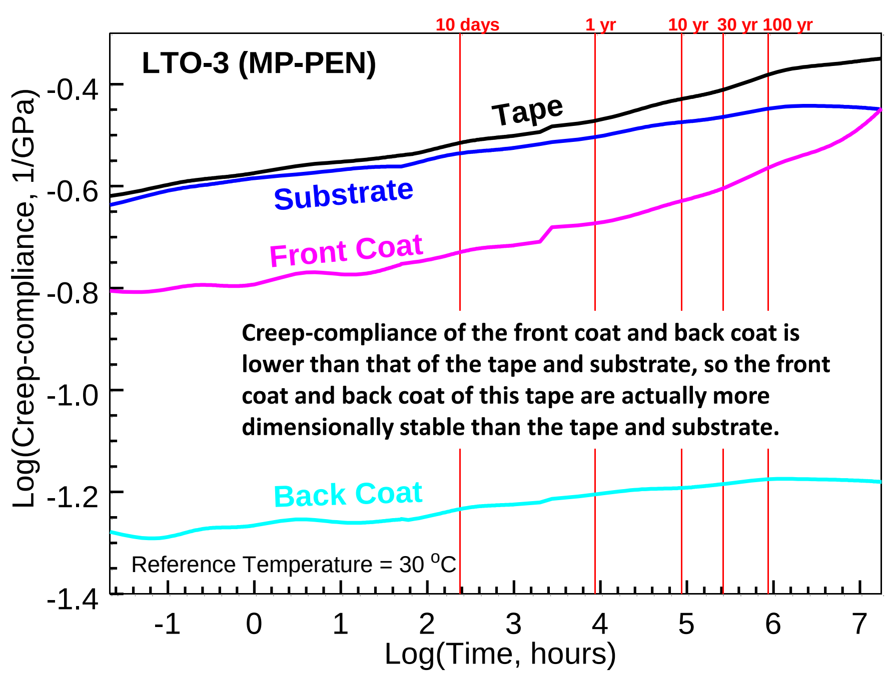


Figure 14. Creep-compliance curves for an LTO-3 (MP-PEN) front coat and back coat determined using a rule-of-mixtures approach compared to tape and substrate creep-compliance curves.[6]

rather closely for about 1 year. Then, the curves diverge a bit with the tape curve continuing to increase and the substrate curve decreasing and rolling-off due to thermal transitions in the PEN substrate.[6] From the rule-of-mixtures equations, the front coat and back coat were separated-out, and have a lower overall creep-compliance than the tape and substrate. This means that both the front and back coat are more dimensionally stable than the tape itself. This is particularly important for the front coat, which contains the magnetic particles with stored information. Note that the slope of the front coat curve is similar to that for the tape in Figure 14, particularly during the 1 to 100 year time period. LTO-2, LTO-3, and similar PEN-based tapes have also had relatively low front and back coat compliances, although back coat compliances tend to vary.[6] However, the influence on overall dimensional stability seems to be from the combined action of the substrate and binder in the front coat.

Influence of Humidity on Dimensional Stability

Humidity is another environmental factor that influences the dimensional stability of magnetic tapes. To evaluate the influence of humidity, creep experiments were performed in a humidity-controlled environment using the creep tester shown in Figure 5. A sodium chloride (NaCl) salt solution was used to elevate the average humidity level to an average of 77.5% at an average ambient temperature of 21.4 °C. This corresponds with a mixing ratio of 13 grams of water per kilogram of dry air. Wide-stock tape samples were used for this study, which are 600 mm X 600 mm wide sheets of tape made before they are slit into 12.7 mm (1/2 inch) lengths. This enabled samples to be cut in the machine direction (MD) as well as the transverse direction (TD), where the length of the tape is the machine direction, and the width of the tape is the transverse direction. Tape and substrate samples were evaluated, where the substrate samples were obtained by removing the front and back coats of the tape with solvent.[3.4.6] Since LTO-4 tapes are pulled in the TD as well as the MD directions, they are said to be transverse tensilized. As shown in Figure 15, this is why the overall creep-compliance of the TD tape and substrate samples is lower than that of the respective MD samples. Transverse tensilization increases the stiffness and lowers the overall creep-compliance of the TD samples. In addition, the substrate samples have a higher overall creep-compliance than the tape samples, which means the substrates are more hygroscopic than the tapes. This also means that the front and back coats of the tape appear to protect the substrate from moisture. Note that the creep velocity of the tapes and substrates in Figure 15 are the same, because the slopes of the lines are similar for the three repeat experiments performed for each sample.

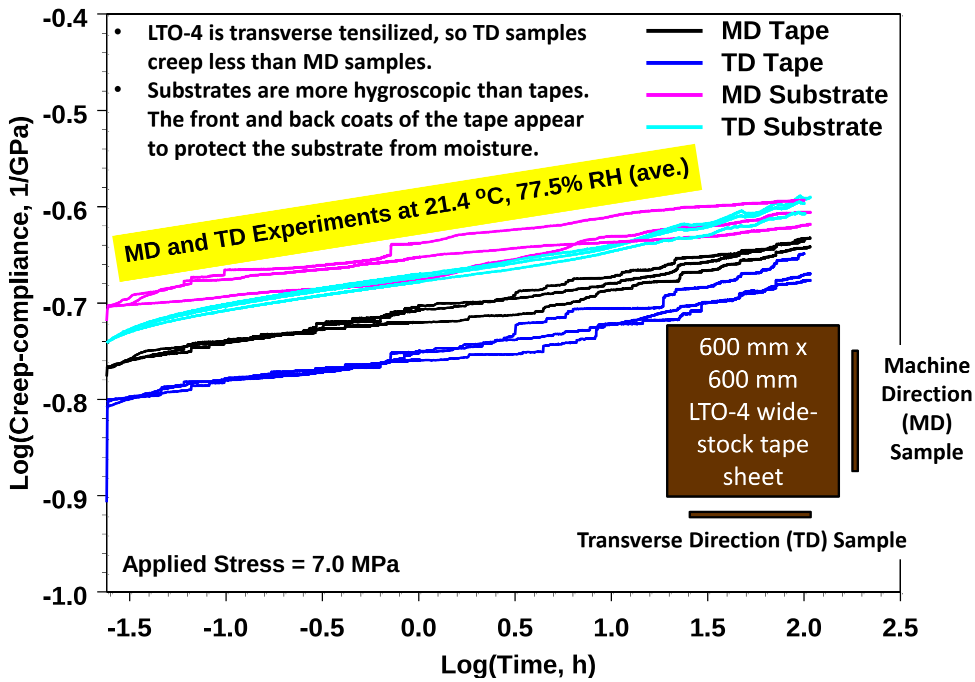


Figure 15. Elevated humidity creep-compliance for LTO-4 samples cut from wide-stock sheets. Mixing Ratio is approximately 13 grams of water per kilogram of dry air.

To see the influence of humidity on creep-compliance, results from elevated temperature experiments performed at low humidity levels from Figure 6 can be superimposed on the elevated humidity results performed at ambient temperature in Figure 15. These combined results are shown in Figure 16. For clarity, it should be understood that the red lines in Figure 16 are creep-compliant at 30, 50, and 70 °C for an LTO-4 tape at low humidity levels, and should realistically only be compared with the black lines in Figure 16 that represent three repeat creep-compliance experiments for a tape sample cut from wide-stock in the machine direction (MD). Recall that each of the 30, 50, and 70 °C trend lines are also a result of three repeat experiments. The 30 °C, 5.6% RH creep-compliance is not only lower than that of the 50 and 70 °C trend lines at even lower humidity levels, but is also lower than that of the MD tape sample at an elevated humidity of 77.5% RH and 21.4 °C ambient temperature. The 50 °C trend line is higher than the 30 °C line, and the 70 °C line is higher than the 50 °C line, with roll-offs at longer time periods attributed to thermal transitions as mentioned previously.[6,7] Note that the black lines for the MD tape experiments at 77.5% RH, 21.4 °C are just a bit lower than the 70 °C, 0.3% RH trend line for about the first 10 hours, which corresponds with a Log(Time) of 1.0 in Figure 16 since 10^1 is 10 hours. Then, the roll-off of the 70 °C, 0.3% RH curve causes the creep-compliance to drop a bit below that of the MD tape at 77.5% RH, 21.4 °C for the remaining ~90 hours of the 100 hour experiment. Keeping the comparison shown in Figure 16 in mind for 100 hours, it is important to consider what could happen if a tape is exposed to elevated humidity levels for longer time periods. Recall from time-temperature superposition in Figure 8 that the 70 °C data set is used to conservatively predict a lateral strain of -434 μm/m after 30 years, or -461 μm/m after 100 years. This is similar to what would be predicted if we could use time-humidity superposition with the 77.5% RH data set at 21.4 °C.

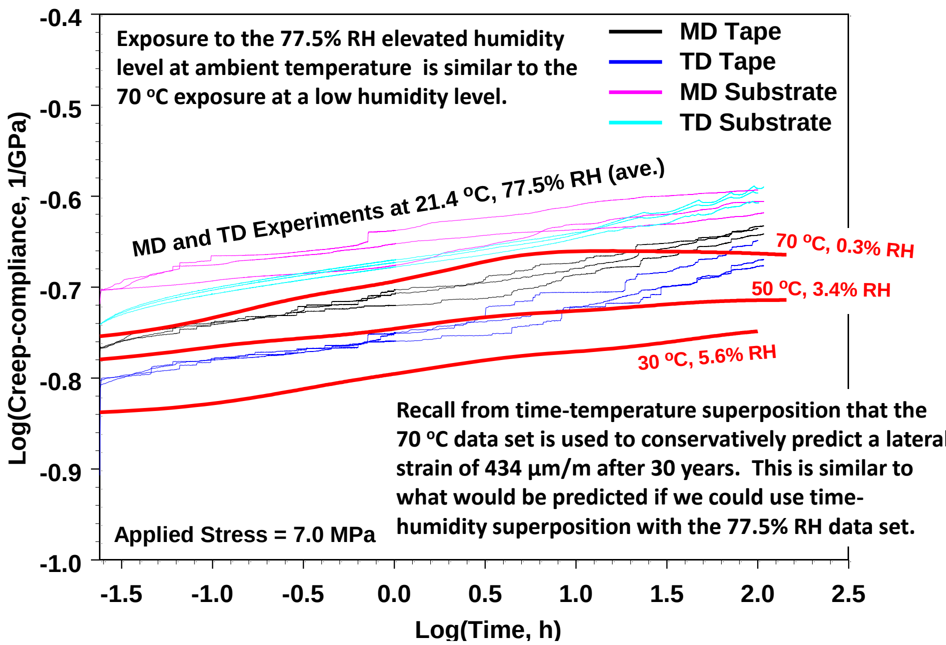


Figure 16. Comparison of LTO-4 wide-stock experiments at 21.4 °C, 77.5% Relative Humidity with elevated temperature experiments at low humidity.

Can Tapes Recover from Applied Stress and Creep?

Yes! As shown in Figure 17, when a viscoelastic material like a magnetic tape is subjected to an applied stress, it undergoes an elastic, instantaneous change-in-length followed by a time-dependent change-in-length. Recall that the instantaneous creep-compliance is D_o in the Kelvin-Voigt equation, and the summation terms in that equation describe the time-dependent response. From Figure 17, when a 7.0 MPa stress is applied to an LTO-4 tape, the instantaneous creep-compliance, D_o, is approximately 0.28 1/GPa. The time-

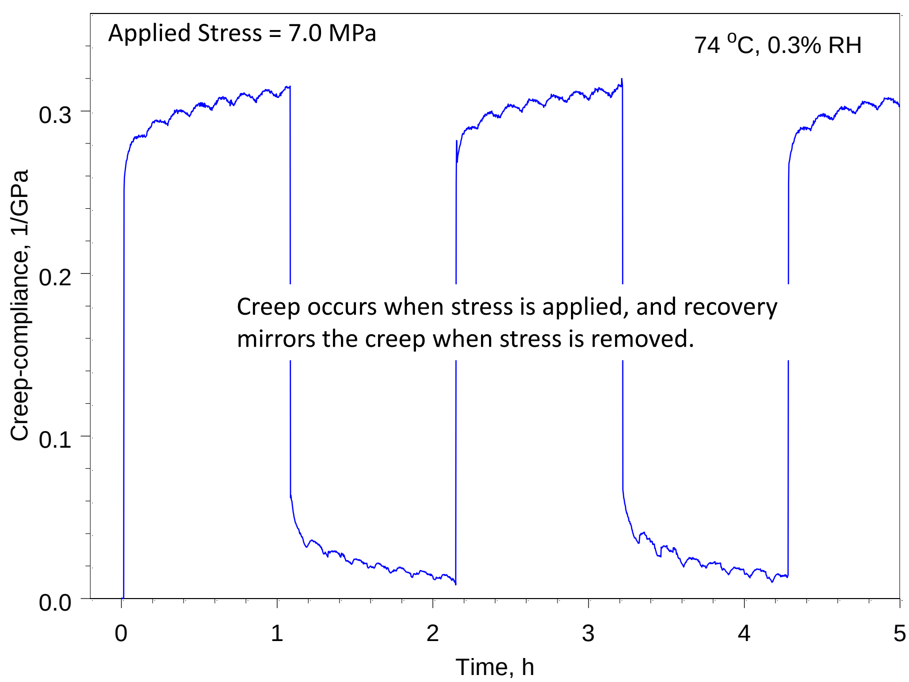


Figure 17. Load/unload creep-compliance data for an LTO-4 (MP-PEN) tape. The load is applied for 64 minutes, then removed for another 64 minutes. This loading cycle is repeated, and approximately 2.5 cycles are shown in the graph.

dependent response occurs for the 64 minutes that the stress is applied, and creep-compliance increases in a nonlinear manner. Small wave patterns in the data set superimposed on the non-linear creep-compliance during this hour are due to minor temperature cycling of ±0.1 ^{o}C in the chamber, and show that the tape is actually creeping and recovering to even this minor temperature fluctuation. When the stress is removed from the tape at the end of the 64 minutes, there is an instantaneous recovery followed by a time-dependent recovery that mirrors what happened when the stress was applied. This recovery occurs for another 64 minutes until the stress is reapplied after a total of 128 minutes. The elastic, instantaneous response followed by the time-dependent response occurs again until the load is removed after another 64 minutes, at which time the sample recovers again. Only 2.5 cycles are shown in Figure 17, but this load/unload process was repeated for many cycles causing the tape to creep and recover each time the stress was applied and removed. Therefore, tapes that are exposed to stresses at elevated temperature levels for a certain period of time need to be allowed to recover over the same period of time when those stresses are removed.

Summary

Precise creep measurements and better mechanical models have enabled the improved prediction of magnetic tape dimensional stability for extended storage periods of 30, 50, and 100 years. Stability goals developed by the INSIC industrial consortium have been met by magnetic tapes developed in the 21st century due to improvements in the properties and characteristics of the materials used to make the tapes. Polyester substrates such as PET and PEN as well as aramid substrates are viable choices for future magnetic tapes when dimensional stability goals are considered. In addition, binder stability appears to have improved over the years, and the dimensional stability of the typical front coat used for tapes is lower than the other layers, increasing the dimensional stability of tapes as a whole. Magnetic tapes should also be written, stored, and read under ambient temperature and low humidity conditions. Lastly, creep-recovery experiments show that magnetic tapes creep due to an applied stress, but can recover from that stress even if exposed to an elevated temperature.

Acknowledgments

The personnel at FUJIFILM Recording Media USA including Rich Gadomski and Take Nambo need to be thanked for their inspiration and review of this paper. The bulk of this research was sponsored by the Information Storage Industry Consortium (www.insic.org) as well as current and past members of the INSIC TAPE Program including IBM, Oracle, Hewlett-Packard, Quantum, Teijin-Dupont, Imation, Toray Industries, Panasonic, and FUJIFILM. Some of this work was performed during a sabbatical at IBM Almaden Research Center, and Wayne McKinley of the IBM Systems Group Materials Lab performed the chemical analyses of the LTO-4 tape. In addition, Dr. Richard Bradshaw, now retired from IBM, provided valuable insights into the properties and characteristics of magnetic tapes. Dr. Katherine Acton was a post-doctoral researcher at University of the Pacific who developed the original advanced predictive model used for calculating tape stresses, and Eugene Ragasa, an M.S. Graduate Student at Pacific, improved upon that model. Lastly, Dr. Bharat Bhushan of The Ohio State University needs to be acknowledged for getting the author started on magnetic tape research in the early 90’s.

References

1. Barrett, R. C., Klaassen, E. H., Albrecht, T. R., Jaquette, G. A., and J. H. Eaton, “Timing-Based Track-Following Servo for Linear Tape Systems,” *IEEE Transactions on Magnetics*, July 1998, Vol. 34, No. 4, pp. 1872 – 1877.
2. *International Magnetic Tape Storage Roadmap,* eds. P. D. Frank and B. H. Schechtman, Information Storage Industry Consortium (www.insic.org), San Diego, CA, 2012.
3. Weick, B. L., and B. Bhushan, "Determination of Coating Compliance and Strain Distribution for Magnetic Tapes Modeled as Multiple Layer Polymer Composites," *J. of Info. Storage and Processing Sys*., July 2000, Vol. 2, pp. 1 – 14.

4. Weick, B. L., and B. Bhushan, "Long-term Mechanical and Viscoelastic Behavior of Constitutive Polymeric Materials used for Magnetic Tapes," *Journal of Applied Polymer Science*, May 2001, Vol. 81, pp. 1142 – 1160.
5. Weick, B. L., "Viscoelastic Analysis Applied to the Determination of Long-term Creep Behavior for Magnetic Tape Materials," *Journal of Applied Polymer Science*, 2006, Vol. 102, No. 2, pp. 1106 – 1128.
6. Weick, B.L., "Viscoelastic Characteristics of Magnetic Tapes with PEN Substrates," *Journal of Applied Polymer Science*, January 2009, Vol. 111, pp. 899 – 916.
7. Weick, B. L., "Correlations between Creep, Shrinkage, and Dynamic Mechanical Characteristics of Magnetic Tape Materials," *Journal of Applied Polymer Science*, April 2011, Vol. 120, pp. 226 – 241.
8. Williams, M. L., Landel, R. F., and J. D. Ferry, "The Temperature Dependence of Relaxation Mechanisms in Amorphous Polymers and Other Glass-forming Liquids," *J. Amer. Chem. Soc*., Vol. 77, 1955, pp. 3701 – 3707.
9. Acton, K. and B. Weick, "Viscoelastic Behavior of Polymer Tape in a Wound Roll," *Journal of Applied Polymer Science*, December 2011, Vol. 122, pp. 2884 – 2898.
10. Acton, K. and B. Weick, "Orthotropic Viscoelastic Behavior of Polymer Tape in a Wound Roll," *Mechanics of Advanced Materials and Structures*, 2014, Vol. 21, No. 1, pp. 53 – 66.
11. Ragasa, E. J., *Predicting Long-Term Dimensional Stability of Viscoelastic Magnetic Tape*, M.S. Thesis, University of the Pacific, 2013.

December 10th, 2015