Dimensional Stability of Magnetic Tapes
Will tape survive archival storage?

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FUJIFILM Global IT Executive Summit 2015
Into Tomorrow with Tape Technology …
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Why do I study magnetic tape?

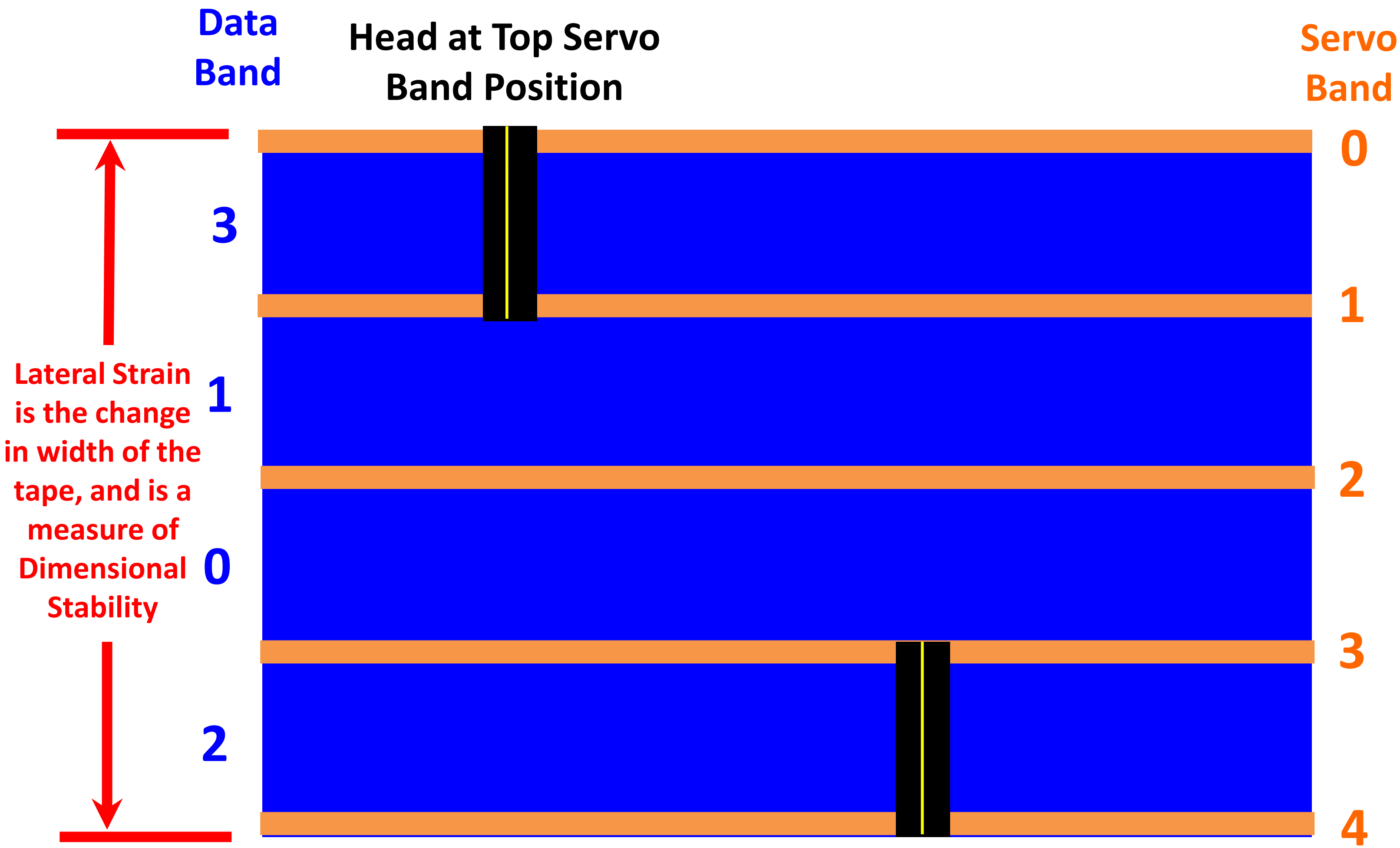
- to understand properties of materials used to make tape;
- to develop mathematical models for predicting the stresses developed in tape when it is wrapped in a reel;
- to use experimental data in these models to predict the dimensional stability of tape during archival storage.

What have I found from these studies?

- Based on the type of mechanical experiments and conservative analyses I have performed with various magnetic tapes, dimensional stability goals for 30, 50, even 100 years will be met if the magnetic tape cartridges are stored in a room temperature, low humidity environment.

What happens when we record information on to a tape?

- Tape streams under a head that can move or "servo" to four different positions.
- Example – for LTO-4, 16 channels are written for each of the 56 tape wraps, with 896 tracks written across the width of the tape. LTO-6 has 136 wraps and 2176 tracks!



$$\text{Strain} = \frac{\text{Change-in-Dimension}}{\text{Original Dimension}}$$

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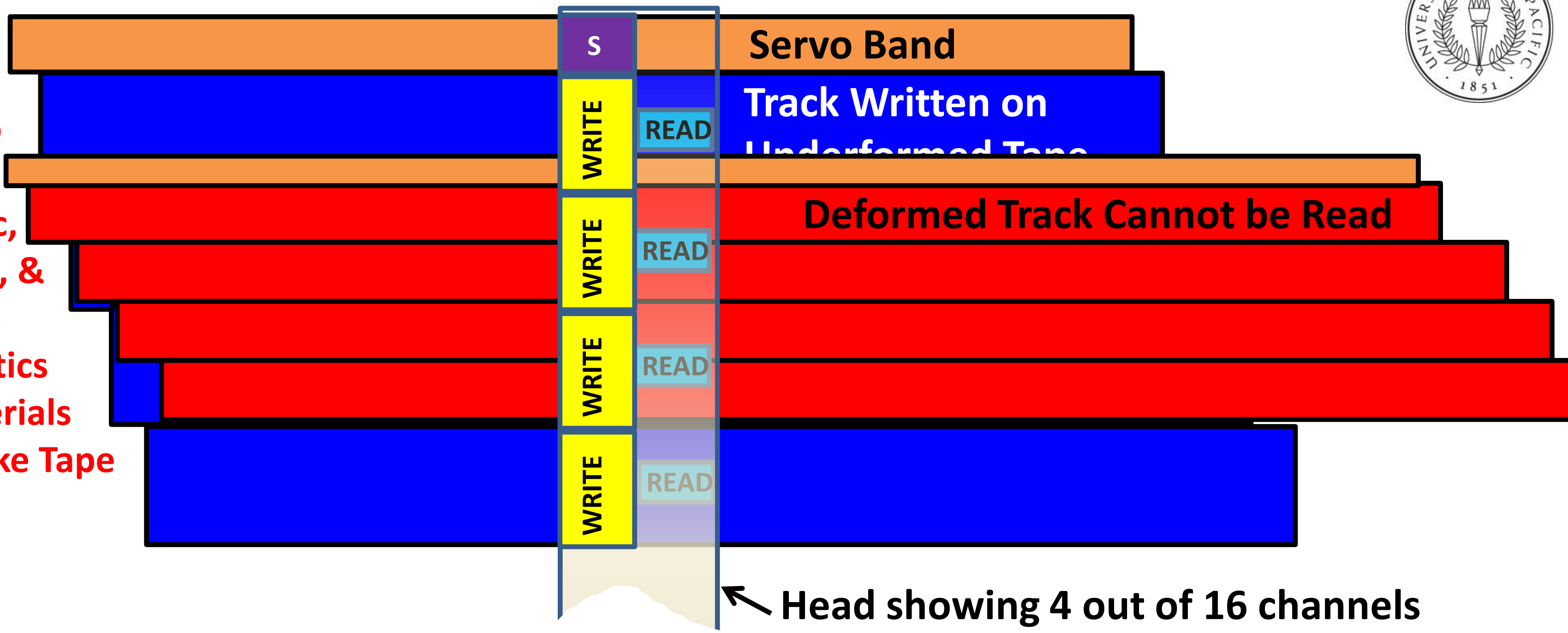
Schematic view of LTO tape layout showing four data bands and five servo bands.

Illustration of Dimensional Stability or “Acceptable” Maximum Lateral Strain

Deformed Tape due to Thermal, Hygroscopic, Mechanical, & Viscoelastic Characteristics of the Materials used to make Tape



Head showing 4 out of 16 channels (schematic)*

2022 Goal: 0.48 µm wide WRITE element
0.20 µm wide READ element.
Data Band = approx. 3000 µm wide

From 2012 INSIC Roadmap:
(INSIC = “Information Storage Industry Consortium”)

$$\text{Acceptable Maximum Lateral Strain} = \frac{0.48-0.20}{3000} = 93.3\ \mu\text{m/m}$$

Units:
1 µm = 1 millionth of a meter
1 micrometer/meter = 1 µm/m

*actual heads come in pairs that face each other with opposing write and read elements.

Important Terms and Units

We have already learned about *Strain*:

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

We also need to learn about *Force* and *Stress:*

Force is a pull or a push in Newtons or N

1 N = 0.2248 lb, so 1 N is roughly ¼ of a lb

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

Mega is a million and Giga is a billion

1 MegaNewton per square meter is 1 MegaPascal or MPa

1 GigaNewton per square meter is 1 GigaPascal or GPa

Viscoelastic Properties and Characteristics:

Viscoelasticity is the "silly putty" behavior of plastic materials, and is due to their ability to "flow" in a viscous manner and "stretch" in an elastic manner depending on temperature, humidity, and type of plastic.

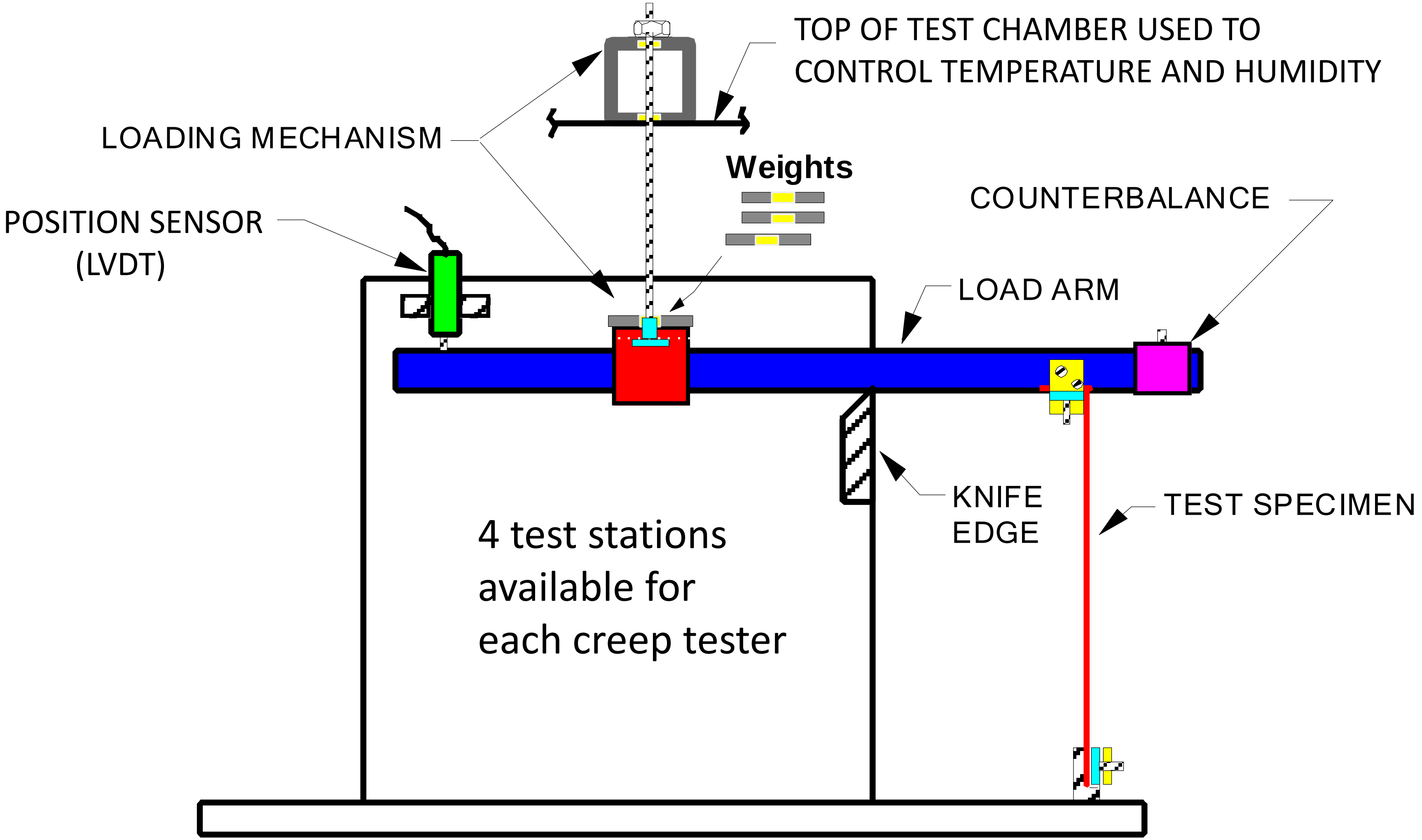
- Creep-compliance or "creep" is measured using strips of tape, substrate, and tape layers. I use custom-built machines to measure how tape samples stretch out at elevated temperature and humidity levels over long periods of time (100 or more hours).

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

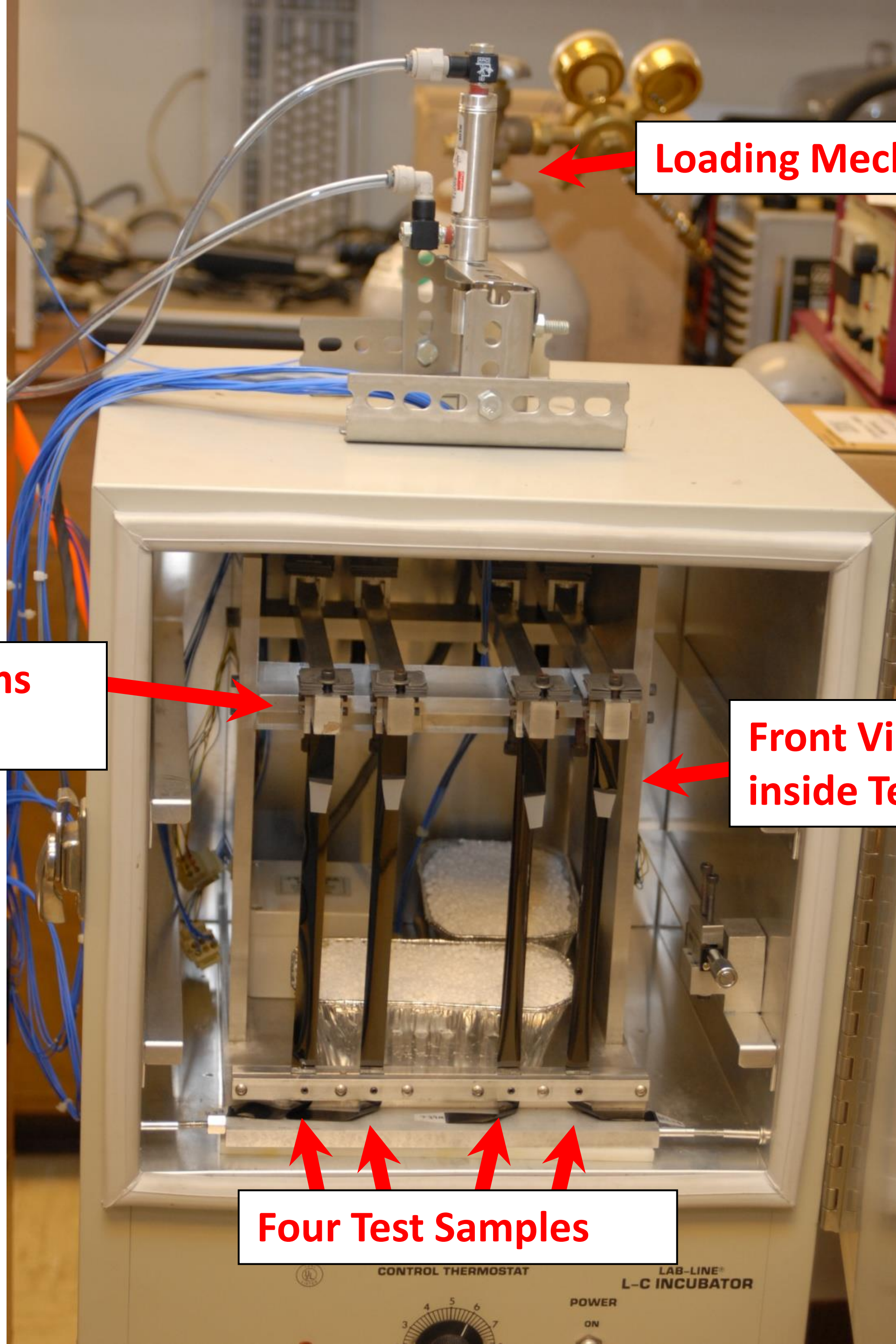
Creep-compliance **is measured in inverse GPa or (1/GPa)**

- Analytical methods such as time-temperature superposition can be used with creep-compliance data to predict how tape will respond over extended time periods of 1, 10, 30, 50, or 100 years.

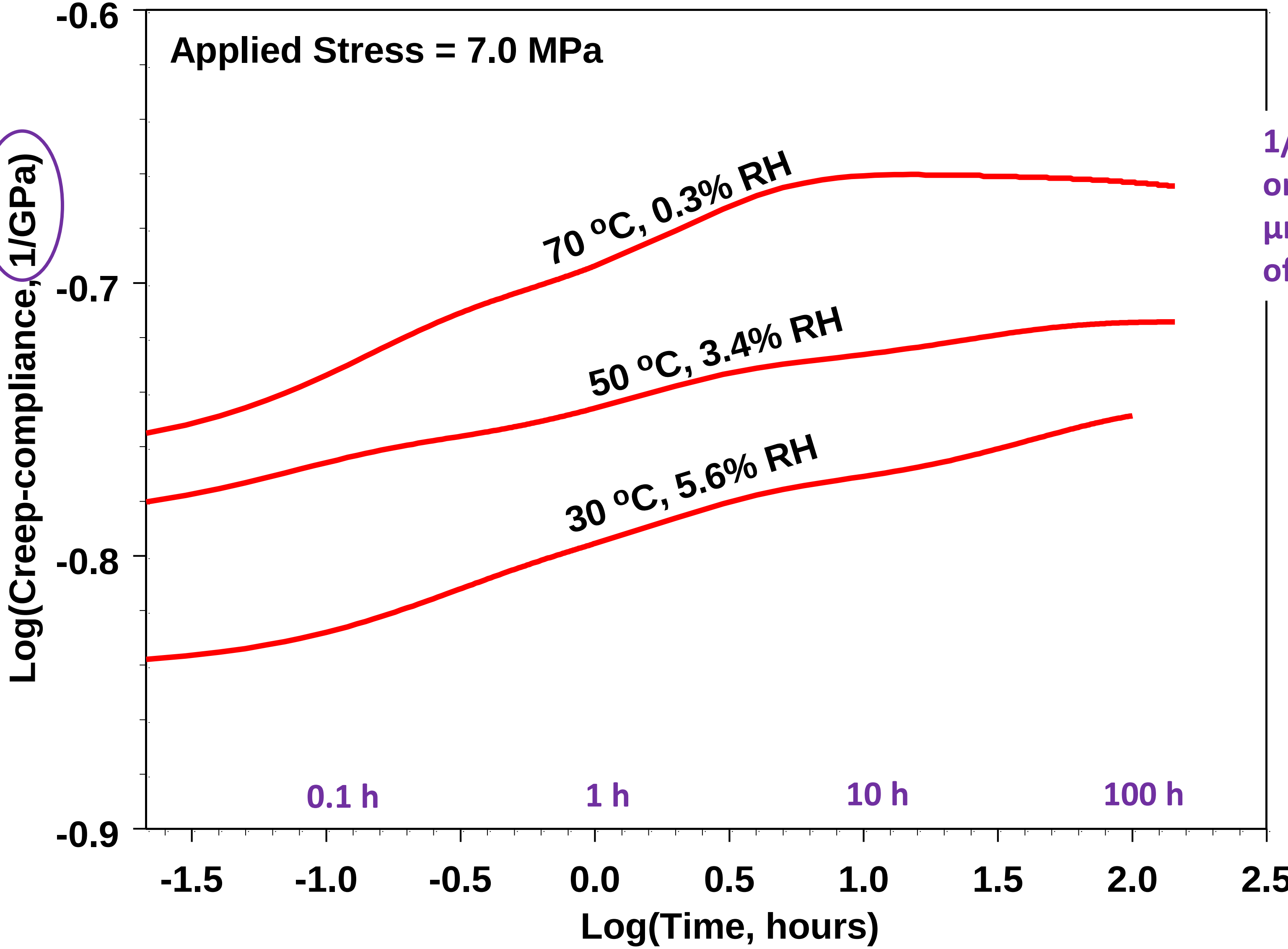
Viscoelastic “creep” characteristics for sample strips are measured using two custom creep testers in temperature and humidity-controlled chambers.



Custom Creep Tester in Temperature Controlled Incubator



Creep-compliance, D, is the time-dependent strain divided by the applied stress : D(t) = ε(t) / σ



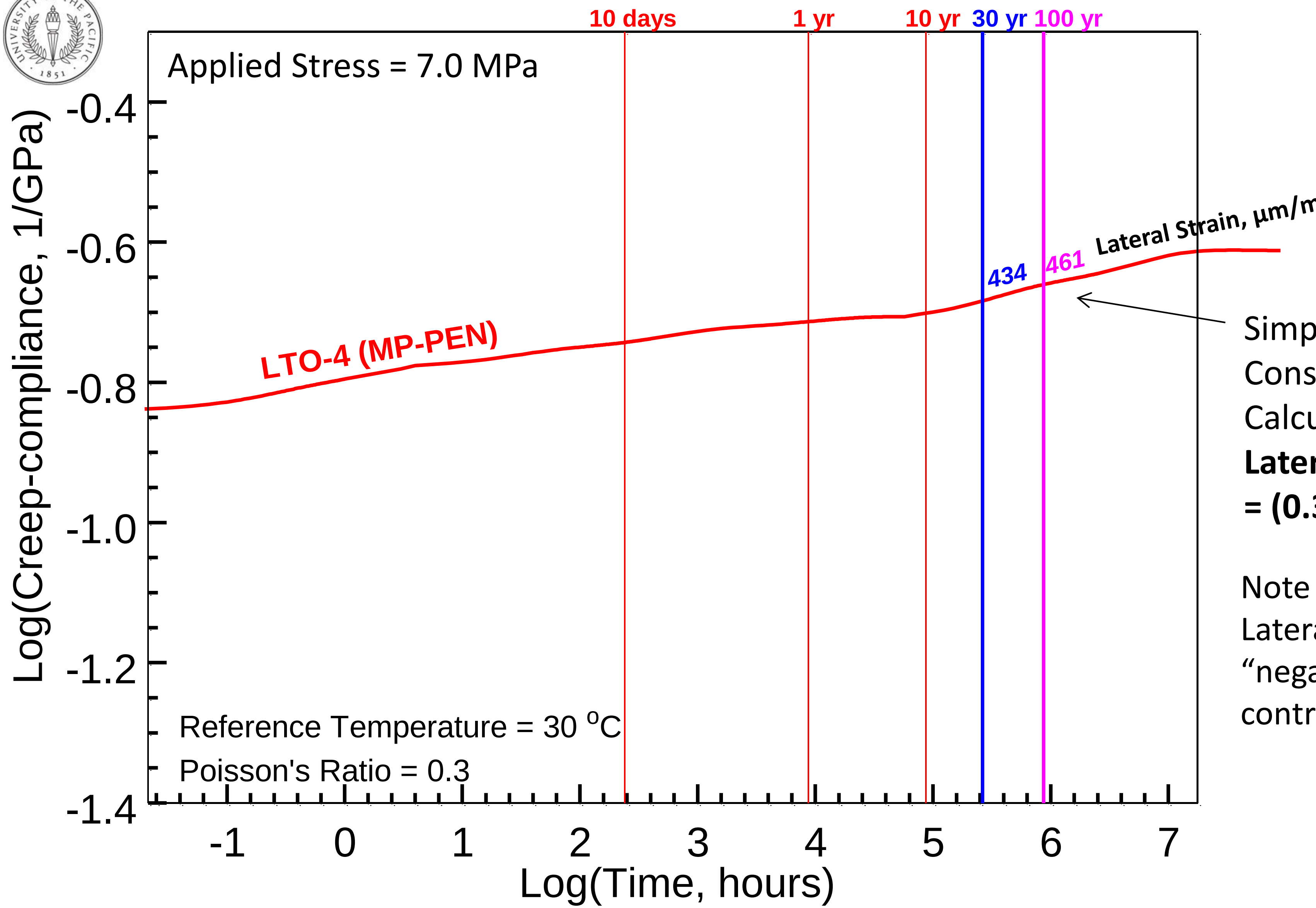
1/GPa or GPa^{-1} is one thousandth of a µm/m per Pa or N/m^2 of applied stress

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

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

Each line is an average of 3 repeat experiments with data sets fitted to a 7 parameter Kelvin-Voigt Model

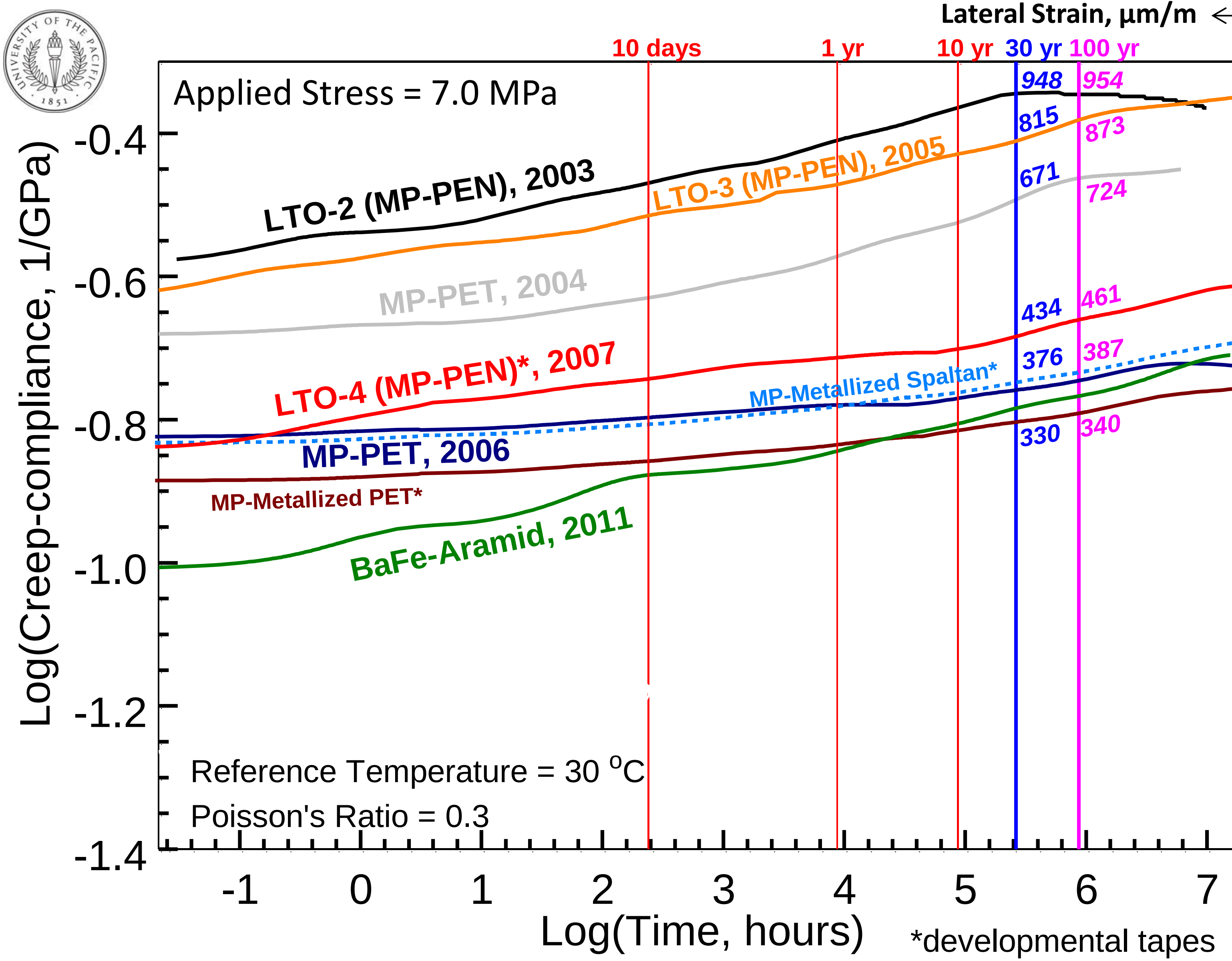
$$D(t) = D_o + \sum_{k=1}^{K} D_k [1 - \exp(-t / \tau_k)]$$



Simple, Conservative Calculation: **Lateral Strain = (0.3)(D)(σ)**

Note that Lateral Strain is "negative" or a contraction.

Using data from the 30, 50, and 70 °C experiments, creep-compliance master curves can be constructed at a 30 °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)



"contractions"

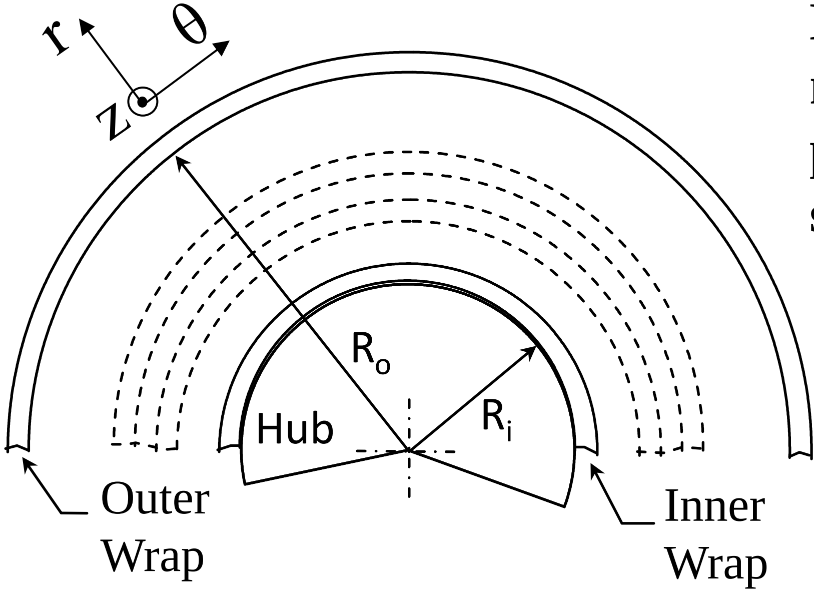
Lateral Strain = (0.3)(D)(σ)

2012 INSIC Roadmap

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

Creep-compliance master curves for selected magnetic tapes from time-temperature superposition using 30, 50, and 70 °C data sets. Tapes with PET, PEN, and metallized substrates are shown with metal particle (MP) coatings as well as an Aramid tape with a Barium Ferrite (BaFe) coating.

 Lateral strain needs to be below these values when these years are reached



Method for combining tape pack stress models with creep-compliance data to predict lateral strain on magnetic tapes stored in a reel.

Stress models have been developed to determine stresses in the circumferential and radial directions (σ_θ and σ_r) as a function of tape pack radius r.

See Acton and Weick, **J. Appl. Poly. Sci.** 122, 2884 (2011).

r – radial direction
θ – circumferential direction
z – lateral or transverse direction

ν is the Poisson's ratio and is assumed to be 0.3

$$\nu = \frac{-\text{lateral strain}}{\text{circumferential strain}}$$

Creep-compliance characteristics D(t) can be combined with stress models to predict lateral strain ε_z on the tape.

$$\varepsilon_z(r,t) = -\nu D(t)[\sigma_\theta(r,t) + \sigma_r(r,t)]$$

Lateral Strain

Poisson's Ratio

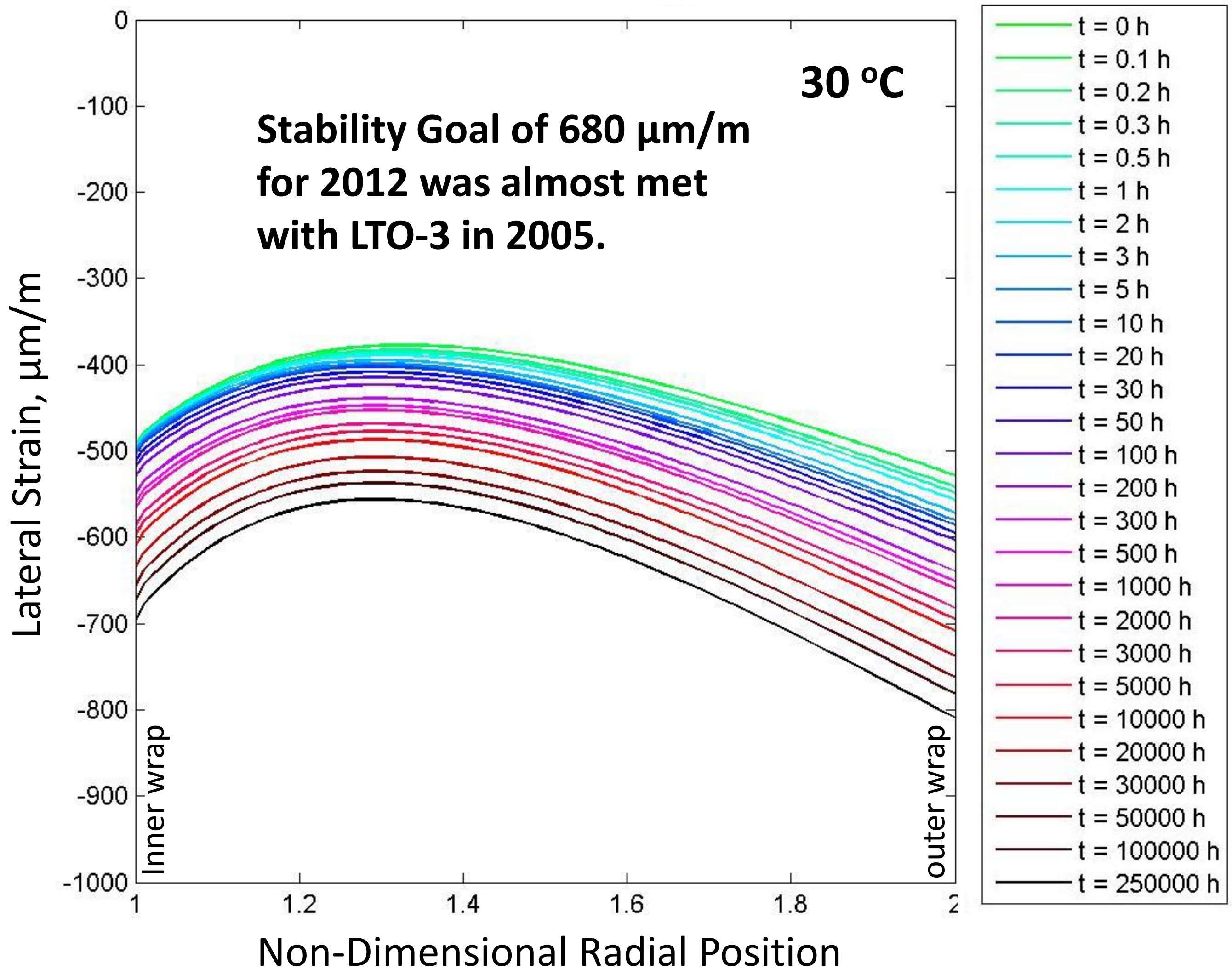
Creep Compliance Experimental Data

Circumferential Stress

Radial Stress

Calculated using parameters from Kelvin-Voigt model

LTO-3 Metal Particle Tape with PEN Substrate (2005 era tape)



28.5 years

2012 INSIC Roadmap

Stability Goals	
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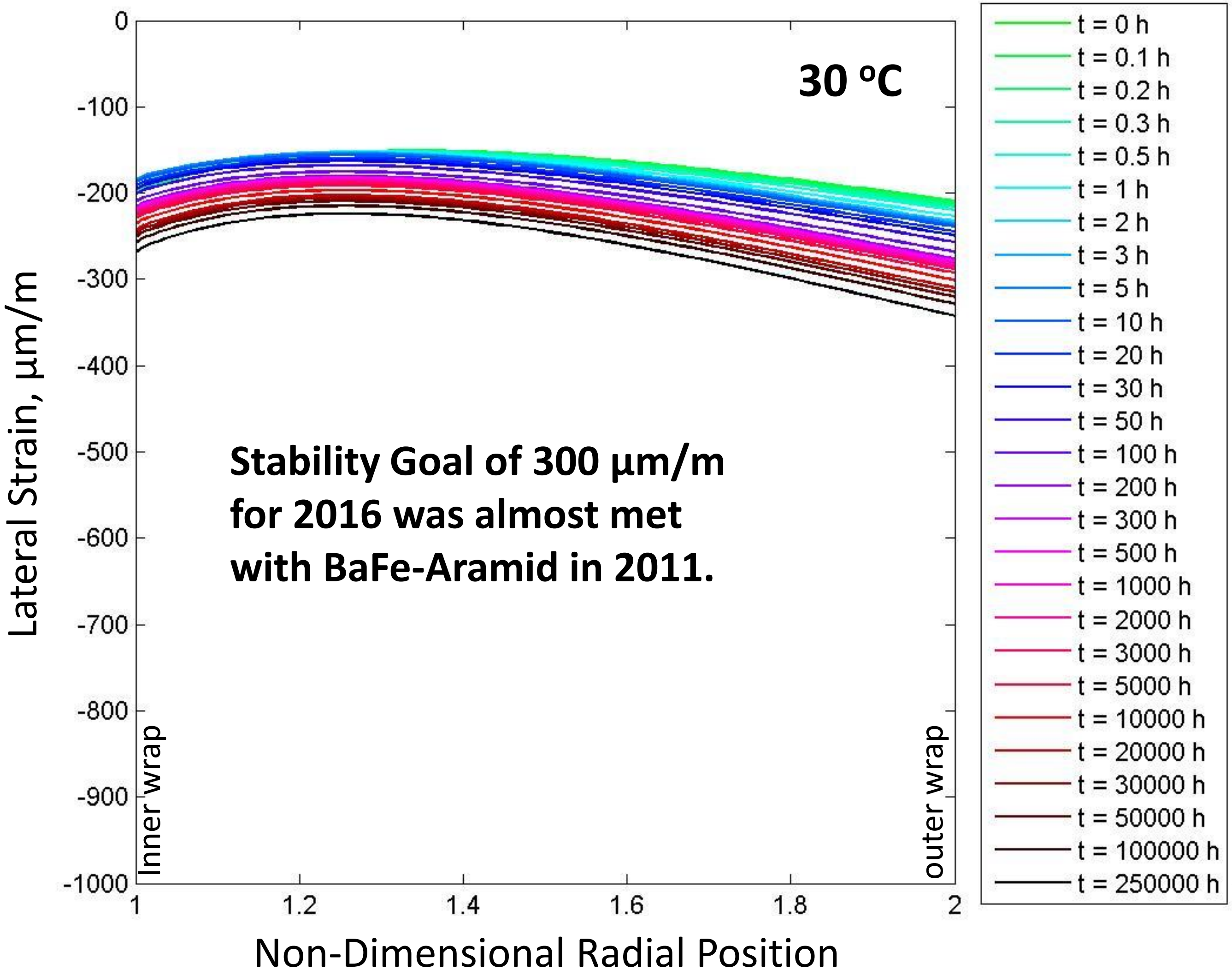
Lateral strain prediction using Acton & Weick stress model for an LTO-3 Metal Particle tape with a PEN substrate. A five parameter Kelvin-Voigt model is used for a winding tensile stress of 7.0 MPa. A “stiff” hub modulus of 10^5 MPa is used, and the orthotropy ratio is 1. (*adapted from Ragasa, Univ. of the Pacific M.S. Thesis, 2013*)

 (Recent experimental results, to be published in a future paper.)

BaFe Tape with Aramid Substrate



← 28.5 years

2012 INSIC Roadmap

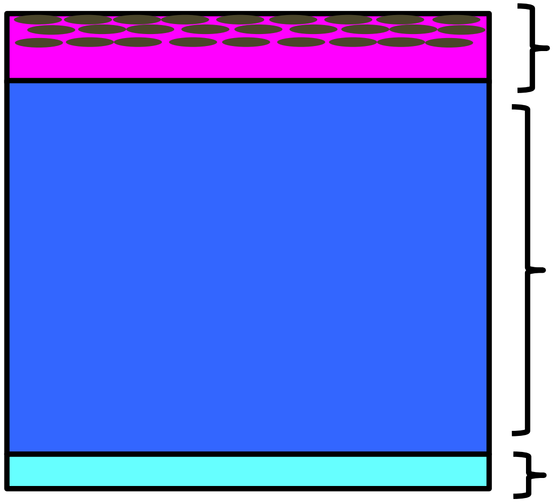
Stability Requirements	
Year	**μm/m**
2012	680
2014	455
2016	300
2018	200
2020	130
2020	85

Lateral strain prediction using Acton & Weick stress model for a BaFe tape with an Aramid substrate. A five 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.

(Recent experimental results, to be published in a future paper.)

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

Layers of an LTO-4 Tape



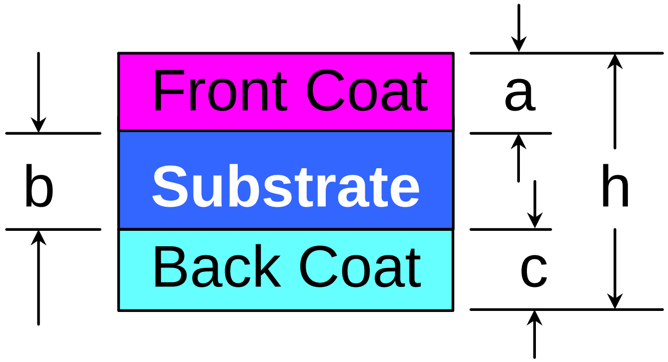
Front Coat – 0.92 µm thick – magnetic particles (MP) held together with elastomeric binder consisting mainly of poly(ester-urethane) with under-layer

Substrate – 5.00 µm thick – poly(ethylene naphthalate) called PEN

advanced polyester

Back Coat – 0.64 µm thick – protective layer consisting of a mixture of constituents including poly(ester-urethane) and cellulose nitrate

Creep-compliances for front and back coats of tapes cannot be measured directly. Instead, a rule-of-mixtures approach can be used to calculate front and back coat creep-compliances using experimental data for the substrate as well as data from dual-layer experiments where the front or back coat has been removed.



Subscripts

a, b, c C front coat, substrate, back coat

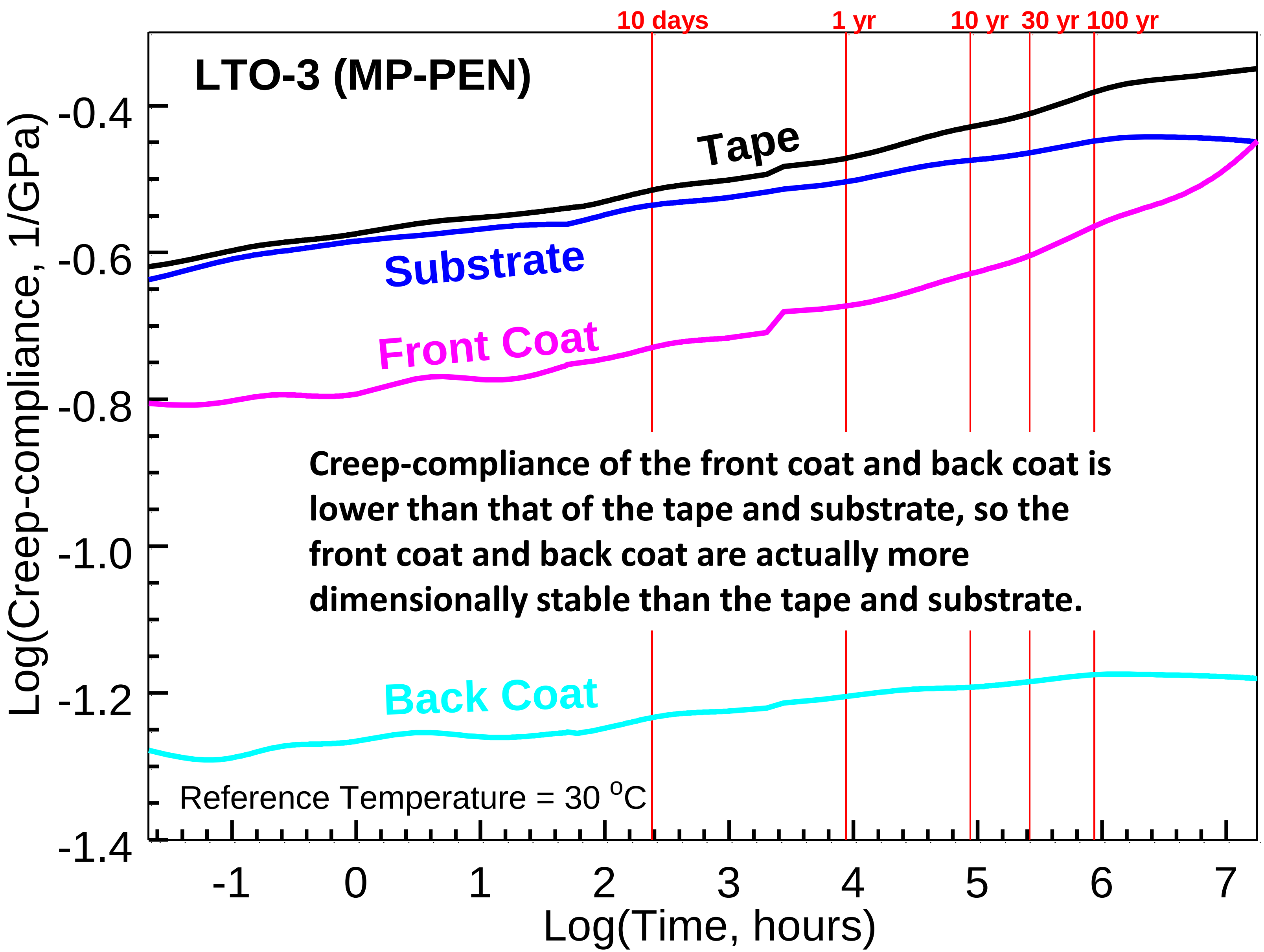
ab C combined front coat and substrate

bc C combined substrate and back coat

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

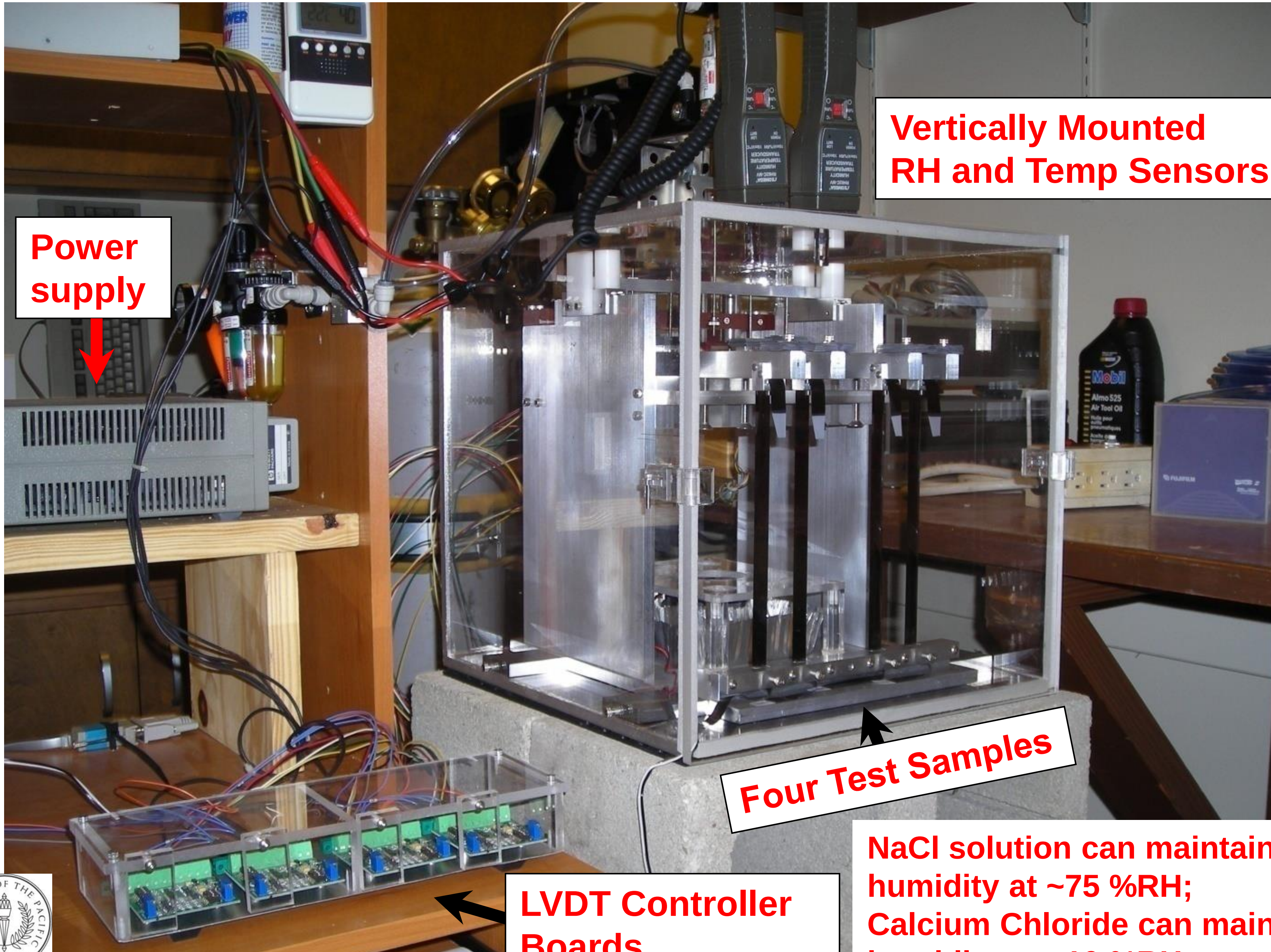
Adapted from Weick, **J. App. Poly. Sci.**, 2009 (111), 899 – 916.



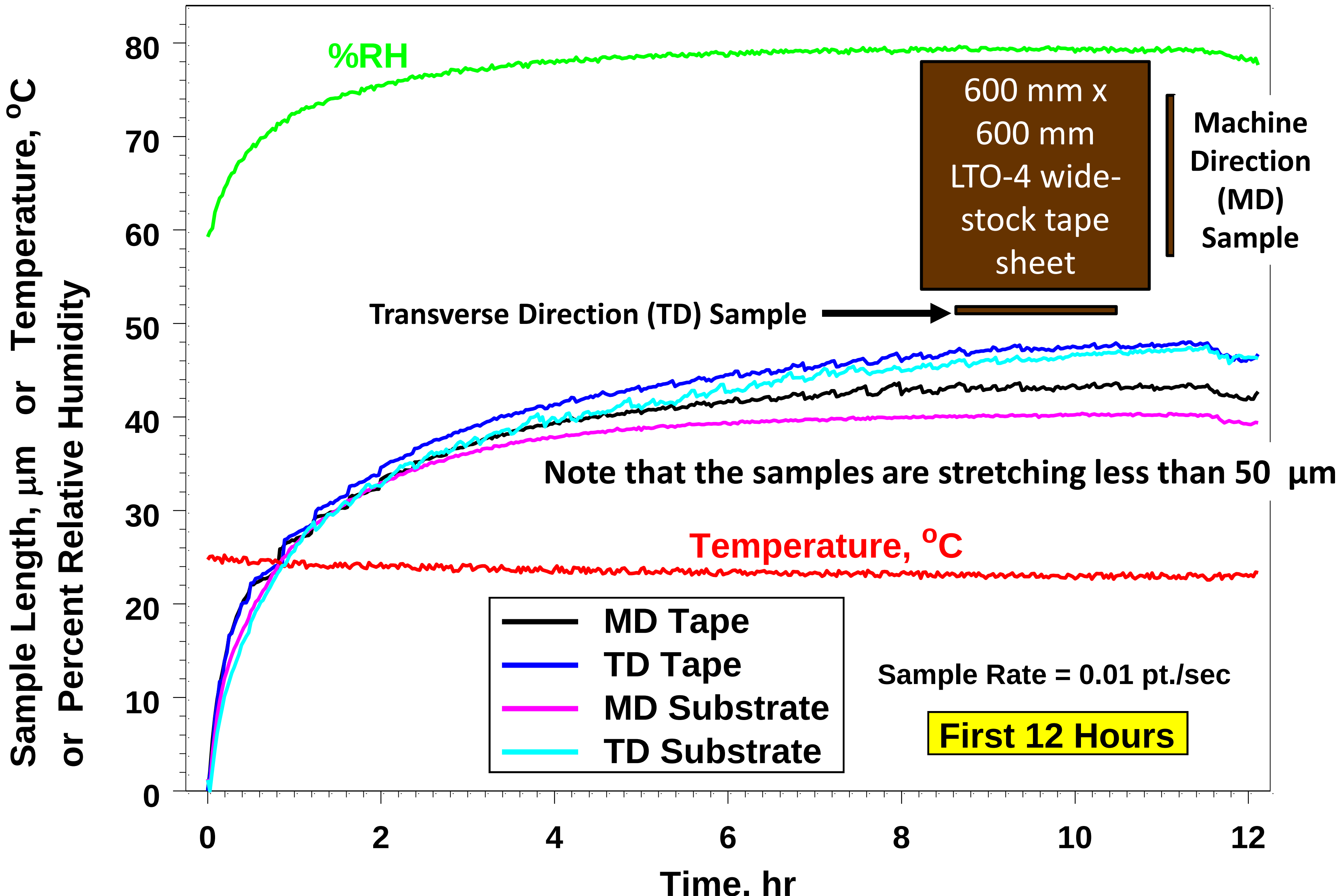
Creep-compliance curves for and LTO-3 (MP-PEN) front coat and back coat determined using a rule-of-mixtures approach compared to tape and substrate creep-compliance curves.

Adapted from Weick, **J. App. Poly. Sci**., 2009 (111), 899 – 916.

Creep Tester with Stainless Steel Fittings in Humidity-Controlled Chamber

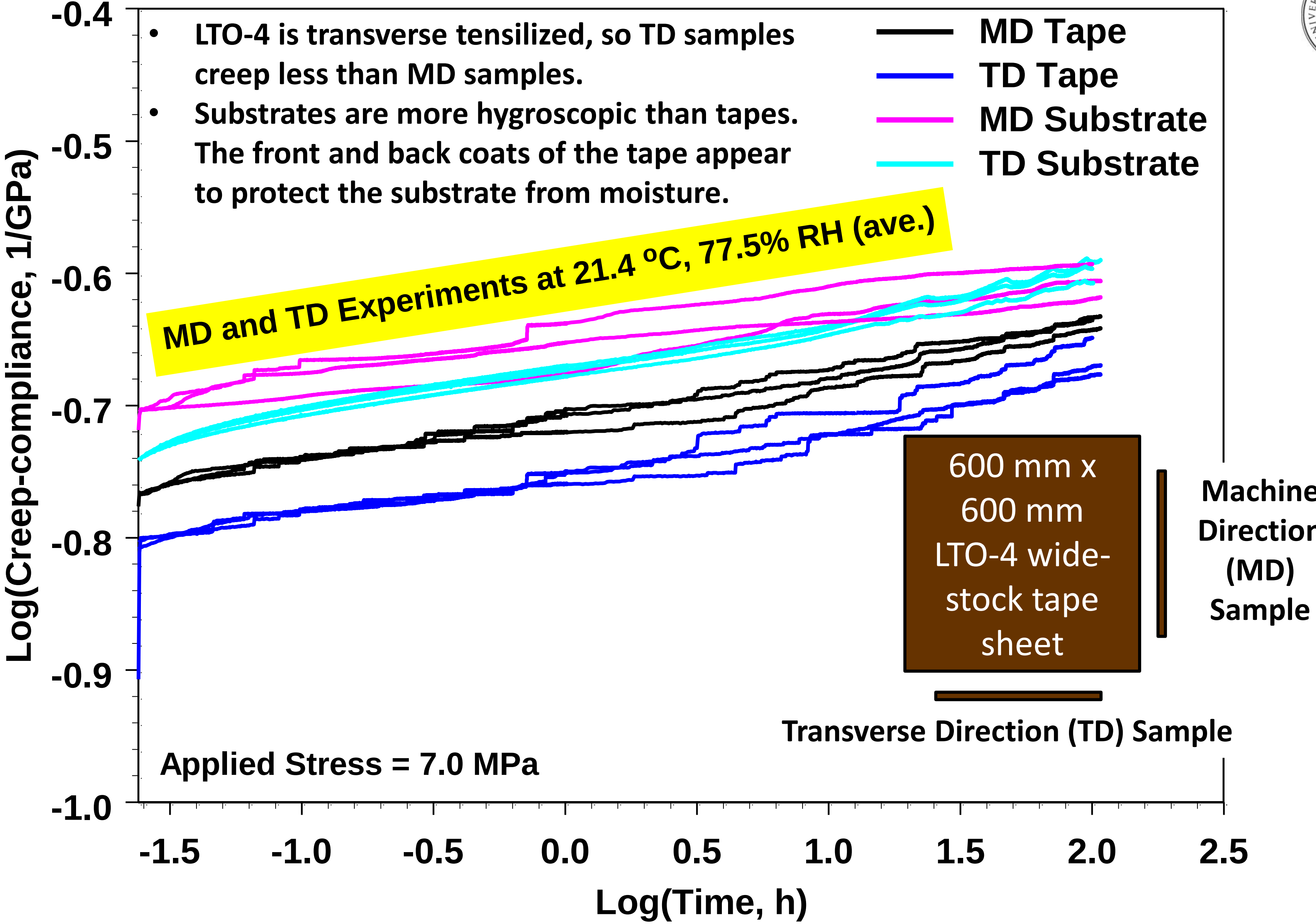


NaCl solution can maintain humidity at ~75 %RH;
Calcium Chloride can maintain humidity at ~10 %RH.



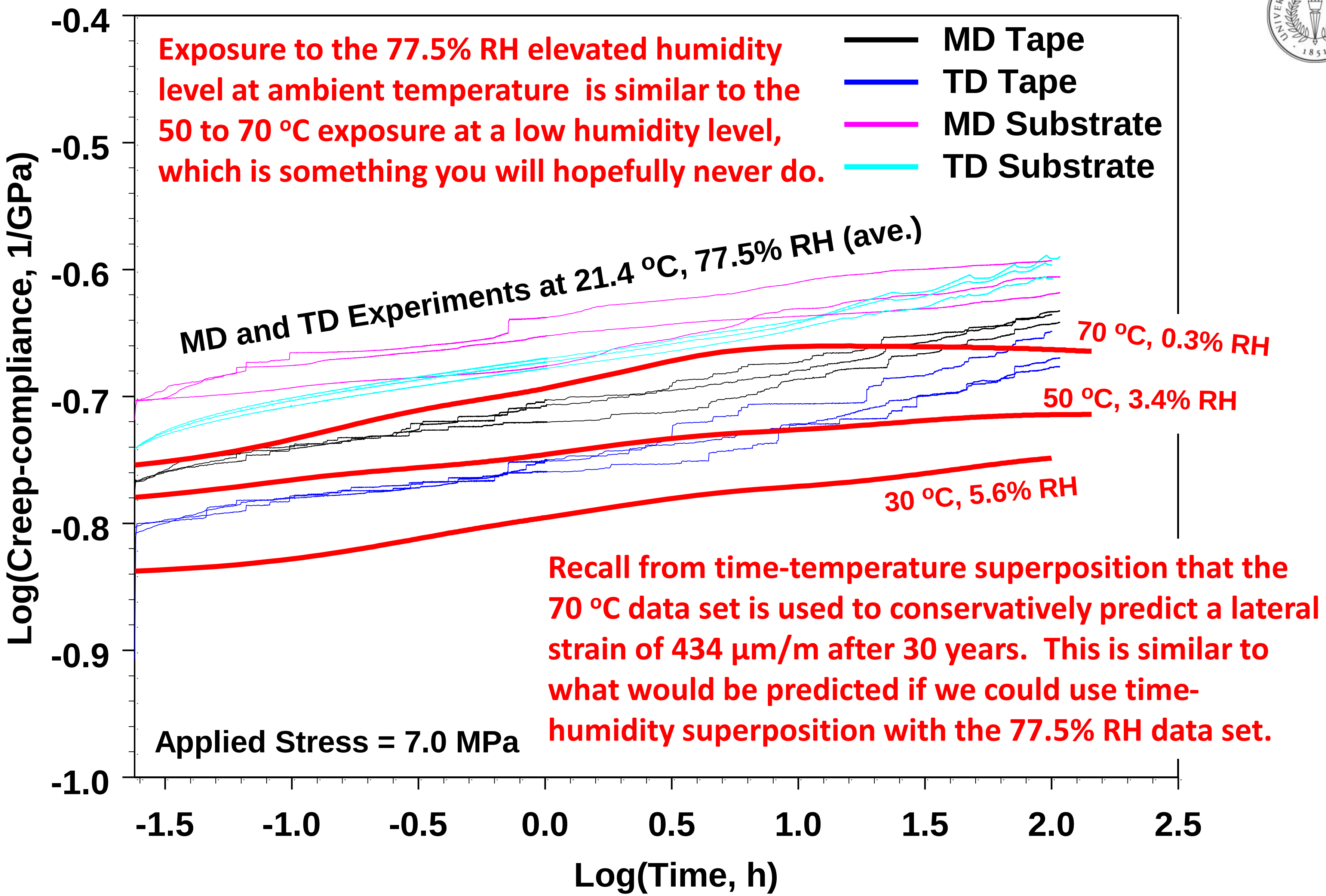
First pre-experimental data set acquired for LTO-4 wide-stock samples as chamber increased in humidity. 0.5 MPa minimal stress applied to samples.

(Adapted from Weick, INSIC Presentation, 5/11/10, Hewlett-Packard, Boise, ID.)



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)

 (Adapted from Weick, INSIC Presentation, 5/11/10, Hewlett-Packard, Boise, ID.)

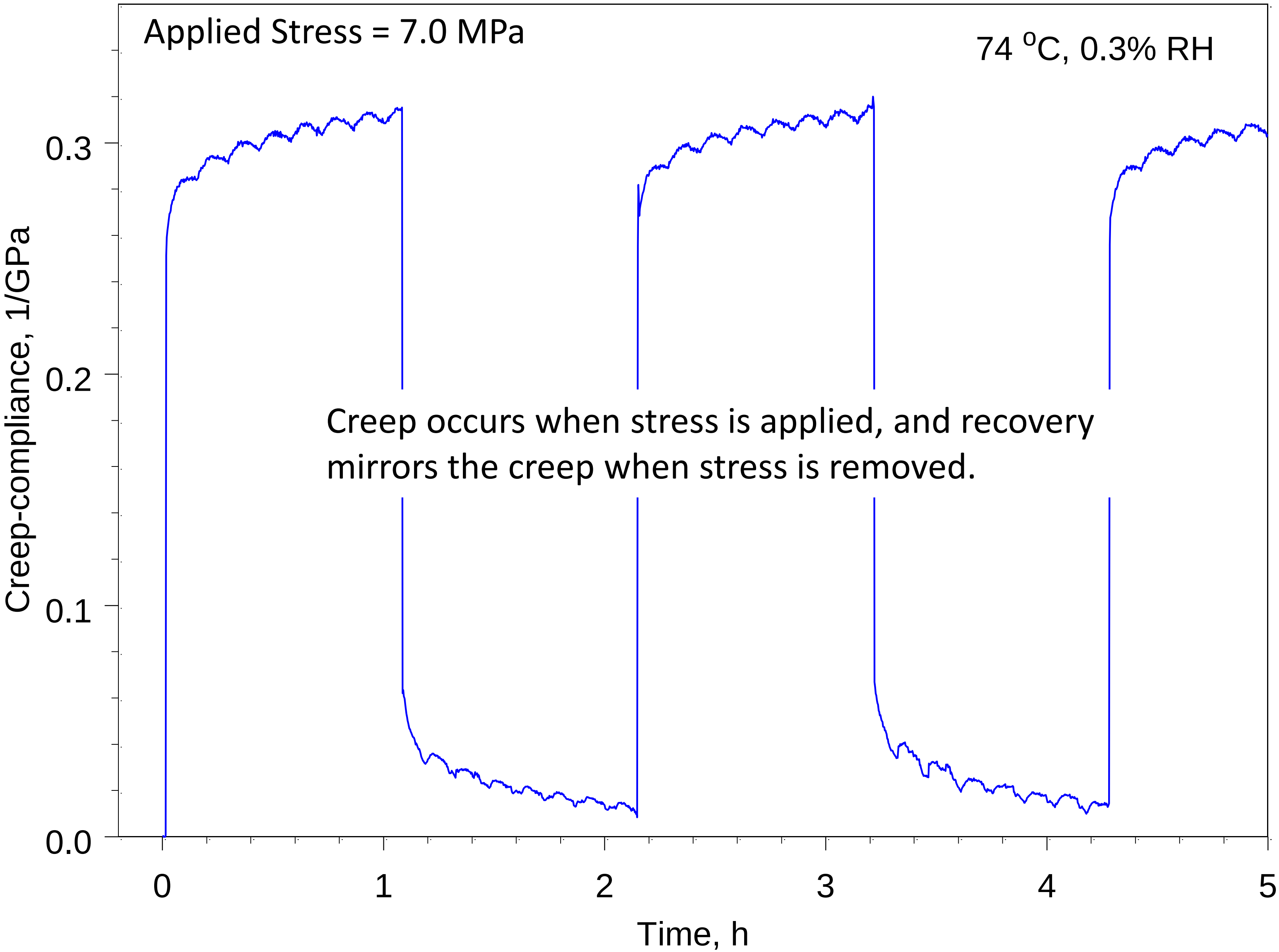


Comparison of LTO-4 widestock experiments at 21.4 °C, 77.5% RH with elevated temperature experiments at low humidity.

PEN Tape (LTO-4 Developmental)

Load Duration = 64 min.

5 hour time period



Load/unload creep-compliance data for PEN Tape (~2 Cycles)

Summary

- INSIC dimensional stability goals appear to have been met for the last 10+ years due to improvements in substrate and overall tape properties and characteristics. Based on these goals, tapes are dimensionally stable for 30, 50, and even 100 years.
- Precise creep measurements and better mechanical models have enabled the improved prediction of lateral strain (and dimensional stability) for storage periods of 30, 50, and 100 years.
- Polyester (PET, PEN) and aramid substrates are viable choices for future magnetic tapes when dimensional stability goals are considered.
- Binder stability appears to have improved over the years, and the dimensional stability of the front coat of the tape is lower than the other layers. This increases the dimensional stability of the whole tape.
- Tapes should be written, stored, and read under ambient temperature and low humidity conditions.
- Creep-recovery experiments show that tapes creep due to an applied stress, and can recover from that stress even if exposed to an elevated temperature.

Acknowledgments

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- Dr. Bharat Bhushan of The Ohio State University, who got me started studying tape in '93.

References

B. Weick., **Int'l J. Poly. Analy. & Char.** 19, 669 (2014).
K. Acton and B. Weick, **Mech. Adv. Mater. & Struct**. 21, 53 (2014).
K. Acton and B. Weick,, **J. Appl. Poly. Sci.** 122, 2884 (2011).
B. Weick, **J. Appl. Poly. Sci.** 120, 226 (2011).
B. Weick, J**. Appl. Poly. Sci.** 111, 899 (2009).
B. Weick, J**. Appl. Poly. Sci.** 102, 1106 (2006).
B. Weick and B. Bhushan, **J. Appl. Poly. Sci.** 81, 1142 (2001).
B. Weick and B. Bhushan, **J. Info. Stor. & Proc. Sys.** 2, 1 (2000).
B. Weick and B. Bhushan, **J. Appl. Poly. Sci.** 58, 2381 (1995).
More References with Complete Titles: http://www1.pacific.edu/eng/faculty/bweick