2.3 Recording Media Technology

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2.3.1 Introduction and Overview

The Roadmap for media has had some significant changes over the last three years. New magnetic pigment and substrate materials have been introduced into new products. These new products accelerated the areal densities beyond the yearly targets in the 2008 INSIC International Magnetic Tape Storage Roadmap [1]. The three factors to increase volumetric density on a tape cartridge are track density, linear density and overall tape length. The previous Roadmap stressed increased track density as the desired mechanism to increase areal as well as volumetric density. This current roadmap also stresses the same approach. Increasing track density is still the most efficient and practical method to increase areal and volumetric density. Substrate thickness has practical limitations while linear density increases have a high cost in signal-to-noise ratio (SNR).

This Roadmap focuses on linear tape technology with single reels, such as LTO, Oracle T10000 and IBM 3592.

The role of tape has also shifted since the last Roadmap. Tape has always been used for data backup, but recently long-term archive has become the primary application of tape systems. With a 30+ year archival life at very large capacities and very large transfer rates it is ideally suited for this role. Due to many factors, including the increase in governmental laws requiring storage of documents for regulatory compliance, the need to archive large amounts of data has risen significantly. These factors are influencing the choices for material on current and future tape products. Tape products need to support a 30+ year archive life by having minimal chemical, mechanical and magnetic signal degradation. For example, chemical degradation may arise due to atmospheric pollutants. Mechanical effects may be caused by inadequate substrate dimensional stability over very long times while wound into spools at rest in cartridges. The chemical stability of binders, lubricants and dispersants used to process the particles is an ongoing issue with tape formulation and is a continuing issue for tape head life.

The mechanical properties of tapes need to be measured and used to predict long term creep and stress relaxation properties, and ultimately to be used for realistic life projection. The roles of the mechanical properties of the substrates as well as those of the coatings as a function of temperature, humidity and stress need to be revisited for thinner substrates using thinner, smoother and evolving magnetic coating composite formulations.

Magnetic degradation has two significant causes. One is the loss of magnetic moment due to corrosion; the second is the thermal stability of the magnetic orientation of the particles. Metal Particulate (MP) particles suffer from corrosion if there is not a passivation layer on the particle. All MP particles have had a passivation layer to minimize the corrosion effect. The thermal stability of the particles is driven by the size of the particle and the material's magnetic anisotropy. As the particle size and particle anisotropy approach the thermal limit, the particles will have tendency to switch polarity independently at random times, under the influence of internal demagnetizing fields or environmental fields. It is currently believed that magnetic storage media, such as disk or tape media, must be designed to have a K_uV/kT (a term related to thermal stability which will be discussed in detail below) of > 75 or 80 in order to ensure a 30 year archival life [2]. Hard disk drives are currently at this limit, and to ensure signal stability, products have moved from longitudinal to perpendicular recording with a magnetically soft underlayer (SUL), and in the future may require implementation of heat-assisted recording and/or bit-patterned media.

To sustain the present cost advantages of tape over other storage technologies and also to maintain backward compatibility with previous generations of tape, the format of the tape cannot change significantly. These constraints limit the practical options for future generations of tape. Innovations, such as recording on both sides of the tape or more significant changes to track following, need to be weighed against the additional cost to the tape drive or cartridge.

The current Roadmap will largely concentrate on barium ferrite (BaFe) particulate media, due to its increased recording performance over MP. It is the consensus of the Media Team that BaFe media is very probably capable of supporting the areal densities required in 2022 as described by this Roadmap, provided that the improvements in drive mechanics, heads and data channel described in other sections of this report are accomplished.

2.3.2 General Roadmap Targets

Table 1, below, presents the targets for track density, linear density and overall tape thickness. The key factors to meeting these targets are improved SNR, improved dimensional stability, and reduced substrate thickness. These three requirements will be discussed here in detail. Other factors such as PW50 (the pulse width at 50% of the peak amplitude in the readback signal) can be designed by scaling the magnetic coating thickness, head-to-tape spacing and the read gap length.

Table 1: General Roadmap Targets.

	2012	**2014**	**2016**	**2018**	**2020**	**2022**
Capacity (TBytes)	4	8	16	32	64	128
Overall Tape Thickness (μm)	6.0	5.5	5.1	4.7	4.3	4.0
Head/Tape Spacing (nm)	36	31	27	23	20	17
Track Density (TPI)	6506	9773	14787	22498	34393	52791
2T Density (KFCI)	234	272	318	371	432	504
2T Wavelength (nm)	218	187	160	137	118	101
Areal Density (Raw Gbits/in^2)	3	5	9	17	30	53
BBSNR Required (dB)	18	17	16	15	14	13
Particle H_c (Oe)	2900	2900	2900	2900	3400	4500
Particle Size (nm^3)	1600	1600	1600	1600	1367	1029
Reader Width (μm)	1.95	1.09	0.72	0.47	0.31	0.20
Dimensional Stability (ppm)	680	455	300	200	130	85
Passes to End of Media Life	30300	33406	36830	40605	44767	49356

2.3.3 SNR Requirements

The signal to noise ratio is the key parameter for electromagnetic performance. The number of particles within a bit or within a transition is one of the key physical parameters that influence the SNR. The head to tape spacing is the other key parameter that affects the SNR.

The signal read from a tape is in general proportional to the number of particles read. Given a specific particle type, if the number of particles per unit volume is increased, the signal will increase proportionately.

Noise is made up of media noise and electronic noise. We will only consider media noise in this discussion, since the electronic noise is dependent on specific head/electronics design parameters and the hard disk drive industry has led the way with highly sensitive read devices (e.g., GMR heads), so as to keep the SNR performance media-noise limited.

The media noise read from a tape is proportional to the square root of the number of particles (N). This is due to the non-coherent nature of the noise signal. In the case of the signal, all or most particles are written in one direction. In the case of noise, the contributing particles can be adding to the signal or they could be subtracting from the signal. Thus the noise becomes proportional to the square root of the number of particles.

The SNR calculation is then shown in Equation 1, below:

$$SNR = \frac{Signal}{Noise} \qquad \propto \frac{N}{\sqrt{N}} \qquad = \sqrt{N}$$ **Eq. 1**

Therefore, the key is to increase the number of particles within a unit volume of the magnetic layer on the tape. The most common method used to do this has been to reduce the particle size. Small increases in the number of particles can also be achieved by increasing the loading of the particles, but there is a practical limit as to how much the loading can be increased due to coating adhesion and integrity.

MP media has utilized particle size reductions to increase performance for many generations since the mid-1990s; however, the passivation layer on the particles limits the degree to which the size of such particles can be further reduced. BaFe media can be fabricated with significantly smaller particle sizes and a correspondingly significantly higher SNR [3].

Particles described in earlier papers and current products tend to have volumes > 2100 nm^3. However, more recent papers have demonstrated particles as small as 1600 nm^3. As shown in Table 1, the particle size required in 2022 will be around 1000 nm^3. In order to ensure the required magnetic stability of the tape media particles of this size, they will need to have a higher magnetic anisotropy constant, compared to current particles, for the media to achieve a 30+ year archive life.

The thermal stability of small magnetic particles is well documented [4]. K_uV/kT is an estimate of the thermal stability of a particle where,

K_u = Anisotropy Constant inherent to the material used
V = Particle Volume
k = Boltzmann Constant
T = Temperature

Larger values of this stability parameter denote a greater thermal stability for the magnetic orientation of the particles. It is currently believed that a value of 75-80 is considered the minimum necessary in order to achieve a 30+ year archive life.

The goal is to reduce the volume of the particles to improve the SNR of the media. The only way to maintain the required K_uV/kT is to increase the anisotropy of the material. Increasing the anisotropy of the particle material has the side effect of raising the particle coercivity. Increasing the particle coercivity may require different head designs and/or materials for writing these higher-coercivity particles.

It should be noted that at the end of the present Roadmap, the tape industry will be approaching limitations similar to those encountered by the hard disk drive industry ten or so years ago. The hard disk drive industry increased coercivity and used perpendicular recording with a soft magnetic under layer (SUL) to write the higher-coercivity particles [5]. There is significant head technology already developed by the hard disk drive industry available to the tape industry to enable similar solutions well beyond the current tape Roadmap, although this technology may require some modification in order for it to be applied in linear tape systems.

For a 128 TB cartridge in 2022, it is estimated that the particle size will have to be around 1000 nm^3 with an anisotropy constant of 1.8×10^6 to 2.0×10^6 erg/cc (a correction factor of 1.5 was applied to the measured particle size in order for the volume and anisotropy constant to agree with experimental data). The anisotropy constant of a pure BaFe crystal is 3.3×10^6 erg/cc [6] with current BaFe particles having values of 1.13×10^6 erg/cc. The current BaFe particles are doped with Co, Ti or Zr in part to adjust the coercivity [7]. There appears to be sufficient capability to increase the anisotropy constant over the next 10 years.

The other major parameter for SNR is head/tape spacing. In particular, the write head-to-media spacing is critical. The read head-to-media spacing can, to a large extent, be compensated for by adjusting the filtering in the channel. However, in the tape industry, the SNR has been measured with a flat filter that included effects of the read head spacing. More recently, the industry is using a parameter termed "detector SNR" which is a measure of the signal-to-noise at the input to the detector within the channel. While this parameter is not immune to read-spacing effects, it is a more accurate measure of the actual SNR capabilities of the head-tape system. The older SNR definition is still useful, in particular, for measuring differences between tape samples and in developing a more fundamental understanding of the contributors to SNR. The older version is the term used in Table 1 as BBSNR (broadband SNR).

The head/tape spacing for each target is also shown in Table 1. There are several factors involved in reducing the spacing. The surface roughness of the magnetic side of the tape is a key factor. The head geometry and distance between the head elements and the tape are also critical.

Table 1 shows the spacing will need to be reduced by approximately 50% by 2022. In order to achieve this, the surface roughness will need to be reduced by approximately 50%. As stated in the 2008 Roadmap, there is no accurate measurement of roughness that predicts head to tape spacing. However, there is a loose correlation between the average roughness (R_a) or the root mean square roughness (R_q) and head to tape spacing. Current products have an AFM R_a of around 2.0 to 2.5 nm [3]. In 2022, these values will need to approach 1.0 nm.

There will be significant tribological challenges to achieve the durability requirements presented in Table 1. The head geometry is already changing to accommodate smoother media [3]. New lubricants and methods to create smoother media will need to be developed. The tape industry has been presented with similar challenges for many years and there are no fundamental physical barriers to achieving the head to tape spacing goals presented in the Roadmap. Much smaller spacings are implemented in current HDD products.

With the shift in emphasis from back-up and recovery to archival storage as the major tape application, tape cartridge usage is very likely to change. Instead of the same cartridge being written many times, the tape cartridge may be written fewer times, but possibly with larger data transfers during a writing session. The result is that the head will, on average, operate with media that is much "newer". As a tape is run over a head many times, the tape tends to get smoother, and thus the abrasivity of the tape may decrease during use. Due to the likely shift to archive applications, the head will thus tend to see relatively new tapes, which have significantly higher abrasivity than would be the case later in their service lives. This change could aggravate problems such as head wear. Tape manufacturers should investigate means of mitigating this issue, through some kind of "breaking-in" process. As increasing amounts of tape are passed over the recording head, the areas around the active elements of the head often wear at different rates which can cause a pole tip recession (PTR) that results in increased head to tape spacing on both the read and write elements of the head. Changes in the abrasive material used in the media and lubricants may need to be made to reduce the PTR of the head.

Also, with the shift in the tape application, the media requirements change in other ways. Table 1 shows an increase in the number of passes over the life of a tape. In actual customer use, the number of passes will probably be significantly less. Balancing the life of the tape with tape abrasivity, lubrication and other tribological factors has been required on all previous tape generations and will be an ongoing issue with all future products.

Improvements in the electronic read and write channels will enable lower SNR requirements for future generations – see the Recording Channel Electronics Technology section. The ability of the channel to operate at lower SNR may ease the head-tape spacing and particle size requirements of the media.

2.3.4 Dimensional Stability Requirements

The dimensional stability of the tape is a key component in limiting the track density of the system. Linear tape technology uses a head with many read/write channels. Typically, these channels span approximately ¼ of the tape width or about 3 mm. If the tracks written on the tape shift due to environmental factors, the read and write elements on the head will no longer be aligned with respect to the center of the track on the tape. Some of the shift can be compensated for in the system design and architecture, but not all of it. The channel track width in 2012 is 3.8 µm, with a reader width that is about 1.6 µm. A rough estimate would be that the dimensional stability needs to be about 700 ppm:

$$\frac{((3.8um-1.6um)/2)}{(3000um)/2} = 700 \text{ ppm} \qquad \textbf{Eq. 2}$$

[Where 3000 µm is the channel span, 3.8 µm is the writer width and 1.6 µm is the reader width].

If the channel span does not change, in 2022 a rough estimate is that the dimensional stability of the media will need to be about 90 ppm:

$$\frac{(0.48um-0.2um)/2}{(3000um)/2} = 90 \text{ ppm} \qquad \textbf{Eq. 3}$$

Some new products are introducing narrower channel spans to help relax the media dimensional stability requirements for achieving the necessary tracking tolerances.

The tape substrate plays a key role due to its thermal and hygroscopic expansion characteristics. There is also a stress-induced component of dimensional stability due to tension and pressure in the tape wound in the cartridge. Understanding the overall mechanical properties of a coated tape as well as those of the substrates is believed to be increasingly needed to better predict the archival properties and to make recommendations for storage conditions needed to ensure acceptable archival performance and data integrity.

There are techniques to adjust the channel span in the drive [8] that would marginally increase drive cost and there are techniques to improve the dimensional stability of the tape through material choices such as aramid, which has a total dimensional stability of ~300 ppm today. The tradeoffs in drive and media cost and drive complexity/reliability must be considered when choosing a solution, but there are solutions available today that come close to meeting the requirements for 2022.

Because of the 30+ year archive life requirement, the media dimensional stability over long time periods is of critical importance. The choice of storage environment may become even more important than in the past for ensuring an acceptable life for tape. Section 2.3.6, below, describes the substrate materials available and their stability properties.

2.3.5 Overall Tape Thickness Requirements

The overall tape thickness determines the length of tape that can be wound unto a cartridge. In present media there are four components that make up the tape thickness. They are the backside coating, the sublayer coating, the magnetic layer and the substrate material. The substrate material is the dominant factor in determining the overall thickness of the tape. At least one recent product has an overall tape thickness of 5.2 μm [9], demonstrating significant progress towards the goal of 3.99 μm required in 2022.

As the length of tape increases, the number of wraps in the cartridge increases and pack formation quality could be an increasingly important issue. Also, as the tape becomes thinner, defects are more likely to deform and “print through” to multiple layers of tape, causing higher defect rates. Again, these issues have been common to the tape migration path and no fundamental barriers are apparent for achieving the goals in the Roadmap.

2.3.6 Critical Materials to Achieve Roadmap Requirements

Magnetic Particles

Barium Ferrite

The magnetic particle of choice for the next few generations of tape is barium ferrite (BaFe). BaFe is a hexagonal crystal whose coercivity is primarily generated by uniaxial crystalline anisotropy as opposed to conventional MP pigment whose coercivity is generated by its acicular shape anisotropy.

BaFe has been shown to have significant SNR advantages. Several aspects of the particles contribute to the better performance. The BaFe particles do not have a passivation layer, which improves the particle uniformity, as opposed to MP particles that have a passivation layer, which limits the minimum achievable size of the particle. Since the coercivity is generated by the crystal structure of a BaFe particle, the size of the particle does not directly influence the coercivity. In the case of MP, however, it is more difficult to make a smaller particle and maintain high coercivity. The shape of the BaFe particle also lends itself to perpendicular recording, which has been demonstrated by the HDD industry to have benefits in SNR [10].

Because of the smaller magnetic anisotropy of BaFe, the thermal stability of the particle needs to be addressed. Magnetic anisotropies of 1.3×10^6 to 1.5×10^6 erg/cc have been demonstrated [11], but higher values on the order of 1.8×10^6 to 2.0×10^6 erg/cc are needed by 2022 in order to maintain acceptable thermal stability of the recorded data over extended periods of time.

Other Particulate Materials

Besides MP and BaFe, other particles having high magnetic anisotropy exist that could potentially be used for particulate recordings.

FePt in the correct crystal structure has an anisotropy value, K_u, of about 6.6×10^7 to 10×10^7 erg/cc compared to pure BaFe which has an anisotropy value of 3.3×10^6 erg/cc. The difference in anisotropy constant would allow about 20X to 30X reduction in particle size and still maintain the same thermal stability. This particle size reduction would give an additional 13-15 dB increase in SNR of the media [12].

The higher anisotropy comes at a price, however. The coercivity of the FePt would be on the order of 58 KOe (~1/2 H_k), which would make writing the material difficult without heat assistance or other similarly complex methods. FePt may also be difficult to manufacture with good particle size and magnetic property distributions. Also, platinum is quite expensive. Analogous materials, such as MnAl, might provide more economical alternatives, but research is still needed to determine if they can be produced in high volume with adequate control of their properties.

Other materials could also become available, but they would also likely result in higher coercivity particles that require innovations in write head technology.

Metal Evaporated and Sputtered Tape

Tape media fabricated using either metal evaporated (ME) or metal sputtered magnetic coatings, similar to those used in the HDD industry since the late 1990's, are alternatives to particulate coating.

ME tape is used in video tape technology and it has been used in helical-scan configurations of data tape products. In the past, these tapes have exhibited different recording properties for the two tape transport directions. Recently, this has been resolved through perpendicular orientation. Identical recording characteristics were obtained for both head-media moving directions, which enables the application of perpendicular Advanced ME tape to linear scan tape systems [13]. SNR corresponding to a recording density of 21 Gb/in^2 was achieved in perpendicular Advanced ME tape by using narrower HDD read heads to write data to the media [14].

Sputtered tape media uses similar recording material(s) to those employed in the disks used in the hard disk drive industry. Generally, the recording material is CoPtCr–SiO_2. A 45 Gb/in^2 demonstration, which utilizes a novel sputtering technique to fabricate the magnetic coating, has been published [15]. The development of a soft underlayer (SUL) has increased the performance of the sputtered tape.

Substrate Film Materials

General Challenges and Tradeoffs

Technical factors such as thickness, roughness, mechanical, and viscoelastic characteristics all influence substrate choice for media. Common tradeoffs encountered include dimensional stability versus thickness, as well as roughness versus thickness. Also, if magnetic layers and nonmagnetic underlayers of the front coat can be made thinner along with the back coats, and adjustments made to the mechanical contributions of these coatings to the finished tape, perhaps substrate thickness does not have to decrease as extensively. Building on previous Roadmaps, the current Roadmap projects a substrate thickness of 3.0 µm by 2022, as shown in Table 2. This allows for a gradual change in thickness in two-year steps allowing for the technology to develop and evolve. Roughness specifications expressed as AFM arithmetic average roughness (R_a) are also shown in Table 2, and the projected R_a is 1.1 nm by 2022. Defects are also a major concern, and are therefore addressed separately in Section 2.3.8.

Table 2. Thickness and Roughness Goals for Magnetic Tape Substrates.

	2012	2014	2016	2018	2020	2022
Substrate Thickness, µm	4.5	4.1	3.8	3.5	3.2	3.0
Magnetic Layer AFM R_a (nm)	2.2	2.0	1.8	1.5	1.3	1.1

Temperature, Humidity, and Tensions Ranges for Operation and Storage

In the 2008 INSIC International Magnetic Tape Storage Roadmap [1], the generic operating temperature and humidity ranges for tape were stated as 10-45 ^{o}C and 10-80% RH. Recommended conditions for archival storage were stated as 18-21 ^{o}C and 35-45% RH. Specifications for some representative tapes manufactured since 2000 are shown in Table 3. Some manufacturers specify environmental shipping conditions, whereas others do not. Note that the operating range stated in the 2008 Roadmap appears to be consistent with current generations of LTO tape, while storage temperatures (16-32 ^{o}C) and storage humidity (20-80% RH) appear to be wider than the 2008 recommended storage conditions of 18 ºC to 21 ºC and 35% to 45% RH.

Table 3: Representative Environmental Conditions for Operation, Storage, and Shipping of Magnetic Tapes.

	Operating Conditions		Long Term Storage		Shipping	
Product	Temperature ºC	% RH	Temperature ºC	% RH	Temperature ºC	% RH
LTO (typical examples)	10-45	10-80	16-32	20-80	-23-49	20-80
Oracle T10000	10-32	20-80	15-26	15-50	-23-49	5-80
IBM 3592	16-32	20-80	16-25	20-50	-23-49	5-80

In order to address ongoing customer concerns, the possibility of relaxing the long term storage requirements for tape media is currently being investigated by the tape storage industry. Customers have asked whether or not it's truly necessary to store tapes in the narrow ranges shown in Table 3. In order to fully address these legitimate concerns, it is highly likely that more research and modeling will be needed to predict the influence of tape pack stresses on dimensional stability as a result of increased temperature or humidity. This is addressed in the section below entitled "Prediction of Archival Life." Vibration during handling is also a possible concern, since it could cause the creation of loose wraps, which is why some manufacturers have specified shipping conditions in Table 3. Research efforts in this area could also be desirable.

Determination of Properties and Characteristics for Dimensional Stability

When information is written on the tape, and dimensional changes occur during archival media storage, the head might not be able to read information stored on the tape. While the substrate film is currently considered to have the primary role in dimensional stability of magnetic tapes, the effects of the magnetic layer, nonmagnetic underlayer, and backside coating must also be considered as significant. There are both reversible and irreversible factors that can cause dimensional changes. Reversible factors include "free" thermal and hygroscopic expansion. Reversible tension variations can also occur, and control systems to adjust for these variations could be designed into the drive.

Viscoelastic behavior of the substrate and constitutive layers due to elevated temperature and humidity is considered to be an irreversible effect, although viscoelastic deformation is theoretically recoverable. Creep testing is typically used to measure viscoelastic behavior, and involves using short lengths of substrate, tape, or dual-layers of the front coat + substrate or substrate + back coat after one of the layers has been removed. Developmental tapes and substrates that have not been slit into long enough lengths required for a complete reel can also be used, as well as samples cut from unslit production rolls to examine anisotropic characteristics.

The engineering metric for determining whether or not a tape meets dimensional stability requirements is called "in-cartridge creep". For the in-cartridge creep test, the industry is interested in how far the data tracks have moved since they were originally written by the end user. Although procedures for measuring in-cartridge creep can vary, the typical procedure used to reach the goals shown in Tables 4 and 5 (which appear below in the section on "Achievable Total Dimensional Stability (TDS) from Substrate Manufacturers") is as follows:

> Tape width is measured for the length of the tape at room temperature and humidity using the servo pattern. The cartridge is then placed in a high temperature environment (typically 55 ^{o}C, 40% RH) for 10 days. The cartridge is then removed from the environment and allowed to reach equilibrium at room temperature and humidity (typically 48 hours). The tape width is then re-measured down the length of the tape. For a given position of tape, the change in width is the tape width as measured after the heat soak minus the tape width as measured before the heat soak. The maximum tape width change over tape length is called the in-cartridge creep.

One fundamental measurement needed for modeling of substrate and tape behavior is the Poisson's Ratio, which is defined as the ratio, under a load in the down-web direction, of the contraction in the cross-web direction to the elongation in the down-web direction. This parameter is not only an input to the models discussed below to predict archival life; it is also a fundamental parameter that relates lateral strain of substrate and tape materials to axial strain due to applied stresses. Poisson's effects are also important in the through-thickness dimension. Current in-cartridge creep experiments for tape can provide Poisson's values between servo bands, and future experiments with advanced equipment are needed for constitutive tape materials.

Shrinkage is another fundamental irreversible change, and occurs along with viscoelastic effects at elevated temperature levels. It can be measured using a short substrate or tape sample in a creep test apparatus. Shrinkage is associated with the coating process, as some polyester substrates appear to shrink more after the front and back coats are applied as compared to virgin substrate material [16].

Fundamental relaxation phenomena for substrates and constitutive tape materials can be studied using dynamic mechanical analysis (DMA), which allows for a detailed resolution of storage and loss modulus properties as a function of time and temperature. As frequencies of the DMA measurements decrease, creep conditions relevant to the 30+ year life are approached, so the scientific understanding of relaxation phenomena from DMA can be used to understand long-term creep phenomena in tape media [16, 17].

Additional studies should continue to be performed, in addition to free expansion tests, custom and in-cartridge creep tests, and DMA, in order to continue to support a 30 year archival life for tape on future products. These studies range from classic tensile tests to nanoscale studies such as atomic force microscopy and nanoindentation [18, 19].

Prediction of Archival Life

Dimensional stability of the tape, particularly creep characteristics, depends not only on the media used, but on the pack stresses of the wound reel. These pack stresses are not uniform, either down the tape length or across the tape width, and depend on the hub design, winding conditions and media properties [20, 21, 22, 23]. For archival storage of tapes, dimensional stability of the substrate and tape is critical when it is stored in a reel, and application of existing stress models as well as new models or simulations could help manufacturers reach the Roadmap goals. Real data from custom creep tests need to be used in these simulations, which can predict tape behavior and enable the design of future magnetic tapes. Individual data sets developed for front coats, substrates, and back coats can be used for this purpose as well as Poisson's Ratio measurements discussed previously.

Because magnetic tapes have been in use since the 1950's, one method for understanding archival life is to simply use legacy tapes with a known history and legacy drives in an experimental study. In addition to simply determining whether or not data can be read from these already archived tapes, external optical sensors could be placed on any drive to measure widthwise contraction or expansion of the tape compared to the original specifications when the tape was manufactured. For LTO tapes, in-cartridge creep experiments could be performed using Generation 1 tapes manufactured and written in 2000. Although this is a direct approach to determining if past tapes have successfully archived information, it does not necessarily enable the design of future tapes with up-to-date or developmental substrates, binder systems, magnetic particles, and back coats.

Achievable Total Dimensional Stability (TDS) from Substrate Manufacturers

We will define the media dimensional stability as the sum of all the factors (relative to the head): thermal, hygroscopic, tension and in-cartridge creep (i.e., a worst case). We are assuming that the head has a thermal expansion of 7 parts per million (ppm) per degree Celsius (or 7 ppm /^{o}C) and a hygroscopic expansion of 0 ppm/%RH. Typical values, current and targeted, are given in Tables 4 and 5, below.

Tables 4 and 5 provide dimensional stability goals for tape media made using substrate films of polyethylene terephthalate (PET), polyethylene naphthalate (PEN), and aromatic polyamide (aramid) composition. The thermal stability values are relative to those as stated above of typical head materials. Manufacturers have currently set a long-term TDS goal of 500 ppm for PET and PEN. Aramid has better properties, and manufacturers have set a possible TDS goal of 100 ppm for tapes made using this film material. Aramid's significantly higher cost may not be compatible with the cost structure of some tape products, but use of this more stable substrate material could provide opportunities to avoid costly future changes to tape drives that might otherwise be necessary to achieve the Roadmap TDS targets.

Table 4a: Dimensional Stability Goals (in ppm) for Tapes using Modified PEN Substrates.

	2012	2014	2016	2018	2020	2022
Thickness, µm	4.5	4.2	4.2	4.0	3.8	3.5
Thermal	0	0	0	0	0	0
Hydroscopic	470	470	320	320	220	220
Tension	130	130	130	130	130	130
In-Cartridge Creep	100	100	100	100	100	100
Total (TDS)	700	700	550	550	450	450

Table 4b: Dimensional Stability Goals (in ppm) for Tapes using Advanced PET Substrates (Tensilized, Metalized, Polymer Blends).

	2012	2014	2016	2018	2020	2022
Thickness, µm	4.5	4.3	4.1	4.0	4	4
Thermal	50	25	0	0	0	0
Hygroscopic	400	375	300	300	300	275
Tension	150	150	150	150	100	75
In-Cartridge Creep	100	100	100	100	100	100
Total (TDS)	700	650	550	550	500	450

Table 5: Dimensional Stability Goals (in ppm) for Tapes using Aramid Substrates.

	2012	2014	2016	2018	2020	2022
Thickness, µm	3.4	3.2	3.0	2.8	2.6	2.4
Thermal	100	100	50	50	0	0
Hygroscopic	100	100	50	50	0	0
Tension	50	50	50	50	50	50
In-Cartridge Creep	50	50	50	50	50	50
Total (TDS)	300	300	200	200	100	100

Substrate manufacturers recognize the need to meet current tape cartridge cost requirements with future substrate materials. Improvements in the dimensional stability of PEN, PET, and aramid substrates are currently being obtained through biaxial tensilization to enable higher and more uniform elastic moduli in the machine (tape length) and transverse directions. Additional methods for improving dimensional stability of polyester (PET and PEN) substrates include proprietary molecular-level modifications as well as the application of metalized layers to the films. The anticipated contributions to the TDS are somewhat different for these two approaches.

One of the approaches, which has been proposed by Teijin DuPont Films as a modified PEN substrate, is to focus on improving the hygroscopic factor, but keep the thermal factor at the current level of PEN. Improvement of TDS by this approach will be achieved through combined effects of decreasing the hygroscopic expansion of modified PEN itself and optimal orientation of the substrate, which gives an ideal thermal expansion of the substrate to meet the head material. Because the approach is based on modification of PEN by a molecular-level method, an additional benefit to this approach besides improving the TDS is to enable the same manufacturing process to be used as the current polyester (PET/PEN) substrate.

Another approach, which has been proposed by Toray Industries as advanced PET with higher Tg, is to focus on improving hygroscopic and thermal expansion based on tensilized orientation and nano-sized polymer blend. Controlled nano-sized structure can play an important role to improve dimensional stability. An additional approach proposed by Toray Industries, to focus on improving both the hygroscopic and tension factors, is a metalized polyester film for future substrates. The reduction of dimensional change is attributed to the reinforced effect of metalized layers. In addition to improving TDS, metalized polyester has a higher Young's modulus in both longitudinal and transverse directions. The above-mentioned technologies can be combined with each other, and the target of TDS in 2022 is 450 ppm.

In addition, aramid has been proposed by Toray Industries as a promising substrate. Aramid has significantly lower dimensional change for thermal, hygroscopic, tension, and creep, due to its rigid polymer structure. Thickness for aramid substrates can be less than 4 microns and can give thinner magnetic tapes and cost effectiveness considering area cost.

2.3.7 Tape Chemistry Innovations

Due to the shift in tape usage patterns, the tape chemistry, particularly the magnetic layer which is in contact with the head, will very likely need a completely new approach to fully utilize very small, high surface area particles. It is also increasingly clear that mobile small molecules present in current coatings need to be eliminated to address head corrosion and pole tip recession. New approaches to tape lubrication to reduce static friction and running friction are clearly needed for the smoother surfaces demanded in the future. The use of smaller head cleaning agents (HCA) and reducing other load-bearing particle sizes may be necessary to reduce head to tape spacing and decrease PTR.

There is evidence that the reduction or elimination of mobile components in the coating formulation, which contain phosphorous and sulfur, would reduce the pitting of alumina at the head surface [24]. Phosphorous and sulfur are key components of the dispersant and dispersing binder wetting groups used in the coating formulation. The issue with phosphorous and sulfur is that these materials exist as acids (carboxylic acids manifest the same staining problems, just less so per their lower acidity). Just as carbon is not a problem if it is not part of a carboxylic acid group, phosphorous and sulfur may not be intrinsically problematic if not used in acid forms or as something that easily hydrolyzes to acids. Just replacing these with other materials would probably not have the desired effect. A totally different formulation and perhaps coating method would need to be developed.

2.3.8 Defects

Defects in magnetic tape are irregularities in the magnetic coating. These irregularities could be caused by voids in the coating, coated-in debris, impressions caused by defects in adjacent wraps within a cartridge or asperities from the substrate, as a few examples. These defects can range from a micrometer or so to hundreds of micrometers. Generally, defects longer than several millimeters are rare and would tend to be detected in the manufacturing process and/or can possibly be corrected for at the systems level using sophisticated write algorithms.

Defects are generally specified by the amount of signal remaining as detected at the defect compared to the signal averaged over many millimeters near the defect. The specification is typically 25%-50% signal remaining. With a 2 µm reader track width, this would correspond to 0.5-1.0 µm defects. These values represent the smallest void that would be considered to be a defect. With a 0.2 µm reader track width in 2022, the defect size becomes 0.05-0.1 µm.

Given a specific tape, as linear and track densities increase, the defect rates will also increase. The rule of thumb is that for each halving of the reader track width, the defect rate will go up fivefold to tenfold.

2.3.9 Other Issues

Tape Edges

Tape edges (specifically, tape edge quality) will continue to be an issue for the media manufacturers. Tracking problems and debris generation are commonly caused by poor edges. At least one drive manufacturer is using a non-edge guided system to mitigate these issues. Tape edges can also affect servo track writing and winding of the media in the cartridge. The quality of the tape edges has a strong dependence on the mechanical slitting operation done during tape manufacturing. Each media manufacturer has a unique process for slitting, which may make it difficult for collaborative research on the topic. However, development of an ideal edge fabrication process, that may or may not be financially practical, could be useful as a methodology to measure of the impact of poor tape edges.

Tape Pack Uniformity

Tape winding mechanics are dependent on the rate the air can be “bled” from between layers on a spool of tape. The backside roughness plays a key factor in determining the rate of air bleed. Tradeoffs exist between smooth magnetic coatings and rough backside coatings. The coating process itself can be a limitation on either parameter, while backside impressions on the magnetic layer surface can occur in the spool.

2.3.10 Summary of Requirements to Meet Roadmap Goals

The following requirements will be needed to meet the Roadmap goals:

1. The media roughness will need to be about half the roughness of today’s media. This will require improved friction characteristics of the head-tape interface.
2. The particle thermal stability, K_uV/kT, will need to be maintained at or above 75-80. If the particle is BaFe, the magnetic anisotropy will need to be increased, which will cause an increase in the coercivity of the particle. This, in turn, will require different head materials or a soft-under-layer under the magnetic layer of the coating.
3. If the particle is BaFe, the media will ultimately need to be perpendicularly oriented, although advanced media have been, and will probably continue to be, made with minimal degrees of orientation.
4. The substrate material will need a Total Dimensional Stability of 50-85 ppm given 8 data bands. Aramid comes close with 100 ppm. Without other solutions in the head or environment requirements, the number of data bands would have to increase. This aramid substrate would also need to be made at a thickness of 3.0-3.5 µm.
5. If sputtered or evaporated metal film tape is used, the head to tape spacing would need to be reduced. The published 45 Gbit/in^2 coating comes close to meeting the requirements, but some improvement would be necessary.
6. The SNR requirement of the channel will need to be reduced by 1 dB every two years. The SNR requirement in 2022 will need to be reduced to 13 dB.

2.3.11 Summary of Unresolved Issues

1. Increasing the magnetic anisotropy of the particles may prove to be difficult while reducing the particle size and the distributions of size and anisotropy.
2. Significant issues in durability could occur due to the smoother magnetic layer requirements. Improvements in tape chemistry and heads will be needed.
3. Significant head pole tip recession could occur. As the density increases, the sensitivity to the head to tape spacing also increases.
4. Affordable channels for use with reduced SNR need to be designed.

2.3.12 Summary of Dependencies on Other Groups

Heads

1. Reduce head friction to accommodate smoother media.
2. Write higher-coercivity media, up to about 4500 Oe (VSM), from today's 2500 Oe (VSM).
3. Optimize materials in the head to reduce PTR.
4. Methods to reduce dimensional stability requirements.

Channel

1. Channels with lower SNR requirements.
2. Channels that can accommodate higher defect rates.

Servo/Transport

1. Guiding improvements to reduce edge issues.
2. Transports capable of handling thinner and smoother media.
3. Improved servo performance, probably requiring two-stage servo.
4. Possibly, a means of compensating for tape dimensional changes, such as servoing of the head span and/or the angle of the head to tape direction (azimuth angle).

2.3.13 Suggested Areas for Future Research

1. Verification of the 2012 Tape Technology Roadmap predictions by numerical micromagnetic simulations.
2. Dual-stage actuator concepts and robust dual-stage control tape path mechanics.
3. Writing high coercivity particles - SUL and heads.
4. 1000 nm^3 particles with K_uV/kT of >75.
5. Evaluate the limit of head-tape spacing of around 2-3 nm.
6. Electrochemical processes that increase head-media spacing in tape drives.
7. Creep characteristics of digital magnetic tapes.
8. Tribological studies of magnetic tape heads for extremely high data storage densities.

9. Supramolecular lubricants as a possible route to self-healing coatings with improved tribology.
10. Long-term archivability recommendations, including air environment.
11. Long-term archivability, including chemical and magnetic stability.
12. Reduction of abrasivity of new tapes.

2.3.14 Conclusion

This tape Roadmap predicts a continuation of tape technology's long achievement of large capacity increases for each generation. The issues raised in this section are not unforeseen and have been resolved for past generations. BaFe has been able to provide a clear 3-4 generation solution going forward. The 2020 and 2022 targets will push the capabilities of BaFe, but should be within manufacturing capabilities. Tape roughness and durability requirements will be one of the more challenging requirements for the tape Roadmap. However, past generations have been able to achieve similar goals.

2.3.15 References

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