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Introduction to Computer Tape Recorders

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INTRODUCTION TO COMPUTER TAPE RECORDERS

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Abstract

A two-volume update on magnetic recording, edited by Denis Mee and Eric Daniel, will be published in 1986 by McGraw-Hill, Inc., New York. The first volume covers magnetic recording principles, and the second book, "Magnetic Recording Applications," describes current magnetic recording technology. This report is taken from Chapter 4, "Data Recording—Tape," in the second volume.

"Data Recording—Tape" contains two major types of information, which will be discussed in two technical reports. This report contains the general descriptive information that is intended to inform novices about the applications and components of computer tape recorders. The other technical report, "Equalization for Computer Tape Recorders," TR-82.0298, describes the more technical portion of the chapter, which explains recording-channel signal processing. Other chapters in the two volumes cover magnetic recording, tape, heads, modulation, and error-control codes; therefore, the descriptive information in this report is not detailed.

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INTRODUCTION

For several decades, magnetic tape provided low-cost input/output capability for computer data interchange and offline storage. Magnetic tape was a significant improvement over its predecessors—punched cards and paper tape. Over the years, newer technologies threatened the existence of computer tape devices; some of these technologies eroded tape applications, but others never materialized in a competitive form. Meanwhile, magnetic tape technology advanced and presented a moving target. Computer tape is not facing extinction because the need for this form of data recording is expected to continue for many years.

With the rapid density increases and cost reductions of semi-conductor memory and magnetic-disk direct-access storage devices, why is magnetic tape storage needed? Tape provides low-cost secondary data storage to support the memory and primary disk-storage functions. Unlike memory and magnetic disks, tape can be removed from the computer system. Magnetic tape is used to store data from the computer and process the input data when needed. The tape drive is sometimes referred to as an input/output device. Magnetic tape advantages include data removability, low-cost data storage, high data-rate capability (through the use of parallel tracks), high volumetric efficiency, and reusability. For example, IBM 3480 tape cartridges currently store data for S72/GByte, which includes the storage-rack price. These cartridges in full racks provide 123 GBytes of data storage per cubic meter of occupied space. As data density increases on magnetic tape, storage cost and volumetric efficiency will significantly improve. The major disadvantage of tape is its slow random-access capability.

COMPUTER TAPE APPLICATIONS

Computer tape devices have five major applications:

- Archival storage
- Disk backup
- Data interchange
- Sequential processing
- Online storage (library or mass storage system).

Magnetic tape provides the lowest-cost solution for these applications.

ARCHIVAL STORAGE

Computer data must often be retained for years after it becomes inactive on the computer system. Archival storage can be on paper or microfilm, but a machine-readable storage system is preferable. Archival data are not frequently accessed. Therefore, cost, data integrity, and volumetric efficiency are the key criteria for selecting a storage medium. Magnetic tape is the usual choice if a tape drive is available on the computer system.

Geographically separated, multiple tape copies provide protection if a major disaster occurs. If recommended tape storage procedures are followed, the archival life of magnetic tape is probably limited by the availability of old technology hardware (which can read the tape) rather than by magnetic or physical deterioration of the tape itself. The capability to recover data from archival tapes introduces a requirement for **downward compatibility**. A new high-density tape machine can also be required to read old low-density tapes. This requirement impedes the motivation to develop advanced tape and hardware technologies.

DISK BACKUP

A removable backup copy of the active online data is frequently required in case a disk malfunctions. Disk files are usually backed up with magnetic tape if tape drives are available on the computer system. As a rule, backing up tape is a write-only operation because data recovery is not frequently needed. The backup tapes can be reused when the data are recoverable from a more recent backup tape. Important considerations for this application are backup time, cost, and data integrity, and matching tape capacity to disk capacity.

DATA INTERCHANGE

Magnetic tape is often used for data interchange between computer systems, except for small machines when flexible disks are commonly used. Reliable data interchange requires product standardization of machines, which includes tapes and devices that are designed and manufactured by different companies. Data interchange with magnetic tapes has also discouraged rapid technological advances, such as density increases. A new high-density device can require **dual-density** write and read capability to interchange old and new format tapes; however, this requirement increases machine complexity and cost. Electronic data interchange is a common method of communicating between computer systems, and is replacing tape for some applications.

SEQUENTIAL PROCESSING

Inherently sequential data files can be sequentially batch processed on a tape drive more economically than on a random-access disk file. For this application, rapid start and stop of the tape is important so that only the desired records are transferred. As the cost of online random-access storage decreases, the advantage of sequential processing diminishes unless it decreases in cost at a comparable rate.

ONLINE STORAGE

The selection of a data storage system is a tradeoff between access time and cost, as discussed by Chi [ref.1]. Online data are retained in memory for submicrosecond accessing or on disk for millisecond accessing. Some data can be economically stored in a low-cost tape library for access in a few seconds and, if the requirement is anticipated, it can be **staged** from the tape to disk or memory for apparent high-speed access. The important characteristics for this application are data integrity, access time, and storage cost, as discussed by Davis [ref.2] and Ito et al. [ref.3].

TECHNOLOGY VARIATIONS

The performance, cost, and size of computer tape drives vary considerably. Performance is usually the critical requirement for large computer systems, but cost and size are more important considerations for small computer applications. Computer tape devices can cost less than $100 (audio-cassette recorders for home computers) or over $1,000,000 (large tape library). The technologies used are understandably different.

Streaming tape drives transfer large quantities of data at a constant rate, but **intermittent** tape drives start and stop quickly between tape records in an interblock gap (or interrecord gap). If the drive cannot decelerate or accelerate the tape within the space provided by the interblock gap, the drive can use a **backhitch**. (The tape is stopped and reversed to a point that allows acceleration to full velocity before the beginning of the next record.)

Some machines use fixed, multitrack heads to obtain a high data rate from a parallel tape format at a low tape velocity. A single-track head with one electronic channel (rather than multiple parallel channels) is less expensive, but requires a higher head-to-tape velocity for the same data rate. A single-track head is usually indexed to another track at each end of the bidirectional tape to create a **serpentine** recording format, as discussed by Daniels et al. [ref.4]. Serpentine recording covers the tape surface like a farmer plows a field—by moving along the length in a forward direction and then returning in a different transverse position. A multitrack head can also be used in a serpentine fashion if the number of tape tracks is a multiple of the number of head tracks.

The tape tracks are not necessarily parallel to the edge of the tape. Rotary heads are used to apply data tracks across the tape as in video recording. This technique achieves the highest areal density on tape, but is usually limited to a serial format, which can impose data-rate and tape- or head-wear limitations. Most tape devices read and write data sequentially, but library tapes must be accessed randomly.

HISTORY OF MAGNETIC TAPE

In the early 1950s, magnetic tape—12.7 mm (half-inch) wide with a parallel track format—was selected to transfer data at high speeds to and from computers. The tape drive was required to start and stop rapidly between records, which were often 80-character images of the popular tabulating card. The IBM 726 tape drive operated at 1.9 m/sec (75 inches/sec) at a density of 3.9 characters/mm (100 characters/inch), which provided a data rate of 7500 characters/sec. Later machines provided higher recording densities and data rates, but they were similar in design. Over the years, tape capacity and data rate were increased by a series of recording density increases. Tape speed was also increased to 5.1 m/sec (200 inches/sec) to improve the data rate. Data reliability was improved by using a read-after-write head that verified the written data and read errors were identified with transverse and longitudinal redundancy. Current high-performance computer tape devices operate at more than 500 times the density, at more than 400 times the data rate, and at significantly higher data reliability than the original machines. This rate of improvement is expected to continue for many years. In addition, many small computer tape devices are available now that outperform the early tape machines at a small fraction of their cost.

Although tape technologies can be significantly different for various machines, their basic functions are essential to all computer tape systems—magnetic tape, electromagnetic transducers, relative motion, and signal-processing circuits. Each basic function influences the overall performance characteristics of the integrated data storage system.

DATA RECORDING

The central component in the data recording system is the magnetic tape that provides removable data storage capability, as discussed by Granum and Nishimura [ref.5]. The physical and magnetic characteristics of computer tape are similar to the characteristics of audio, video, and instrumentation tape.

As computer customers migrated to equipment with higher densities, they still needed to read the data from old tapes, which were frequently rewritten at the new density. Therefore, the magnetic properties of compatible computer tapes did not change appreciably over more than three decades. The substrate was changed, more durable coatings with improved lubricants were developed, and the tape noise level was reduced by improved magnetic pigments and surface uniformity, but the tapes were basically interchangeable. The introduction of tape cartridges and cassettes, which were not interchangeable with the old open reels of tape, permitted the use of tapes with superior magnetic characteristics. Chromium dioxide and cobalt-modified iron tapes are now frequently used for computer applications.

TAPE CONTAINERS

Due to the requirement for removability, a tape container is needed to protect the fragile tape from physical abuse and contamination. This protection is important when the information density on tape increases. A simple reel, consisting of a hub upon which the tape is wound and flanges that protect the tape edges, was used as a tape container for more than three decades. The open reel is frequently enclosed in a dustproof container for storage. The tape from an open reel can be manually threaded through the machine, but the trend is toward reduced manual tape handling and providing automatic threading.

Early tape reels had flange openings that frequently caused tape damage because they provided easy access for fingers and dirt to contact the tape edges. Solid flanges are preferred and now commonly used. Metal hubs replaced the older-style plastic hubs on many computer tape reels, and a simple, space-saving, wraparound band is frequently used to enclose the reel for protection, as discussed by Townsend [ref.6].

Additional tape protection and reduced human intervention are achieved by using tape cartridges or cassettes. In this report, a **cartridge** denotes a single reel of tape in a machine-useable container. A **cassette** includes a take-up reel as well as the supply reel. The cartridge is more compact, but it requires a more elaborate threading mechanism than the cassette needs. Both cartridges and cassettes eliminate manual handling of the tape, and thus make automatic tape loaders and libraries practical.

A variety of tape containers is widely used. The simple reel with a wraparound seal is commonly used. A self-loading cartridge is also available, as discussed in ANSI [ref.7]. Various cartridges and cassettes are also popular. In the early 1960s, a cassette machine for one-inch computer tape was developed, but it was not widely accepted. In the late 1960s, a high-quality audio cassette was used to input programs to small computers. In the early 1970s, a cassette for quarter-inch tape was introduced that allowed a single motor to drive the supply and take-up reels from an internal belt. The container uses a metal baseplate to provide a reference plane within the cassette, and thus improves tape-positioning accuracy. This design permits the use of higher track densities than the more conventional audio-type cassette, and it grew into a family of tape cassettes that was well accepted. In the early 1970s, a 68.6-mm (2.7-inch) wide tape cartridge was developed for the mass-storage-system tape library; it provided faster access to data than if a longer and narrower tape with the same surface area was used. In the 1980s, a variety of cartridges and cassettes was proposed; some of them are now widely accepted for computer applications. Figure 1 shows several computer tape containers.

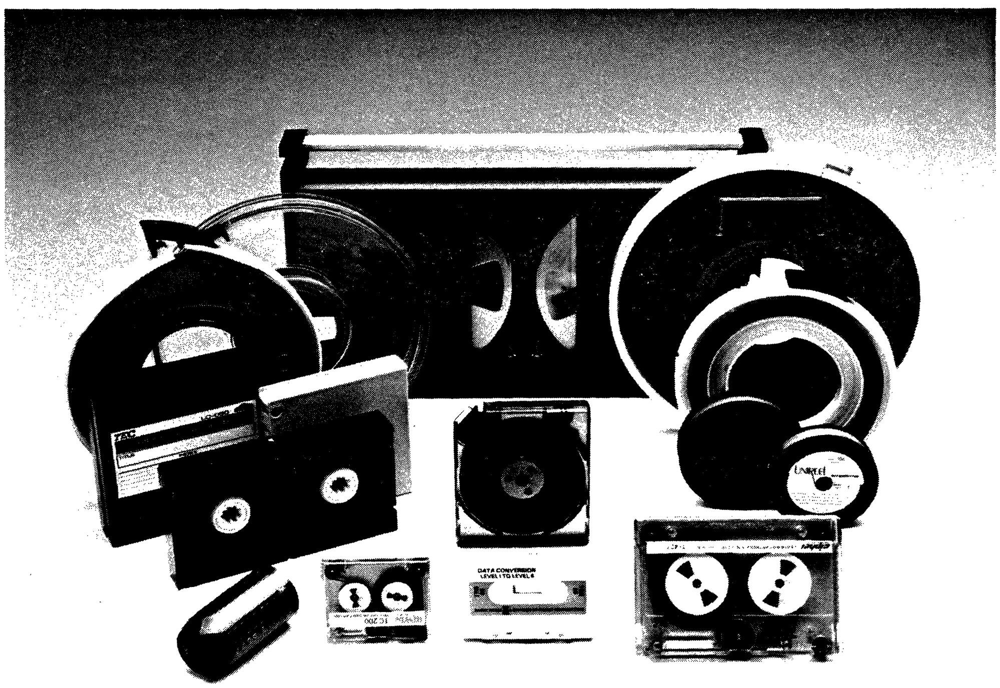

Figure 1. Tape Containers

COMPUTER TAPE

A unique requirement for computer tape used on a high-speed intermittent machine is the capability to withstand high acceleration without excessive physical distortion. Tape acceleration of more than 500 g (to 5 m/sec in less than 1 ms) is required by some open-reel, vacuum-column tape drives, as discussed by Harris et al. [ref.8]. Hiratsuka et al. [ref.9] indicate that an important requirement for these machines is tape durability, which leads to the common use of a 36-µm thick substrate rather than a thinner substrate that provides more capacity. Under these high stress conditions, the dynamic properties of the tape can result in multimodal oscillations. In general, computer tapes use thicker substrates than video or audio tapes.

SIGNAL DROPOUTS

In a high-speed computer tape drive, the head and moving tape are usually separated by a thin hydrodynamic air film of about 0.2 µm. This separation reduces both head and tape wear, but it introduces a spacing loss. At low recording densities, this loss is not significant, but it limits the density capability of the tape.

If the tape surface contains a protrusion that is larger than the air bearing, the tape-to-head separation increases momentarily as the surface defect passes the head. This additional spacing loss produces a signal **dropout**, which is the major cause of tape data errors. Signal dropouts can also be produced by voids or inhomogeneities within the magnetic coating, but surface protrusions are a more common cause, as discussed by Baker [ref.10]. Figure 2 on page 8 shows typical tape signal-dropout envelopes.

As tape passes through the machine at high speeds, it frequently generates an electrostatic charge that can attract mobile contaminants. The ambient relative humidity influences the polarity and magnitude of the electrostatic charge. When the tape is wrapped on the reel, any debris between tape layers is pressed into the magnetic coating by high layer-to-layer pressure that is developed by the tape tension and the debris protrusion. The contaminant can eventually become welded to the tape surface, which causes a separation between the tape and head at the defect location. If this separation occurs after the tape is written, it produces a dropout that can result in a permanent read error if it is not corrected. A conductive back coat is sometimes used to reduce electrostatic attraction of airborne pollutants near the tape.

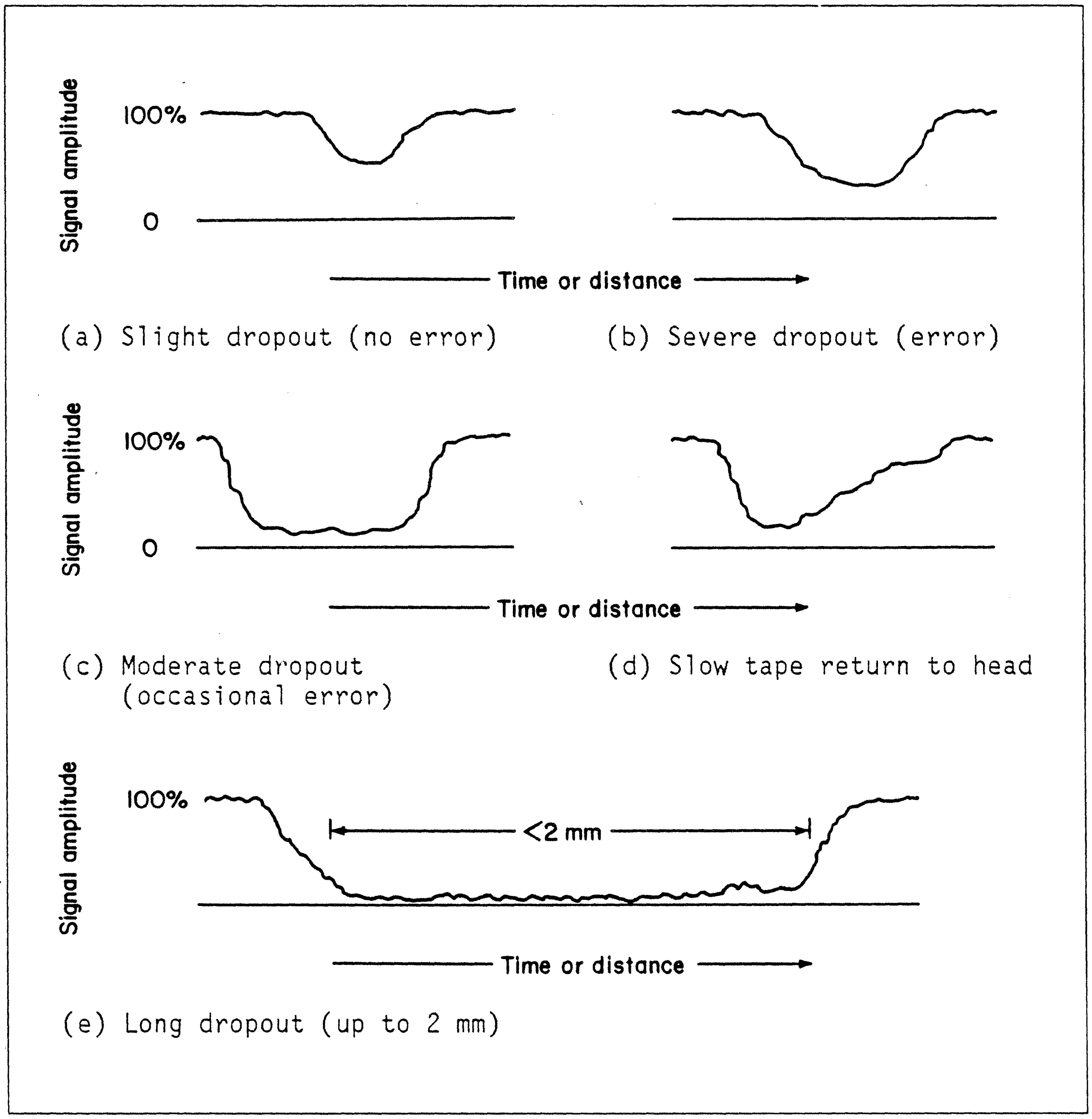

Figure 2. Signal-Dropout Envelopes

Unfortunately, some debris is generated by the tape itself. If the slitting process generates loosely attached pieces of substrate or coating material, the tape guides can eventually knock the particles from the tape edge. If these particles adhere to the tape surface, the tape performance will probably be degraded. A large defect, such as a piece of slitter debris, can separate the write head from the tape sufficiently to prevent the tape from being properly written. Even if the defect is subsequently removed, the tape will contain a written dropout. The tape surface can also generate wear debris during rapid start/stop operations. At low velocities, the hydrodynamic air bearing cannot support the tape, which results in contact and wear.

The wear products are usually a fine, dry powder. Tapes that produce sticky wear materials are undesirable. The rapid start/stop operation creates tape-tension transients that accentuate the wear problem. The head sometimes acts like a snowplow and pushes the fine powdery tape debris into piles, which are large enough to create a dropout.

Not all surface particles permanently adhere to the tape. Some particles are loose, and can be moved by the head or guides. The results are migratory and stationary tape defects. A migratory defect that causes a temporary read error can sometimes be removed by **shoeshining** the tape back and forth a few times. Most high-performance computer tape drives include a tape-cleaning device that removes loose surface contaminants, and can significantly improve the data reliability.

A surface protrusion can form a tape **tent** due to tape stiffness. The duration of the resultant signal dropout is, therefore, longer than the time required for the defect to pass the head gap, as indicated by comparing the dropout signal with photomicrographs of the actual defect. Probability density functions of dropout size were measured, as discussed by Alstad and Haynes [ref.11]. Baumann [ref.12] showed that the tent radius extension can be approximated if the head radius is significantly larger than the tent size.

$$r_t = (64\ r_h\ D\ h_p/T)^{0.25} \quad (1)$$

where

r_t = radius extension of the tent (μm)

r_h = radius of the head (μm)

D = tape flexural rigidity (N-μm)

h_p = height of the protrusion (μm)

T = tape tension per unit width (N/μm)

Flexural rigidity is a function of the tape thickness.

$$D = E\ t^3/12(1-\nu^2) \quad (2)$$

where

E = Young's modulus (typically 3.4 GPa = 0.0034 N/μm²)

t = tape thickness (μm)

ν = Poisson's ratio (typically 0.33)

The tent height at the peak of the defect is the same as the protrusion that supports the tape. The unsupported tape in the extension region is defined by Equation 3 and shown in Figure 3b on page 10.

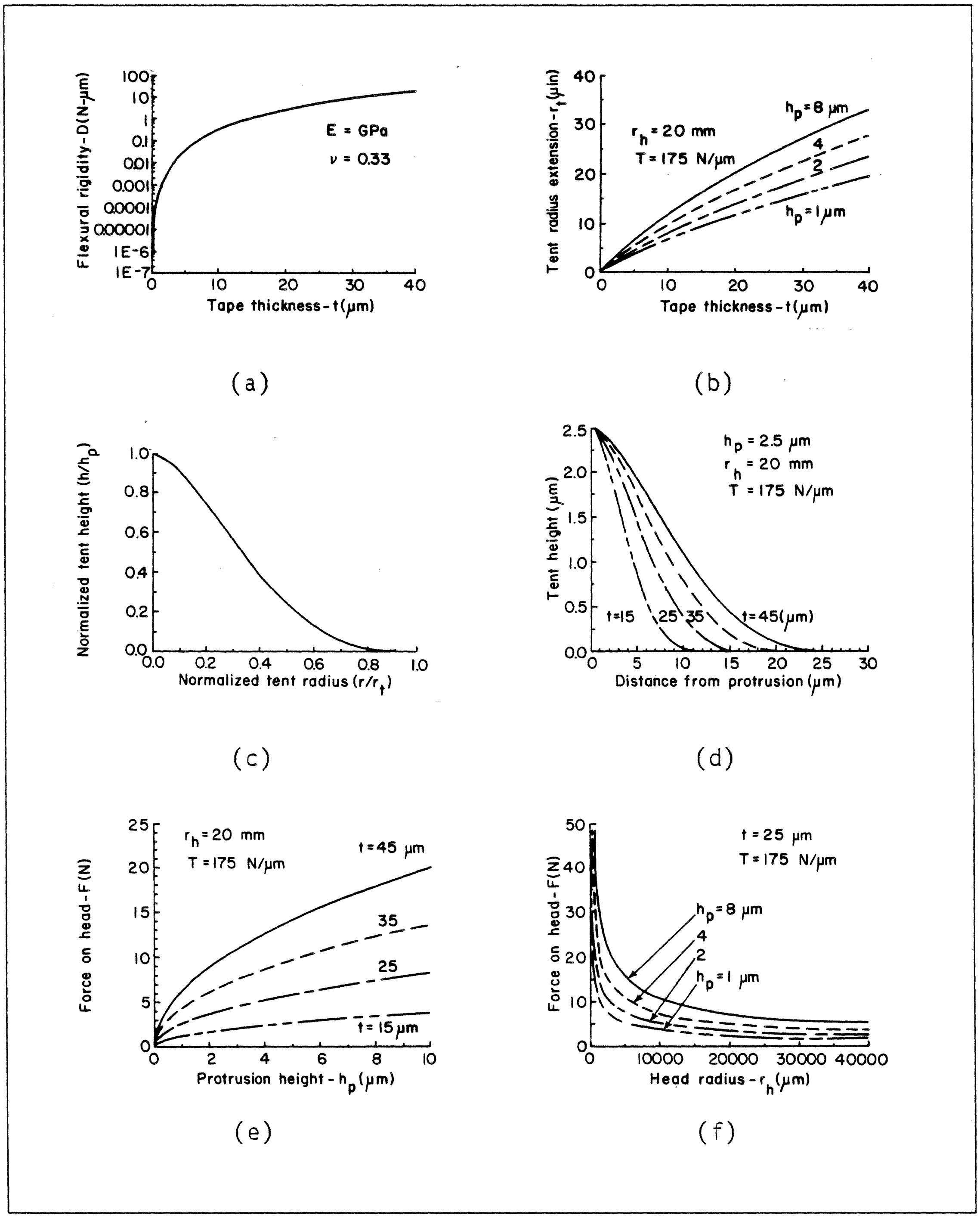

Figure 3. Tape-Tent Parameters

$$h_n = 1 + r_n^2 \ln r_n^4 - r_n^4 \qquad (3)$$

where

h_n = normalized tent height at radius r ($h_n = h/h_p$)
r_n = normalized tent radius ($r_n = r/r_t$)

Also, the force of the head on the particle, F (in Newtons), can be predicted.

$$F = \pi T\ r_t^2/2r\ h \qquad (4)$$

The tent area is large for thick tapes, large radius heads, low tape tension, and large defect protrusions. The normal force, F (and thus the head wear), is greater for thick tapes, small radius heads, high tape tension, and large defect protrusions. Figure 3 on page 10 shows how head and tape parameters affect tenting, as discussed by Baumann [ref.12].

Most computer tapes are reused many times, and eventually they can degrade. Several computer-tape maintenance devices are available, as discussed by Geller [ref.13] and Buschman [ref.14]. **Tape cleaners** typically clean and rewind the tape without erasing the recorded data. **Tape certifiers** erase and rewrite the tape as they detect and count data errors. Some tape certifiers stop the tape at errors for visual inspection and defect removal when possible. Some dropouts are caused by physical abuse, such as tape creases or edge damage that cannot be repaired.

COMPUTER TAPE PROBLEMS

A major advantage of magnetic tape over other computer-data storage systems is the low cost—about one dollar per square meter; however, tape has some disadvantages as well. The low-cost polyethylene-terephthalate substrate that is used has small surface asperities, which require a thick (>2 μm) magnetic coating to cover the defects. The high linear density recordings for which tape is now used often contain wavelengths that are shorter than the coating thickness. This density requires **partial penetration** or **surface recording** rather than the full thickness **saturation** recording that is used in rigid disks. The disadvantages of this technique are tape noise and incomplete overwriting, as discussed by Bate [ref.15].

Although the effect of tape dropouts on data reliability is a major concern, the frictional characteristics of the tape are also an important consideration. If the coefficient of sliding friction is high, excessive tension is required to overcome the tape frictional **drag** forces. Occasionally, the tape is still accelerating at the end of the interblock gap because of drag, which can cause a malfunction due to low tape velocity. The coefficient of friction depends upon the ambient humidity, and increases rapidly above 40%, as discussed by Miyoshi and Buckley [ref.16]. Head wear was also observed to increase rapidly above 40–45% relative humidity, as discussed by Kelly [ref.17].

These experimentally derived dependencies of friction and head wear on relative humidity are similar, as shown in Figure 4. Miyoshi and Buckley attribute the increase in sliding friction to water vapor on the tape surface. Their data indicate that the process is reversible, and the coefficient of friction returns to normal when the relative humidity is reduced.

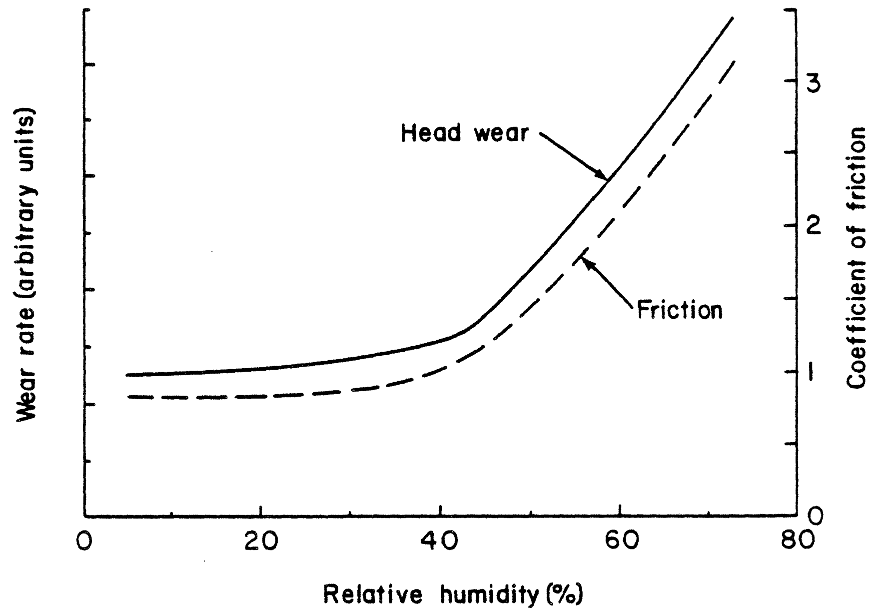

Figure 4. Friction and Head Wear versus Relative Humidity

Low humidity can also create a problem at tape speeds above 2 m/sec. At relative humidities below 30-35%, some head materials become stained with a "varnish" that increases the head-to-tape separation, and reduces high frequency response. The stain develops even when uncoated or titanium-dioxide coated substrate passes over the head. The stain must be mechanically removed, because chemical cleaners are ineffective, as discussed by Kelly [ref.17]. Because of the inverse relationship between stain and head wear, the increased tape abrasivity at high humidity is suspected of removing the stain as it forms. Stain apparently does not develop on ferrite heads, as discussed by Waites [ref.18].

Some tapes tend to adhere to the head or other points of contact when the tape stops. This condition is called tape **stick** or **seizure**; in severe cases, the tape cannot be restarted. Sometimes the tape alternately seizes and then releases, which is known as **stick-slip**. In this situation, the instantaneous tape speed over the head varies excessively, as discussed by Kalfayan et al. [refs.19,20]. These tape characteristics must be avoided. Theoretical and experimental analyses of frictional characteristics of magnetic tape were discussed by Bhushan et al. [refs.21,22].

Computer tapes are typically wound with a tension of about 175 mN per mm of tape width, which creates high pressures within the tape pack. Layer-to-layer pressures as high as tens of MPa are not uncommon, as discussed by Geller [ref.13]. Tape-surface protrusions result in even higher pressures when the layers are separated by the protrusion. Large temperature and humidity changes cause the tape to contract or expand, which result in tension and pressure changes. Sometimes layer-to-layer slippage occurs. The tape pack can be distorted so that individual tape turns are not circular. In extreme cases, the pressure increase can crush a plastic reel hub. Aluminum or magnesium reel hubs are preferred as they reduce tape damage due to environmental changes. Temperature and humidity cycling can cause negative tape tension, which can result in loose windings or even open **windows** in the wound tape. The loose windings are serious on an intermittent computer tape drive because inertia causes part of the tape pack to slip when the reel is accelerated or decelerated. This condition can result in tape folds, which are called **cinching**. Nonuniform winding tension can cause **spoking** irregularities in the tape pack. These winding problems can irreparably damage the tape, as discussed by Waites [ref.18], Jorgensen [ref.23], and Davis [ref.24].

Blocking is another serious tape-pack problem. Occasionally, the combination of high winding pressure, temperature, and humidity causes the tape coating to adhere to the substrate or back coat of the adjacent layer. If this occurs, the tape cannot be properly unwound and, in extreme cases, the tape pack becomes a solid cylinder.

Transverse bowing of the tape, due to the differences between the coating and substrate coefficients of thermal and hygroscopic expansion, is called **cupping**. This environmentally induced tape problem can cause track-to-track, signal-amplitude variation. **Curvature** results from a thick edge, which can be caused by poor slitting. The pack diameter is larger than normal at the thick edge, and the tape is, therefore, stretched on one side. Eventually, the thick edge of the tape becomes permanently elongated, and the tape cannot be properly guided past the heads.

If the recommended tape shipping, storing, and operating environments are observed, and the tape drives are properly cleaned and maintained, computer tape provides long life and dependable performance, as discussed by Geller [ref.13].

TAPE TRANSPORT

The purpose of the tape transport is to move the tape past the write/read transducers. Tape reeling, guiding, and metering are required on all tape transports; tape buffering, cleaning, and loading or threading are performed by many high-performance transports, as discussed by Athey [ref.25].

TAPE REELING

Tape reeling involves moving the tape between the supply and takeup reels, which is needed for high-speed search or rewind as well as for normal write or read operations. Reeling requires proper winding of tape on the reels and tape-tension control. The reels and reeling mechanism are massive, and cannot be started or stopped as rapidly as a short segment of tape. Therefore, tape buffers, such as **vacuum columns** or **tension arms** (sometimes called **swing arms** or **buffer arms**) can be required between the reels and the metering mechanism on a high-speed, intermittent tape transport, as discussed by Ebenezer and Harris [ref.26]. These buffers are shown schematically in Figure 5 on page 15. Reel motion is provided by using motors, clutches, brakes, or belts. Motion control varies from a simple belt to elaborate servo systems.

A streaming machine does not require rapid starting and stopping of the reels. A backhitch or large interblock gap is used if the tape is stopped and restarted. Reel accelerations can be low, and simple reel motion and control components can be used, as discussed by Eige et al. [ref.27]. An intermittent motion machine, which is commonly used for high-performance applications, must start and stop the tape rapidly and frequently, and a tape buffer can be required with a sophisticated reel-motion control system.

Unless the tape-reeling portion of the transport does a good job, the tape can be damaged as it is wound onto the reel, or as the tape is handled or stored. An ideal reeling mechanism produces a uniformly wound tape pack without any projecting tape layers. The tape is wound at constant or controlled tension, because irregular tape tension on the reel will accentuate the problems in tape storage and handling.

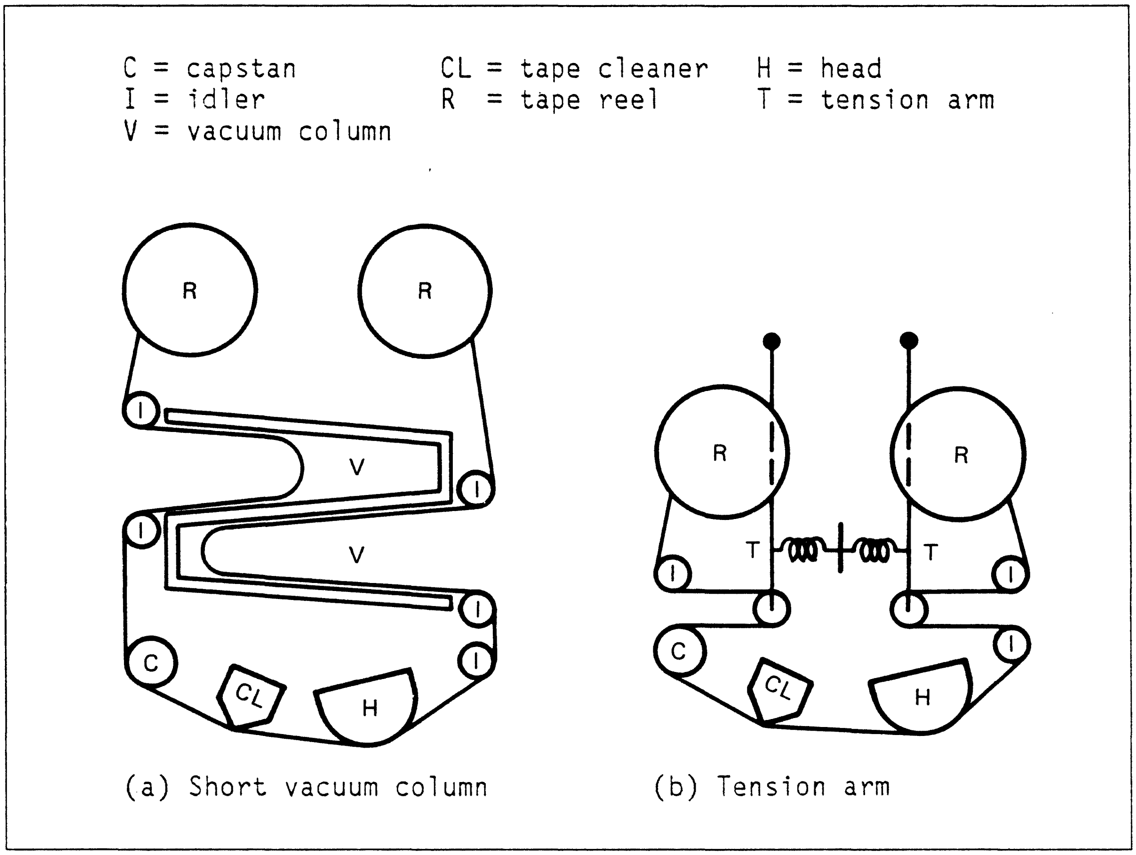

Figure 5. Tape Buffers

TAPE GUIDING

As the tape moves between the supply and takeup reel, it must be guided precisely over the transducers. Typical guiding components include flanged or crowned rolls, fixed or compliant edge guides, and hydrostatic or hydrodynamic surface guides.

The transverse position of the tape relative to the heads is important to achieve tape interchange and avoid misalignment between the recorded track positions on different machines. Such tracking errors can result in adjacent track interference, which can reduce data reliability. Tape width is not constant because slitting tolerances and environmental conditions cause variations in the width; therefore, guiding is usually based upon one reference edge. Temperature and humidity variations cause the position of the tape away from the reference edge to change with time, which results in tracking errors. If the tape edge deviates from a straight line (for example, from the slitter blade runout), the position of the tape relative to the head can depend upon the physical location of the guides.

Improper guiding can cause tape skewing as it passes the head. In a multitrack format machine, skew causes the data from one track to lose synchronism with data in other tracks. If the track is wide, skew can also result in an azimuth loss of the high frequency signals. **Dynamic skew** is a variation in the tape skew with time. The average velocity must be the same across the tape width, but the instantaneous velocity varies across the tape if it "fishtails" through the transport at high speed. In practice, static and dynamic skew cannot be completely eliminated, but they can be reduced to acceptable levels through proper transport guiding design.

The tape guides normally change the direction of tape motion, and provide lateral constraint to the tape. Either the front or back tape surface and the tape edges must contact the guides, which can generate wear products. To reduce this risk, air bearings are sometimes used at appropriate guide locations. If a tape buffer is used, it can provide part of the guiding function; for example, a long vacuum column constrains the tape position, and thus provides lateral guidance.

TAPE METERING

Tape metering controls the tape motion past the heads. In a streaming machine, tape velocity should be constant for a long time, and the metering problem is similar to the requirements for an audio or instrumentation tape drive. However, intermittent motion machines rapidly start and stop the tape, which necessitates the use of low-mass components. A lightweight capstan is usually driven by a low-inertia motor, and the tape is buffered in a vacuum column or tension arm device, and mechanically coupled to the capstan that controls tape velocity. Tape tension is controlled by the low-inertia buffer.

Several servo systems can be required to control the acceleration and steady-state velocity of the capstan and tape, to maintain the proper amount of tape in the buffer, to provide the correct motion for the supply and takeup reels, and, sometimes, to control tension. These controls are not independent of each other.

For a fixed-head machine, the tape-metering function has moderate velocity tolerances, but stringent acceleration limits. A clock is regenerated from the data during the reading operation and, although the exact speed of the clock is not critical, the rate of change of clock frequency is important to minimize reading errors.

A high-speed intermittent tape transport usually requires two reel motors for supply and takeup, and a separate capstan motor to meter the tape. Many streaming devices meter the tape with the reel motors, which is a substantial simplification because it eliminates the two buffers as well as the capstan and its motor, as discussed by Conti [ref.28], and Nagayama and Tamaru [ref.29]. A tension servo then replaces the buffer position control. Streaming-machine performance can often be improved through the use of a data memory, which makes it appear like a start/stop device to the computer. In some streaming devices, a single motor performs both the reeling and metering functions. An elastic belt mechanically couples the periphery of the supply and takeup reels to the tape so that everything moves synchronously, as discussed by ANSI [ref.30], Bate [ref.31], and Newell [ref.32].

HEAD MOTION

Most high-data-rate computer tape drives use a multitrack fixed head. For lower data rates, a moveable head is commonly used in a serpentine fashion in which a **head actuator** positions the head over the correct track. The head positions are determined by mechanical detents at the low track densities but, at high track densities, some form of track servo can be required. The tape edge or a recorded track is used as a reference for the head positioning servo.

Some computer tape drives use rotary heads to achieve high information densities on tape, as discussed by Ito et al. [ref.3] and Damron et al. [ref.33]. In addition to the reeling, guiding, and metering functions, a rotary head machine must move the heads synchronously with the tape motion. The tape can be metered at constant velocity past the heads, but it is usually stepped for each diagonal track. The stepping mode has the advantage that a track can be reread if necessary. The heads are contained on a rotary drum around which the tape is wrapped. A control system is needed to synchronize head motion to a longitudinally recorded servo track. Rotary head machines are used primarily for tape-library applications.

TAPE CLEANING

Data reliability is improved by using a tape cleaner, especially for high-speed start/stop machines. The cleaner removes the loose or lightly attached debris that is generated from tape contact with the transport or ambient air contamination. By removing the contaminants before the tape is wound up in the reel, a permanent defect is often avoided. Many different tape cleaners were tried. A cleaner blade often scrapes away tape surface protrusions, and a vacuum removes the debris from the cleaner. Various wiping materials are also used to clean the loose debris from tape, as discussed by Waites [ref.18] and Davis [ref.24].

Cleaning the tape as it passes through the transport and keeping the transport clean are important because tape debris tends to build up on the guides and head. Some machines even include an automatic head cleaner; other machines use special cleaning tapes to remove harmful debris from the transport.

TAPE LOADING OR THREADING

A tape cassette does not require manual handling of the tape. The tape is connected to the supply and takeup reels within the cassette. Inserting the cassette into the machine brings the reeling, metering, guiding, and heads into proper position relative to the tape. A tape cartridge requires a threading device to properly position the tape relative to the guides and heads, and to attach the end of tape to the takeup reel. Tape loading is usually activated after the cartridge is inserted. Sometimes the cartridge or cassette is automatically loaded into the machine from a multitape storage device. An open reel of tape is more difficult to load or thread automatically. Although automatic reel loading is not common, automatic threading of a manually loaded reel is available on most high-performance, open-reel tape transports.

MINIATURIZATION

The large demand for desk-top computers created a need for small tape drives, primarily for disk backup, as discussed by Domshy [ref.34] and Hirshon [ref.35]. Some of these devices are designed to fit into a computer in the space provided for a diskette, as discussed by Kotelly [ref.36] and Makmann [ref.37]. Most of these miniature tape transports use cartridges or cassettes.

Because many portable computers are now produced, power consumption is an important design consideration for the small tape drives. Hardware cost is a key factor due to the competition between tape drive manufacturers and with other technologies. Many simple and clever designs are employed to provide the necessary performance at the lowest possible cost. Most of these designs include streaming devices, but many are start/stop and can be used in either the streaming or intermittent mode. Tape speeds range from 0.75–7.6 m/sec (30–300 inches/sec).

Even high-performance tape drives are now designed to reduce size, power consumption (and air-conditioning requirements), and floor space to meet the customer's needs. The trend is away from the refrigerator-size machines, and to more compact packaging techniques.

TAPE FORMATS

The information to be recorded comes to the computer tape device as a series of binary **data bits**, organized into **data bytes**, which represent the desired characters (numbers, letters, punctuation, and symbols). Redundant or overhead bits or bytes are added for error control, synchronization, and identification. The bits can be concatenated into a serial bit stream, which is applied to a single tape track. Most low-cost, low-speed tape drives are single-track serial devices. For high data rates, the information is usually recorded in a parallel format.

The binary input data is modified by a **modulator**, which attempts to match the data signal to the head and media characteristics. Although many types of modulators are possible, those modulators used with computer tape drives produce a binary signal, which reverses the direction of tape magnetization according to the data. The modulation code rate, which is usually known as the **modulation rate** (R_m), is the ratio of modulator input bits to output bits. To differentiate between the unmodulated and modulated signal, we will refer to the modulator output binary digits as **binits**. The modulator output bits are also called code bits or chips. The modulator output binits are organized into groups called **codewords**.

The recorded data usually consists of **records** that are typically 2^n bytes in length. If n is small, multiple records can be combined into a **block** of data that is physically separated from other blocks when it is written on tape. The beginning of each record or block normally contains a preamble in each track to synchronize the clock. Block or record identification information is also provided. The block can periodically include special synchronizing characters, which cannot be found in normal data, to resynchronize the read clock to the data after a long dropout. The block or record ends with a postamble. A cyclic redundancy check is usually included for error detection, and additional redundancy for error correction can also be used.

TRACK ORGANIZATION

A byte-wide parallel format simultaneously writes an entire character on multiple tape tracks. More tape tracks than the original number of bits in each byte provide redundancy for error detection and correction. The byte-wide format is used in most high-performance computer tape drives. For many years, a 6-bit (64-character) byte was used. An additional parity bit per byte was added by the tape machine for error detection, which resulted in a 7-track tape format. In 1964, an 8-bit (256-character) byte was adopted. The high-performance tape drives changed to a 9-track format, which included 8 data bits plus an error control bit.

A parallel format does not always write a single byte at a time. The data bits can be combined in many different ways, so any number of tape tracks is feasible (theoretically). For example, the IBM 3480 tape drive uses an 18-track format with 8-bit data bytes. The data are applied to 14 tracks, and 4 tracks contain the error-correction redundancy information. In this case, each data byte is written along the length of the track, and 14 data bytes are simultaneously written.

Tape interchange between drives can cause tracking differences that can result in detrimental adjacent track interference. This problem is solved with unused areas between tracks called **guard bands**. The tape is completely erased by a dc magnetic field. The written track is narrower than the track pitch (center-to-center distance) to provide an erased **write guard band** between tracks. Separate read and write head elements are normally used. The read element is narrower than the write element to provide a **read guard band**. Write-head **fringing fields** record a wider track than the head-track width, and read-head **side sensitivity** can increase the effective read track width beyond the actual head width. The combination of write and read guard bands eliminates, or greatly reduces, the in-band off-track noise due to tracking errors. In addition to the write and read guard bands, there is an **edge guard band**. Data reliability on the edge tracks is almost always poorer than on the center tracks. The outer tracks are usually spaced as far away from the tape edges as is practical to reduce the number of data errors due to edge debris. Tape utilization is reduced by the guard bands.

Rotary-head machines position the head from a servo track. This positioning reduces the write guard band to accommodate the write fringing field and servo error only. The read guard band is also smaller than for a fixed- or indexed-head machine. As a result, rotary-head tape utilization is better than for a fixed-head machine, as discussed by Nakajima and Odaka [ref.38].

TAPE DENSITY

High information density is desired for computer tape to provide high data capacity, low storage cost, good volumetric efficiency, and high data rate. Different densities are associated with computer tape, and the designations are not always consistent. Therefore, we will define the terminology used in this report. **Track density** is the number of data and redundant tracks in a unit of distance normal to the track direction. **Recording density** is the maximum number of modulated flux reversals that can be contained in a unit of track length. **Linear density** is the maximum number of data bits in a unit of track length. **Recording ratio** is the ratio of information bits to flux reversals. Recording ratio can be more than, equal to, or less than unity. **Modulation density** is the number of modulation code cells or binits per unit of track length; it determines the read clock speed. Users are interested in the linear-data byte density, which is specified in the product advertising literature. All redundant bits are ignored for this **data density**. **Areal density** is the maximum number of information bits per unit area. Symbolically,

$D_l = D_r\ R_r$ = linear density (bits/mm)

$D_a = D_t\ D_l = D_t\ D_r\ R_r$ = areal density (total bits/mm²)

$D_m = D_l/R_m = D_r\ R_r/R_m$ = modulation density (binits/mm)

$D_d = (1-Q)(D_a\ w_t)/N_b$ = data density (data bytes/mm)

where

D_r = recording density (flux reversals/mm)

R_r = recording ratio (information bits/flux reversals)

D_t = track density (tracks/mm)

R_m = modulation code rate (input bits/output binits)

Q = redundancy (overhead bits/total bits)

w_t = tape width (mm)

N_b = number of bits per byte (typically 8)

Areal density has three components—track density, recording density, and the number of information bits per flux reversal, R_r. A flux reversal can carry more than a single bit of information if there are multiple possible locations where the transition can occur, as with some modulation codes.

Historically, track density did not increase rapidly due to the requirement for downward compatibility of data interchange and archive applications. Data-density increases resulted primarily from higher recording densities, as shown in Figure 6 on page 22. In 1966, the reduced modulation rate was required for self-clocking purposes; previous machines used a simple modulation technique from which individual track clocks cannot be recovered. This modulation, usually called **NRZI**, reverses the magnetization direction for each one but does nothing for a zero. A long sequence of zeros results in no readback signal. At low densities, the data clock is recovered from other tracks but, at high densities, this is not practical due to track-to-track skew.

Ship date	IBM type	D_t	D_r	R_m	D_l	D_a	D_d
1953	726	0.55	3.93	1.00	3.93	2.17	3.93
1955	727	0.55	7.87	1.00	7.87	4.34	7.87
1958	729	0.55	21.87	1.00	21.87	12.05	21.87
1962	729	0.55	31.50	1.00	31.50	17.36	31.50
1964	2401	0.71	31.50	1.00	31.50	22.32	31.50
1966	2401	0.71	125.98	0.50	63.00	44.64	62.99
1973	3420	0.71	351.52	0.80	281.20	199.29	246.06
1985	3480	1.42	972.00	0.89	864.00	1224.57	1512.00
Net density increase for 1953–1985		2.57	246.90	0.89	219.40	564.30	384.00
Note: N_b = 6-bit byte for the IBM 726 to the IBM 729 = 8-bit byte for the IBM 2401 to the IBM 3480							

Figure 6. Net Density Increase for Half-Inch Computer Tape

TAPE UTILIZATION

The ratio of tape surface actually used for information storage to the total tape surface area, including the "wasted" area devoted to guard bands and redundancy, is surprisingly low. The losses include three major components—transverse, longitudinal, and interblock gap utilizations. Transverse and longitudinal components are not appropriate terms for a rotary head device that records diagonally or across the tape, but the concept is valid.

Transverse-format efficiency is the ratio of the sum of recorded data-track widths to total tape width; it varies from 58–78% for typical computer tape devices, if we disregard read guard band losses. The wider tapes, and those with redundant tracks for error-control purposes, have the poorest transverse utilizations.

Longitudinal utilization, which is the ratio of data bits (redundant bits excluded) along a track to the total recorded bits, can be poor for small data blocks. For example, the 6250 BPI half-inch tape format, which is commonly used for data interchange, encodes 7 data bits into 10 binits along the tape length for modulation and error control codes. A 20-bit resynchronization burst is required for every 1106 data bits along each track. Thus, the minimum value of redundancy, Q (on a long record), is 0.32. In addition, the preamble and postamble each contain 80 bytes. The interblock gap is nominally 7.6 mm (or 8.3 mm if the preamble and postamble are considered with the gap). The interblock gap ranges from 7.1 mm to 4.6 m in length, as discussed in ANSI [ref.39].

On short records, the longitudinal tape utilization is poor due to preamble, postamble, and interblock gaps, as shown in Figure 7. The gap loss decreases for large blocks, and is usually insignificant for 10-25 Kb blocks, depending upon data density.

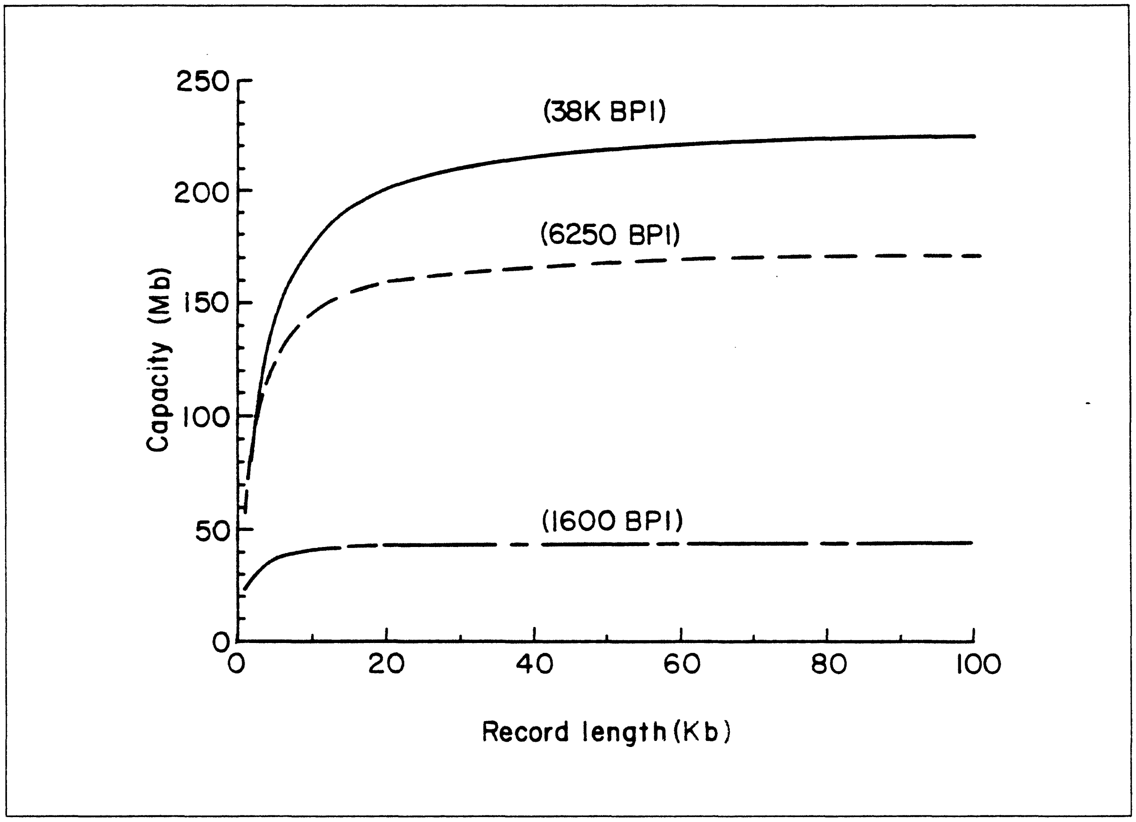

Figure 7. Capacity versus Record Length or Block Size

The trend toward more capacity on smaller tapes is usually accomplished by increasing density. Tape utilization or format efficiency should not be overlooked as an alternative method for increasing the overall information density on computer tape.

DATA RELIABILITY

Data reliability is a key requirement for a computer tape system. It is usually defined as the mean number of data bytes between permanent errors. Reliability depends upon the raw error-rate and error-correction capability. The raw error rate is the mean number of data bits between error events. An error event can involve a few bits (**random error**), or it can be a **burst error** containing as many as hundreds of error bits. After demodulation, even a single binit error frequently causes several data bits to be in error. The error event can involve a single data track or multiple tracks. Many of the bits in an error event are correct; the end of the error event can be defined as the end of a short record or data block. In the case of long records, an arbitrary number of good bits sometimes defines the end of the raw error. Typically, 64 or 128 sequential good bits indicate the end of the error event.

Computer data rate, system size, and system use influence the need for data reliability; users are often more sensitive to the mean time between errors than the mean bytes to error. A large computer installation with numerous high-speed tape drives requires a higher data reliability than a small computer system with a single, low-speed tape device.

ERROR PREVENTION

A tape recording channel is expected to make occasional errors. A raw reliability of 10^6 to 10^8 bits per error event is not unusual. The reliability of the signal directly from the tape is seldom satisfactory except for low-cost, low-speed, low-density applications. Some improvement in the raw error rate is usually needed. Even if error correction is used, the raw reliability should be as high as possible to minimize the error-correction complexity.

Error prevention starts with the design of a recording channel that is error free during most signal anomalies. It must read severe dropouts and not be affected by interference, such as electrostatic discharges, which can occur during normal operation. Tape interchange, tape or head wear, and environmental changes alter the channel response, but must be accommodated.

Error prevention also eliminates dropouts from the active recorded area. This is accomplished with a read-after-write operation that verifies the accuracy of the recorded information. Detection of a **write error** (a read error during the write operation) causes the incorrect record or block to be rewritten until it is correctly verified. A **temporary write error** can be rewritten on the same section of tape. A **permanent write error** must be rewritten farther down the tape due to multiple unsuccessful attempts to write at the original location. This tape move is called a **write skip**. A streaming device is slow to perform the stop/backup/rewrite operation.

The write-verify operation reduces the write throughput due to retries and skips. Because it can greatly improve raw reliability on a poor tape, most high-performance computer tape devices include the write-verification feature. Even with good error-prevention techniques, the raw reliability frequently does not meet the customer's requirements.

ERROR CORRECTION, DETECTION, AND RECOVERY

Intermediate- and high-performance tape devices include error correction to improve data reliability. A high-performance machine can encounter several raw errors each second. Errors must be corrected on-the-fly, or performance is seriously degraded. A low-speed machine does not encounter errors so often so the host computer can correct the error with software.

Several error-correction techniques were used with magnetic tape. As speeds and data reliability requirements increase, even better error-correction techniques will be required. A high-performance tape system can typically improve data reliability by four to seven orders of magnitude with an error-correction code.

Error correction requires the addition of redundant bits or bytes that reduce the effective tape utilization. A 30% increase in recorded bits improves data reliability by seven orders of magnitude, which is a good payback. In addition to redundancy, on-the-fly error correction requires additional hardware to encode and decode the recorded information. The limitation on error-correction power is usually hardware cost rather than redundancy. Computer tape devices could be designed to operate at higher densities, which results in poorer raw reliability, if the error-correction cost was not prohibitive. Fortunately, logic-circuit speed continually increases and cost decreases, which allows enlarged error-correction power at an affordable cost.

Tape machines often operate 24 hours a day and seven days a week. At 3 Mb/sec, a single tape drive can read over 10^{12} bytes per week. Multiple tape devices in simultaneous operation can have a data throughput of tens of Mb/sec. A large tape installation can process many Gb of data per day. The data reliability must be high.

A large defect on tape cannot be corrected by the error-correcting code. The computer system must be notified of this occurrence by some form of foolproof error detection with redundancy. Neither the redundancy nor the hardware cost is large for this requirement.

An error that is not corrected on-the-fly by the error-correction code is identified by the error-detection circuits. This method initiates an error-recovery procedure whereby the tape is usually reread several times if necessary. This "shoeshining" operation will dislodge loosely adhered debris from the tape surface. If the tape can be correctly read during the retries, the error is classified as a **temporary read error**. If the head position can be altered relative to the written tape track, this repositioning can be attempted during the retries. If the error persists through a specified number of retries, it is a **permanent read error**. The recovery of permanent read errors is usually difficult. Sometimes the tape is tried on a different machine. If this method fails, the data can need regeneration. Obviously, regeneration cannot occur often. Fortunately, the combination of error prevention, correction, detection, and recovery can eliminate most permanent read errors. The requirement for data reliability constantly increases so economical methods are needed to achieve the desired results for each new generation of tape device. Fortunately, advancing technologies will permit higher data densities and data reliabilities for several more generations of computer tape devices.

SUMMARY

Computer tape recorders provide the most economical means for storing large quantities of online data. Other technologies can challenge tape with attributes such as areal density or random access, but it is doubtful that any other technology will provide lower-cost data storage during this century. Tape can compete well in terms of data rate and volumetric efficiency as well as cost.

Significant technical progress was made in tape and tape drives since the introduction of the first machine in the early 1950s. Several more generations of improvements are available to the magnetic tape industry. Data storage costs can decrease to about S1/Gb by the end of the century. Data rates of about 20–50 Mb/sec are achievable if needed. Data reliability will approach the reliability of the circuits that perform the error correction.

Yet, with all of these improvements, the basic components of a magnetic tape recorder remain similar—tape, electromagnetic transducers, relative motion, and signal-processing circuits.

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