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High Performance Quarter-Inch Cartridge Tape Systems

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The Industry

More Quarter-inch Cartridge (QIC) tape drives are sold than all other data tape recorders combined.[1] By the end of 1993, the installed base will be over ten million units. In terms of unit volume, QIC tape drives are second only to consumer video systems, although that separation is measured by orders of magnitude. A comparison of estimated volumes of data systems shipped in 1993 is shown in Figure 1. QIC's unique self-contained tape transport and guidance system within the cartridge allows for low-cost, highly reliable, small form factor transports which meet the needs of small to medium computer systems such as the IBM AS/400, workstations and personal computers. QIC systems provide solutions for computer systems which require the back-up of a few hundred megabytes of data for less than $200 (single user) in the 3.5 inch form factor Mini-Data Cartridge to 5 gigabytes of data for under $2000 (less than $1000 in large OEM quantities) in the 5.25 inch form factor Standard Data Cartridge. The proliferation of 100+ MByte disk drives in PCs is driving a large increase in the penetration of Mini-cartridge tape drives as the back-up storage device of choice.

In the workstation, LAN server, and small-to-medium computer system, however, 4 mm and 8 mm helical scan devices have made significant inroads on the larger capacity Standard Data Cartridge. In the past few years, their sales growth has been flat and is predicted to decline slightly in the next few years. Helical scan systems have been able to provide large multi-gigabyte storage capability in the $2000-$5000 range, suitable for unattended back-up for small-to-large systems. Two years ago helical scan solutions were able to offer 10X storage capacity for a 2X-4X price over the top-of-the-line Data Cartridge systems. This capacity difference is shrinking as new technologies are introduced into Data Cartridge systems. Today, the capacity ratio is 2:1 with the introduction of the five gigabyte (5 GB) systems by several QIC drive manufacturers. With the next generation, the Standard Data Cartridge will exceed its 8 mm rival in capacity while maintaining its lower cost advamtage.

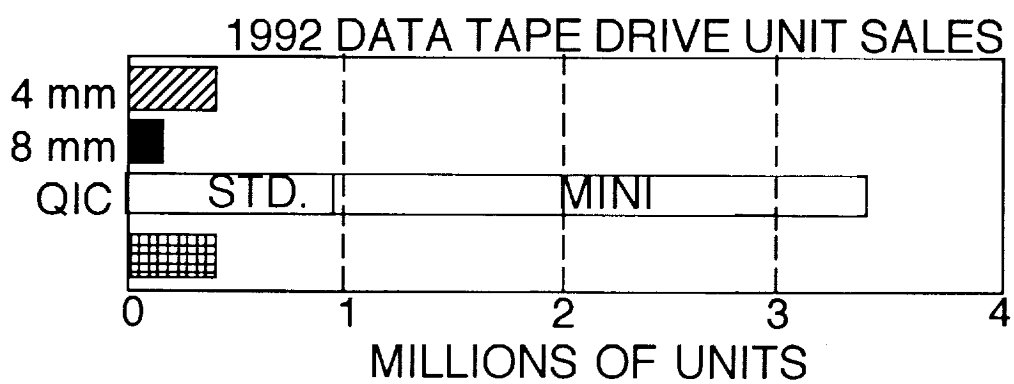

Figure 1. 1992 Tape Drive Sales

Quest for 1 Gbit/in^2

The migration path of the Data Cartridge Technology, DCT, to higher areal density and, hence, higher capacity is shown in Figure 2. Data Cartridge Technology shares the National Industry Consortium's (NSIC) goal for tape of achieving an areal density of one 10^9 bits per square inch (1 Gb/in^2). The diagonals correspond to lines of constant areal density. For reference, the published path of 4 mm helical scan . The 10 Gb/in^2 NSIC target for rigid disks along with its present achievements is also shown. The usable range along the 1 GB/in^2 is bounded by the maximum demonstrated bit density recording, approximately 500,000 transitions per inch (500 kfci or 20000 fcmm), and the maximum demonstrated rigid disk track density of almost 10,000 tracks/in (400 trks/mm). Given the issues of tolerances and media substrate instability, it is expected that for tape, the track density will be in the range of 3000 to 4000 tracks per inch. To achieve 1 Gb/in^2 the corresponding bit density will need to be 250 kbpi to 333 kbpi. Current QIC technology under development and due as products in 1994 is the 13GB generation. Its predecessors, the 1.35GB generation and its derivatives are already in production. Future technology generations code named "Hawk", "Condor", and "Eagle" represent areal densities of approximately .150, .500, and 1.000 Gbit/in^2, respectively.

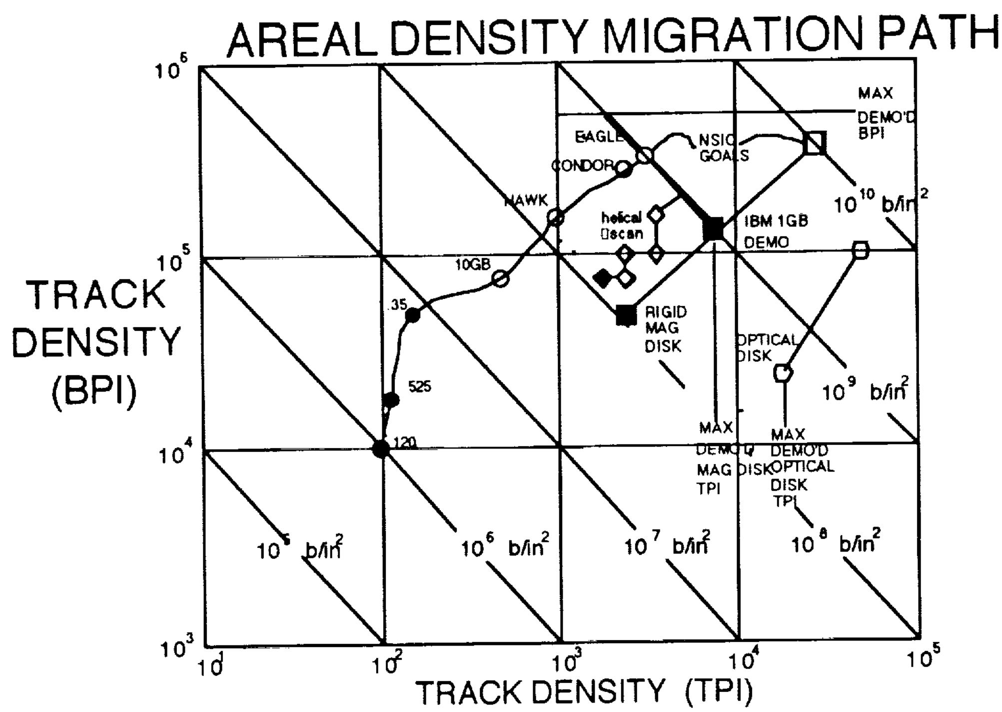

Figure 2. QIC Areal Density Migration Path

The areal density curve in Figure 2 is nearly vertical from the QIC 150 drives to the 1.35GB generation. In that period, nearly all the increase in areal density is the result of increases in bit density. Bit density increases have been made possible, primarily, by increasing the coercivity of the media and changing the data modulation code to provide more data bits per flux transition in the media. The horizontal break in the curve between the 1.35GB and the 13GB technology families has come about by the introduction of track following servo systems and thinfilm magnetoresistive, MR, heads. The plan is then to progress with increases in both track and bit densities towards the "Eagle" generation goals.

The quest for areal density is reflected in Figure 2. The real measure, however, is the increase in capacity. This is more difficult to predict because of the increasing length (area) of the tape. The media substrate thickness, which plays a dominant role in the tape length, has been plunging. It has decreased from 25 microns in the IBM 3480 tape to about 6 microns (.00025 inch) for the current generation. New substrate materials such as Polybenzoxazole, PBO, may make it possible to achieve thicknesses of 1-2 microns. The length of tape has increased from 760 feet in the 1.35 GB system to 1200 feet for the 13GB family. Future capabilities for the 5.25" Standard Data Cartridge and the 3.5" Mini-data Cartridge are illustrated in Figure 3 as bands reflecting potential tape lengths. Because of this variation and other modifications to the areal density, the advanced technology generations have been identified by code names rather than capacity or areal density designations. The Mini-data Cartridge holds about 30 percent of the tape length of the Standard Data Cartridge.

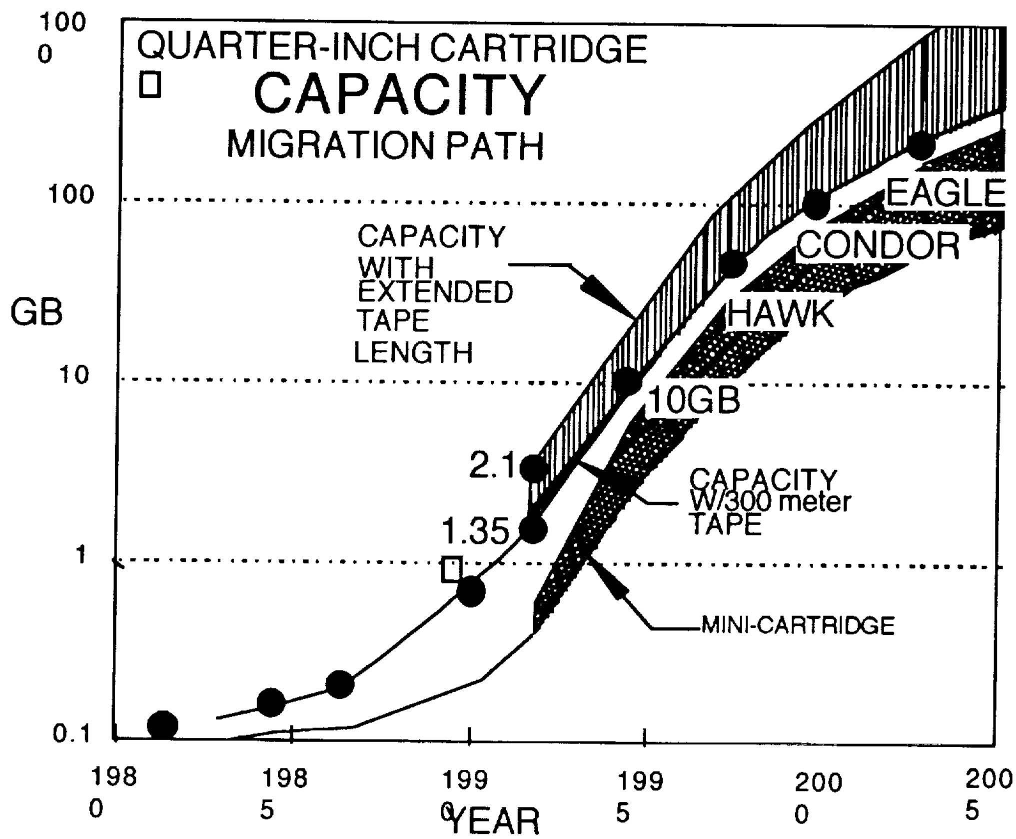

Figure 3. Data Cartridge Capacity Growth.

New Technologies

New technologies in the following areas will fuel the capacity growth in the current development and future Data Cartridges:

Heads
Servo
Encoding
Media

It is planned to introduce one or two major technology advances in each new generation. In this way, the absorption of technology is reasonable and yet, the growth in areal density and capacity is strong and sustainable. The specific key technologies for each generation are shown in Table 1.

Table 1. Key Generational Technologies

Technology Family	**New Technologies**
1.35GB	900 Oe Co-Fe_2O_3 Media 1,7 RLL Encoding
13GB	MR Thinfilm Heads Track following servos
Hawk	Barium Ferrite (BaFe) Media Partial Reponse Encoding
Condor	ME Media/Advanced BaFe Media Ultra-Thin substrate
Eagle	Perpendicular Recording Media Perpendicular Recording/playback Heads

From this list the critical technologies that differentiate linear scan Data Cartridges from helical scan systems are MR heads and track following servos. The other technologies are equally applicable to both philosophies. The DCT track following servo allows it to approach helical scan in track density by reducing the difference from an almost 20:1 factor down to about a 1.3:1 factor. The MR head allows the Data Cart to achieve very high data rates inexpensively through multiple data channels and operate over wide speed ranges, unlike inductive heads, since its output signal voltage is speed insensitive. Because the MR head is DC powered and is built as a planar array, it does not lend itself to multi-element azimuth recording or operation through transformer coupled systems. It is unlikely that MR heads will be incorporated into helical scan systems.

Head Technology

The thinfilm MR head being introduced in the 13GB generation represents a quantum jump in technology and capability. It allows the system to be approached differently than with conventional inductive heads. This head senses dF/dx versus dF/dt. Hence, its output is the same, barring any separation losses, from 0.1 inch/sec to 2000+ inches/sec. It is also a much more sensitive transducer, producing approximately 1000 microvolts, uV, per mil, .001 inch, of head width versus 100 uV/mil for an inductive head when the latter is optimized for the head-to-media speed at which it is intended to operate. An inductive head output, e_o, is compromised by its maximum operating frequency, f_{max}, which is limited the number of turns, N.

$$f_{max} \sim 1/N^2$$

$$e_o \sim M_r \cdot t \cdot N \cdot W \cdot v$$

N	is the number of turns
M_r	Remanent Magnetization of the Media
t	effective recording depth
v	is the head-to-media velocity
W	is the read track width

Running at a sub-optimal speed, i.e. multi-speed drives, results in an even greater difference between the output of inductive and MR heads. The much greater output of the MR head results in a system performance that is dominated by the magnetic medium's signal-to-noise-ratio, SNR, rather than the system noise. Hence, the raw signal output from the medium is less important than its intrinsic SNR. The configuration of the 13GB head is illustrated in Figure 4.

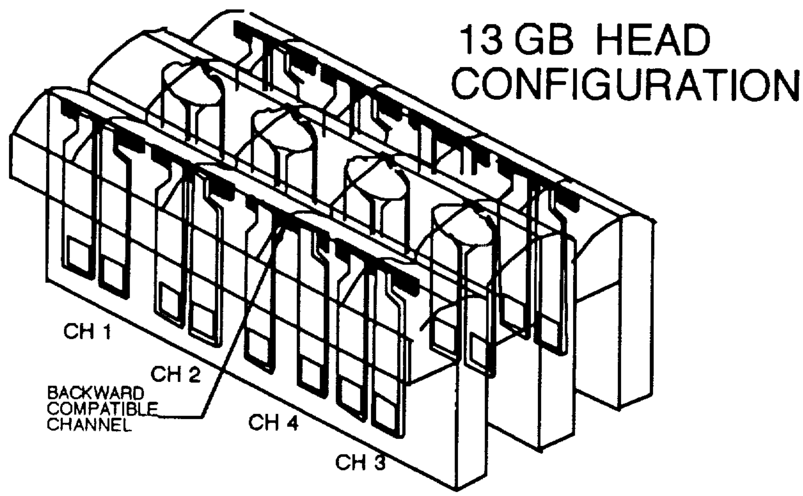

Figure 4. 13GB Head Configuration

The head contains three "13GB" data channels, capable of read-while-write for tape motion in either direction, arranged in an asymmetrical 2:1 spacing separation. Two channels are used for data and the third is used to read servo data. The functions of the channels are alternated between servo and data as shown in Figure 5 to minimize both the number of elements and the overhead for the servo band. Only 14 percent of the tape surface is devoted to servo information in this configuration. Two servo bands are required, as long term tape substrate instability of the current PET media and current head manufacture/assembly tolerances would cause excessive misregistration of the outermost head because of the additional separation if only one servo band were utilized.

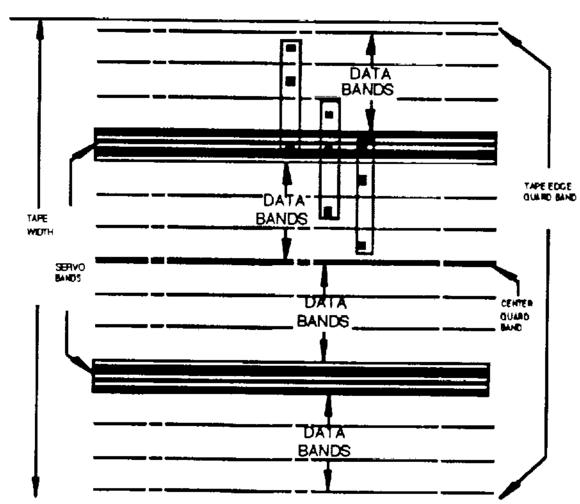

Figure 5. Servo Band and Head Configuration

In the wider separation region between the two 13GB channels, a 1.35GB compatible channel is inserted. This provides backward compatibility for several generations of systems, allowing old tapes as far back as QIC-24 (60 MBytes) to be readable in this system.

Track-Following Servo

As previously illustrated in Figure 2, the track density for Data Cartridges has been limited to about 150 tracks per inch by tape tracking and distortion in the cartridge. The non-repeatability in track has both a quasi-static component associated with the direction of the tape motion and a dynamic component resulting from the composite of rotating parts. The 13GB system incorporates a full-time tracking system. The tape is divided into two servo bands to reduce the effect of tape distortion due to time variations in temperature, humidity, tension, and creep. The servo pattern and resultant "on track" signal are illustrated in Figure 6.

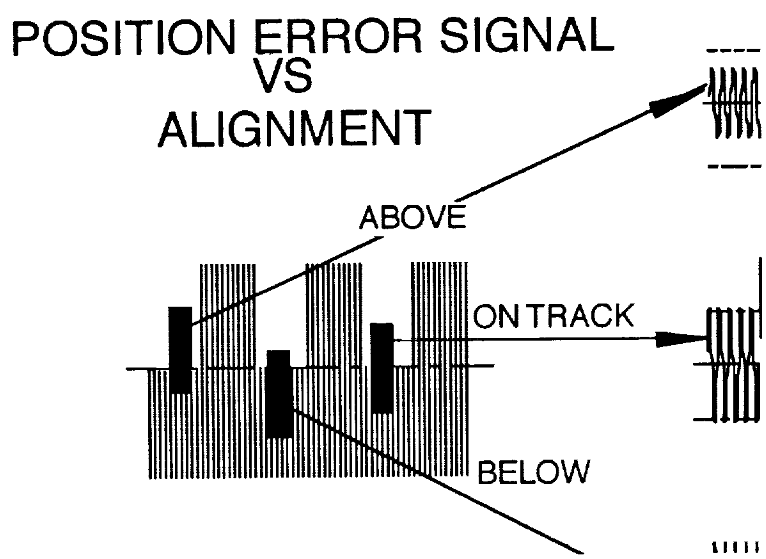

Figure 6. Servo Pattern and "On-Track" Position Error Signal

In the "on-track" condition, the "B" signal is 50 percent of the reference "A" signal. The system has allowed the tracking error to be reduced from .001 inch (1000 microinches) to 30 microinches. The number of data tracks has been increased from 30 in the 1.35GB to 144 in the 13GB drive. The latter is the equivalent of about 750 tracks per inch (tpi). This track density breakthrough is illustrated in Figure 7. Azimuth recording used in helical scan still allows an extra 30 to 40 percent in track density but, is inefficient in other ways such that its future areal density advantage is only 15 to 25 percent.

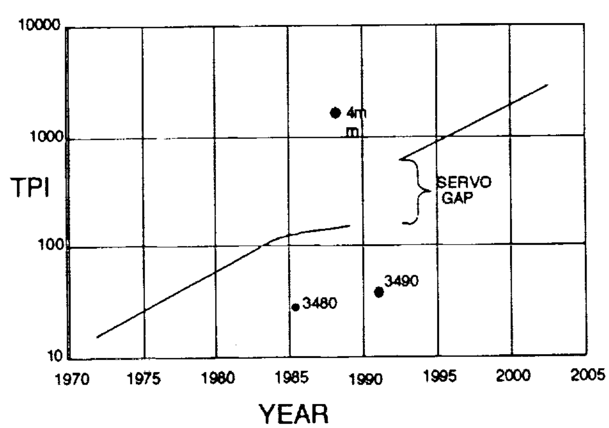

Figure 7. Data Cartridge Track Density Migration Path

Data Encoding

The path for data encoding for Data Cartridges has generally followed that of rigid disk drives. Historically, the codes employed were MFM, 4/5 GCR, 1,7 RLL. In the near future, a form of Partial Response may be employed. The 2,7 RLL disk drive code was not incorporated because of its much smaller clocking window which is incompatible with the poorer time base instability (jitter) of tape. These codes and their data bit to transition on the tape efficiency are shown in table 2.

Table 2. Data Encoding

Type	Efficiency
MFM	0.5
4/5 GCR	0.8
1,7 RLL	1.33
2,7 RLL	1.5
Partial Reponse	1.5 - 2.0

Partial Response encoding is the first non-peak detecting system. It operates by sampling the waveform and determining from a sequence of sampled amplitudes what the signal was. It has several variants (PR4, EPR4, and E^2PR4) .These are differentiated by the number of times the waveform is sampled. The most effective configuration is highly dependent on the system characteristics. For a given error rate, the efficiency ranges from 0.9 to 2.0 Disk drives utilizing thinfilm inductive heads have not achieved efficiencies much beyond 1.6-1.7 because of anomalies in their isolated pulse reponse characteristics. The MR head, however, gives the smoother, more classical response, of a conventional ferrite head and efficiencies approaching 2.0 are anticipated. This technology change will have the least impact on increasing the capacity.

Media

For all forms of magnetic recording, the magnetic medium is the key ingredient in propelling increases in areal density. The most important characteristics of tape medium are its magnetic properties and its surface finish. The surface roughness, which is semi-independent of the magnetic characteristics, impacts head-to-media separation, hence, output and density response. Its other key characteristic is "defects" which cause drop-outs in the signal resulting in errors.

13GB generation of Data Cartridges employ the standard SVHS 900 Oe cobalt doped iron oxide ($Co\text{-}Fe_2O_3$) particle which was also employed for the 1.35GB generation. It was selected at that time because of its superior environmental stability, availability, and noise characteristics relative to metal particles (MP). Since then, improved passivation has greatly reduced the corrosion concern for MP. Future generations will require new media. It is anticipated that either a super-fine MP or BaFe particle will be used. While metal-evaporated, ME, media such as NiCo or CoCr hold out the promise of the higher performance required for future systems, the issues of sufficient durability and chemical stability to meet long term data storage requirements have yet to be demonstratedfor these media. Progress has been reported and, perhaps, ME media will be ready by the very late 1990's.

MR heads with their much greater sensitivity have altered the prioritization of characteristics for magnetic media. Where the system noise dominates the SNR, such as with inductive heads with a few hundred microvolts of signal or less, the output from the tape is paramount. Among the particulate media, MP has the highest magnetic moment, hence, the highest output. ME films offer even higher outputs. In Data Cartridges, where MR heads are utilized, however, the medium's SNR dominates the overall system SNR. Here particle size, packing density, and uniformity of dispersion are the most important characteristics. Based on the data cell size for the projected track and transition densities for current and future generations and assuming an effective recording depth of one fourth (1/4) the minimum spacing between transitions, the calculated SNR is shown for each of the media in Figure 8. The high performance "HDTV" MP particle is assumed to be .01 micron (um) in diameter by 0.1 um long with an .005 um thick passivation layer. In all cases it is assumed that a 50 percent by volume fractional packing density is used since this is dependent on the process capability of the manufacturer. This is optimistic for Co-Fe_2O_3 and MP which are typically closer to 40 percent and pessimistic for BaFe which is closer to 60 percent. Both NiCo and CoCr ME media are also compared. Here the SNR is derived based on the surface granularization. The NiCo is assumed to have magnetic domains with an approximated dimension of 300 angstroms (1.2 microinch) and the CoCr to have hexagonal crystals of 150 angstroms in diameter.

The SNR in Figure 8 is calculated. Practical experience indicates that the actual SNR will be about 6 dB lower. This can be attributed to head-to-media separation, surface roughness, non-uniform distribution, etc. Figure 8 does give the relative SNR, however. The required SNR to for a raw error rate needed for a 10^{-15} corrected error rate (error bursts between bits) in conjunction with other system parameters is approximately 27 dB. 900 Oe Co-Fe_2O_3 is adequate for both the 1.35GB and the 13GB generations. A new medium is required for the Hawk generation. This is likely to be BaFe whose calculated SNR is 3-6 dB greater than that projected for MP. The additional advantage resulting from dual layer coating may allow BaFe to suffice for both the Hawk and Condor generations.

Use of particulate media is very desirable in that it provides substantial cost savings over sputtered or evaporated metal film media. ME media is expensive because of both the cost of the equipment and the overall throughput of that equipment. Vacuum deposition equipment is both expensive initially, requires a significant amount of downtime for maintenance, and has coating speed rates in the hundreds of feet per minute instead of thousands of feet per minute for particulate coaters.

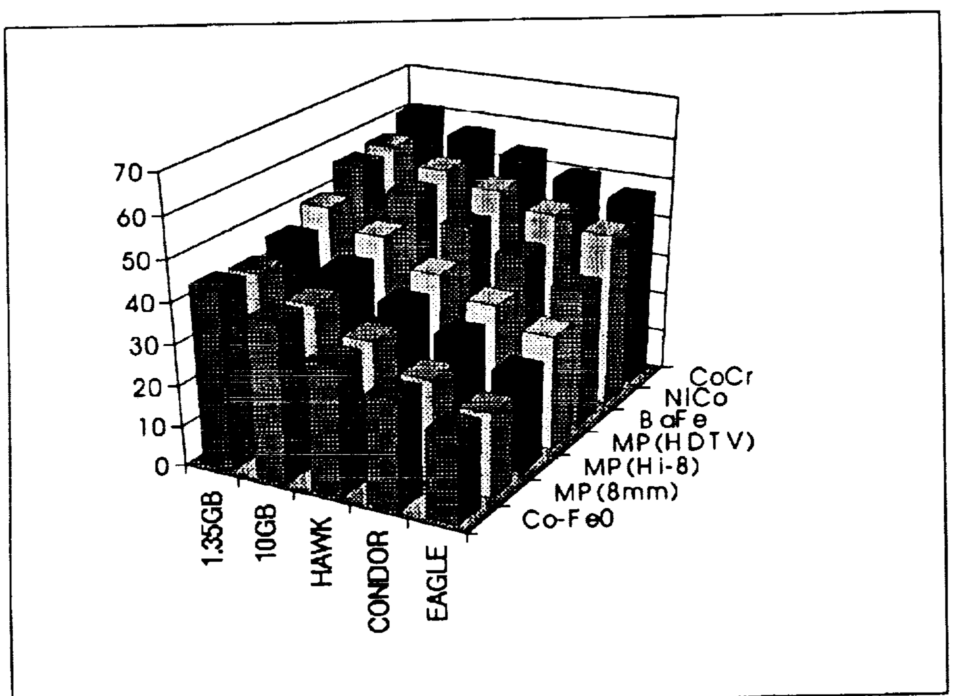

Figure 8. SNR for Various Media

The transition to ME media would appear necessary for the Condor technology generation (approximately 500 Mb/in^2). However, Fuji has demonstrated dual layer media in which a smooth thin 0.2-0.5 um layer of MP is coated over a thicker layer of lower coercivity media or a non-magnetic layer with special characteristics such as titanium oxide. Dual coating has the potential of achieving a magnetic layer as thin as 0.1 um. The output of this medium at very high densities approaches within a few dB of that of the ME media with the density response and overwrite characteristics of thinfilm media. Yet, it retains the producibility, lower cost, and tribological characteristics of the current particulate media systems. This thin layer characteristic may reduce one of the more difficult characteristics of BaFe, namely the difficulty in overwriting this very high coercivity (>1500 Oe) material. Hence, the migration to the more expensive ME media may be delayed until after the turn of the century. The construction of such a medium for Data Cartridges is shown in Figure 9.

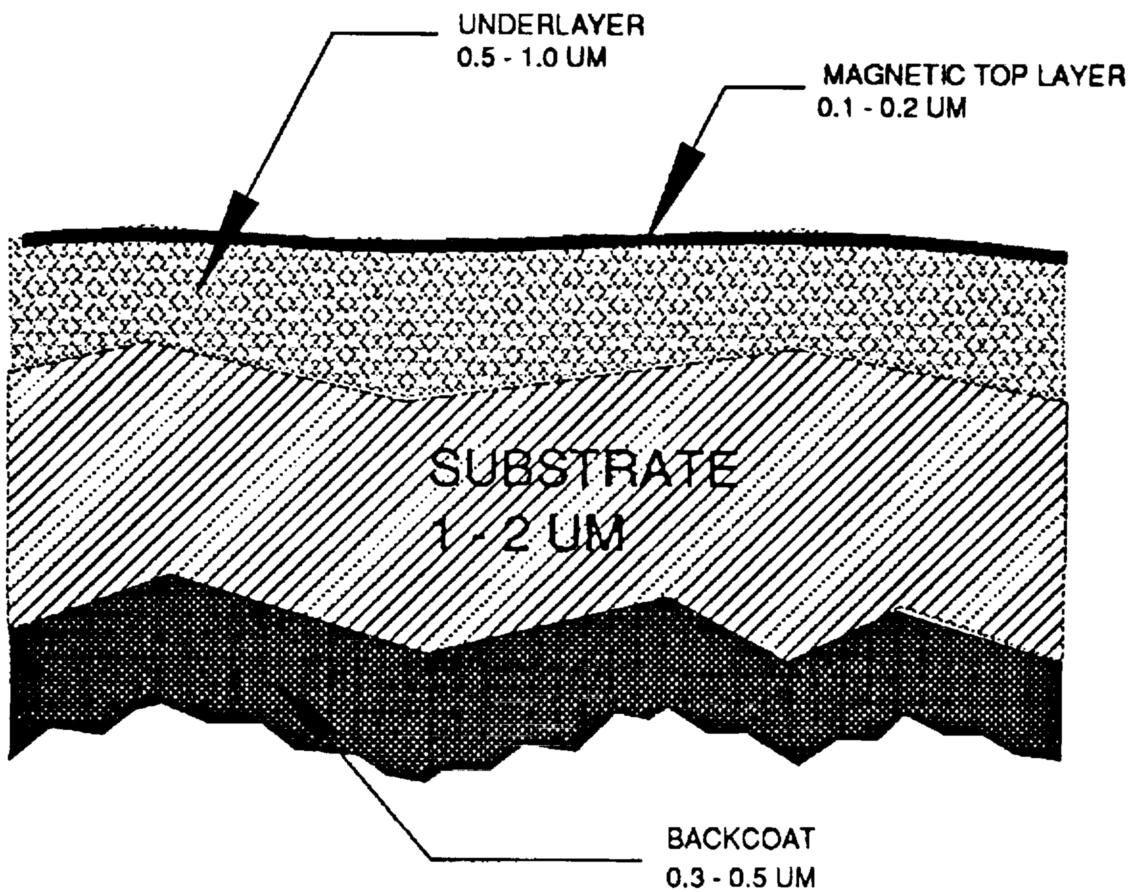

Figure 9. Potential Dual Layer Particulate System

A straightforward method of increasing the capacity is to make the tape longer. This can be achieved by making the magnetic layer, substrate, and backcoat layers thinner. The front and back layers are already quite thin and further reductions will provide little opportunity to lengthen the tape significantly. The current PET and PEN substrates are reaching their mechanical limits as the substrate thickness approaches 4 um. Materials such as the polyaramides or Polybenzoxazole, PBO, offer promise of higher modulus and, in the case of PBO, other improved characteristics. A comparison is shown in Table 3.[2] PBO or a material with similar coefficients of creep and expansion will be necessary for Data Cartridge Technology to reach 3000-4000 tpi.

Table 3. Substrate Characteristics

Characteristic	units	PEN	PET	ARAMID	PBO
Density	g/cm^3	1.395	1.355	1.420	1.54
Melting Temperature	^oC	263	272	350	None
Young's Modulus	kg/mm^2	500-850	650-1400	1000-2000	4922
Tensile Strength	kg/mm^2	25	30	50	56-63
Tensile Elongation	%	150	95	60	1-2
Long Term Heat-Pool Temp	^oC	120	155	180	>300
Heat Shrinkage (200° x 5 min)	%	5-10	1.5	0.1	<0.1
Coeff of Thermal Expansion	$10^{-6}/^oC$	15	13	15	-7
Coeff of Hygroscopic Exp.	$10^{-5}/\%RH$	10	10	18	<1
Moisture Absorption	in/in/% RH	0.4	0.4	1.5	<1

The mechanical strength of PBO may allow the thickness of the substrates to approach 1.0 um. Figure 9 illustrates the effect of total tape caliper on length. It is expected that the magnetic and back coatings will add from 0.6 to 1.5 um to the substrate thickness for total caliper.

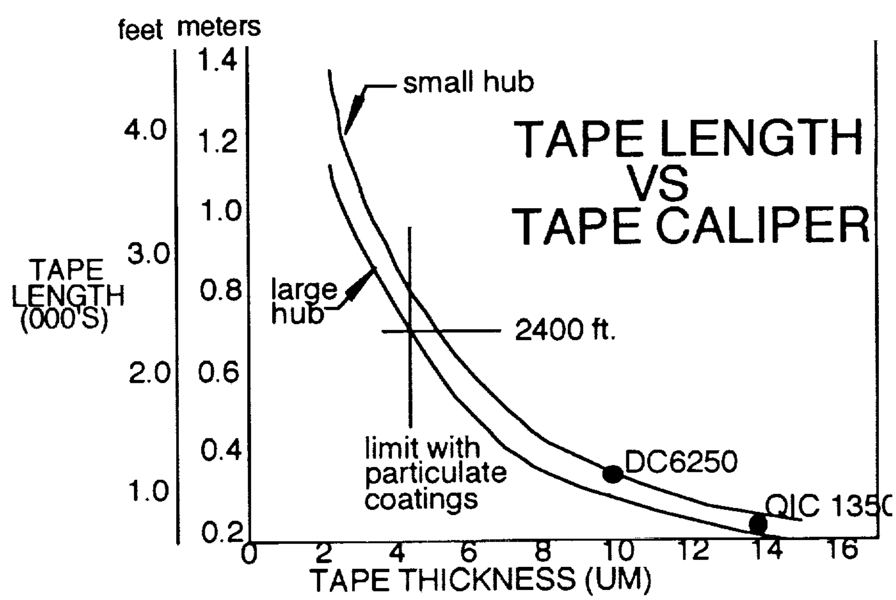

Figure 9. Tape Length versus Caliper for 5.25" Data Cartridge

Other factors such as tape handling, tension variation, achievable substrate roughness, etc. also figure into determining the maximum length achievable.

The Marketplace

In the past, Data Cartridge Technology has carved out a large segment in the PC to medium system marketplaces for back-up and data exchange where the emphasis has been focused on low initial cost and compactness. While retaining these characteristics, the enhanced capacity and potential for high transfer rate opens up new markets. The "Tertiary Storage " market graph by Ann Drapeau from last year's NASA Conference on Mass Storage[3] has been updated with helical scan and Data Cartridge next generation capacity, due in late 1993 or early 1994, in Figure 10.

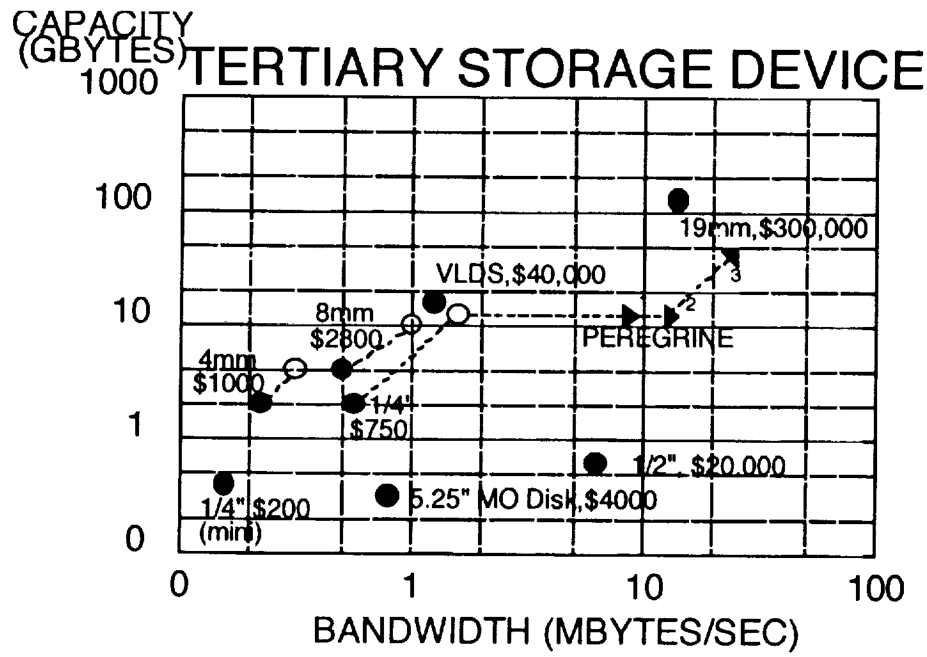

Figure 10. Capacity and Transfer Rates for Assorted Removable Technologies

It should be emphasized that the growth paths for certain technologies are not shown as they have not been announced by their developers. Undoubtedly, they too will be growing in capacity and data rate. The latter, though, is likely to be much slower for helical technologies. Their improvement rates will be primarily paced by the increases in bit density which is similar for all the above technologies with the exception of optical.

High Performance Systems

"Linear Scan" technology such as Data Cartridge Technology offers the opportunity to incorporate many parallel channels at minimum additional drive cost. A 12-channel system compatible with the 13GB cartridge has been proposed. This class of drives is called Peregrine. There are two versions. The first is simply a 12-channel version of the 13GB drive. It increases the maximum data rate from 1.54 MBytes/sec to 9.3 MBytes/sec. A later second version, called Peregrine II, uses an 180 ips 13GB cartridge to achieve a sustained data rate of over 100 Mbits/sec or more precisely, 14.3 MBytes/sec. These are shown as the breakout points in Figure 10. The multi-channel approach is also applicable to the Mini-cartridge. Because of the size of the cartridge, the tape speed is limited to 120 ips. Hence, the maximum data rate for the Mini-cartridge is 9.3 MBytes/sec. The twelve-channel configuration was selected because of its compatibility with the 13GB systems and a feature geometry that is relatively economical to produce. Utilizing only half the width of the tape because of the tape related track distortion, TRTD, the elements are set on a 204 um (.008 inch) pitch. Use of advanced substrate materials and tighter tolerances in the head fabrication may allow future generations to easily expand to 24 channels. It is not anticipated that the channel pitch will be reduced much below 200 um. Multiple gaps might increase this number to 48 channels but, the structure and the termination of the elements would be very complex. One possible configuration of the 12 channel head is shown in Figure 11. Contrasted to the 13GB head in Figure 4, it appears very complex, and even more so when compared to a single-channel head. However, a good analogy can be drawn from the individual transistor and integrated circuits. The fabrication processes and dimensions between IC's and thinfilm heads is quite similar.

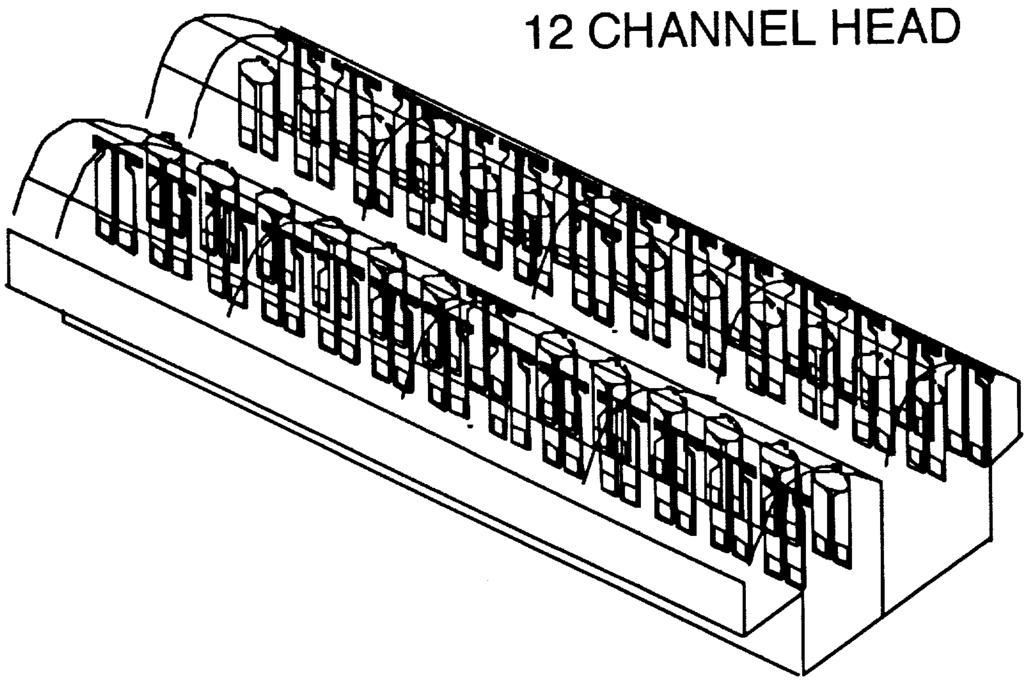

Figure 11. Twelve-Channel Peregrine Head

The Peregrine head is symmetrically divided into two groups of six channels centered about a servo channel. The outermost data channel is no farther away from the tracking servo channel in the Peregrine configuration than it is in the 13GB configuration except for the small delta displacement of one quarter of a 13GB servo band. Hence, the issues of TRTD on the head-to-track misregistration is little worse than in the 13GB. The layout of the Peregrine head to the 13GB head is illustrated in Figure 12.

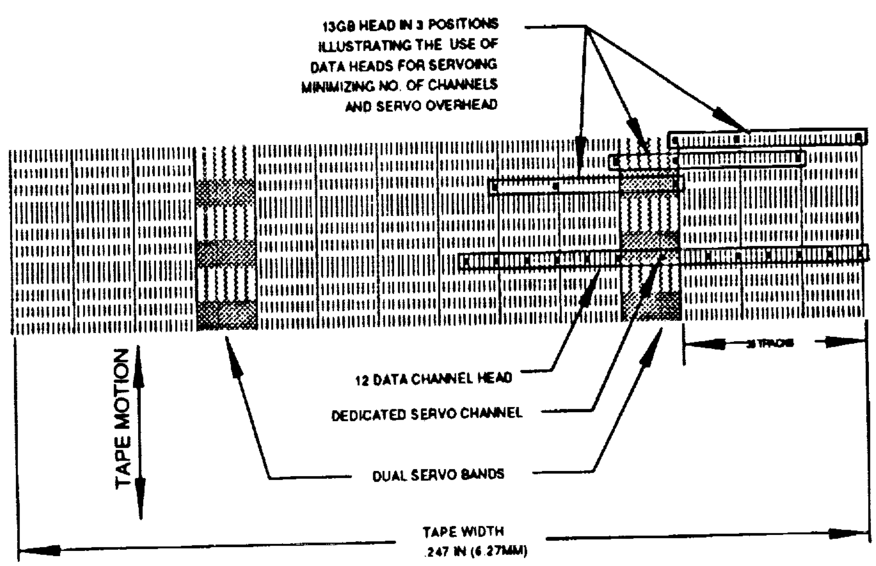

Figure 12. Tape, Peregrine, and 13GB Head Layout

The bit and track configurations for the next generation "Hawk" are fairly well defined at this time. The Peregrine version of that technology will provide over 250 Mbits/sec and 56 Gbytes of data in the maximum configuration. This is illustrated in Figure 10 as the P3 extension. The principal characteristics for the first three members of the Peregrine family are listed in Table 4.

Table 4. Peregrine System Characteristics

Parameter	Peregrine 1	Peregrine 2	Peregrine 3
Technology	13GB	13GB	Hawk
Capacity (GBytes)	13.5	13.5	56
Data Rate (MB/s)	9.3	14.3	31
Data Rate (Mb/s)	76	114	253
No. of Channels	12	12	12
Bit Density (kbpi)	67.733	150	150
Data Tracks	144	144	216
Media	Co-Fe_2O_3	Co-Fe_2O_3	BaFe
Media Speed (ips)	120	180	180
Tape Length (ft)	1200	1200	1500

The progression of Data Cartridge Technology to higher bit density, more channels, and a practical upper limit of tape speed to the region of 200+ ips, should make Data Cartridge systems with 1-2 Gbit/sec data rates readily achievable in the future.

Summary

Within the established low cost structure of Data Cartridge drive technology, it is possible to achieve nearly 1 terrabyte (10^{12}) of data capacity and more than 1 Gbit/sec (>100 Mbytes/sec) transfer rates. The desirability to place this capability within a single cartridge will be determined by the market. The 3.5" or smaller form factor may suffice to serve both the current Data Cartridge market and a high performance segment. In any case, Data Cartridge Technology provides a strong sustainable technology growth path into the 21st century.

1. International Data Corporation
2. National Media Lab Newsletter
3. NASA Conference Publication 3198, Vol. II pg. 203