High Density Hard Disk Drive Trends in the USA

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The United States is a major center for disk drive technology. Feeding the current extraordinary growth in data storage areal density has been the developments in component technology. This explosion in storage capacity has provided a remarkable value for our global information society. As the cost of storage has gone down new non-computer markets have opened up for disk drives and new form factors for mobile markets have appeared. Technically it appears that disk drive areal densities can go well above 100 Gb/in^2. However the lack of profitability in the disk drive and component industries could prevent the capital investments required to achieve these higher areal densities. This has already led to a great deal of consolidation in the drive and component industries. Key developments in heads, media, channel, disk and head actuator motor technologies will be described with projections for the future. We complete this review by projecting three classes of enterprise disk drives developing by 2002 to address different market needs.

Key Words: hard disk, technology trends, head, medium, channel, motors

I. Introduction

The disk drive industry has been a technology "wonder of the world" over the last several years. The rate of technology development, measured in data areal density growth is about twice that of Moore's law for semiconductor transistor density. As a result, disk drives deliver a tremendous value to our global technological civilization. This has resulted in new uses for disk drives in the past few years outside of traditional computer data storage.

The growth of E-commerce and information demands on the Internet has created an explosive growth in storage demand. The companies that make storage systems for the growing Internet and corporate data storage markets have been extremely profitable. Meanwhile the companies that supply the disk drives used in these devices are financially floundering while continuing to deliver outstanding technology at commodity prices.

This article will look at several trends in the hard disk drive industry in the United States including the business trends, technology trends, limitations to the growth of areal density, form factor trends and new uses for disk drives. It will finish with some predictions on disk drive technology and products for the next couple of years.

II. Disk Drive Business Trends

The last year has brought great changes to the hard disk drive industry in the United States. There were several mergers between component and drive suppliers and some component suppliers have gotten out of the drive business or are refocusing their activities to other industries. Maxtor and Quantum's disk drive operations merged. Seagate went from a public to a private company. MMC and Trace merged their disk operations. Komag and HMT merged their disk operations as well. Read-Rite is getting into the optical filter business in addition to its traditional magnetic recording head business. There are rumors that large disk drive players who have long participated in this industry will pull out of disk drive production if they are not soon profitable. The number of major disk drive companies in the United States has dropped to 4 (Seagate, Maxtor, IBM, and Western Digital) and the only remaining head and medium component suppliers based in the United States are Read-Rite and Komag. The remaining component suppliers, in addition to suppliers in Asia (mostly Japan) serve Maxtor, Western Digital and the remaining Japanese and Korean drive companies since IBM and Seagate have a great deal of vertical component integration. Disk drive and component supplier stocks have been at very low levels for the last few years.

What has brought the industry to this state? It is certainly not demand. The total demand for data storage capacity has more than doubled in the last couple of years. The actual number of disk drives sold worldwide has increased by an average of 17% annually over the last three years. At the same time the rate of data areal density growth in shipped disk drive products has been over 100% per year for the past several years. Figure 1 shows areal density history and projected trends for IBM products vs. DRAM[1]. This has resulted in a great increase in capacity per disk so that for the consumer storage market, which handles the largest volume of disk drive sales, the numbers of disks and heads in the drive have declined. Today the most popular drive models have only a single disk with about 20 GB capacity. Thus although the number of drives sold has increased, the demand for disks and heads have decreased. This had a negative impact on the component suppliers and resulted in the closure of many head and disk companies over the last three years.

Another factor in the depressed state of the disk drive industry in the United States is the decline in the average sales price for the drives themselves. Between the first half of 1995 and the last half of 1999 the average price of high-end disk drives dropped from $700 to $300[2]. Figure 2 shows the decrease in the price per MB of storage, showing the dramatic decline in the price of storage over the last three years and comparing it to the cost of competing technologies[1]. This decline in drive price has been even steeper than the decline in the number of disks and heads. The drive price decline has been greater than the decline in costs of the disk drives. The result has been a string of bad operating fiscal quarters for American disk drive manufacturers for the last three years. Finally in 2000, and partly due to the consolidation in the industry and some component shortages, it appears that disk drive prices may be stabilizing and the remaining drive companies are beginning to show profitability.

This dramatic price erosion, in most drive markets, appears to have been due to aggressive price competition between the disk drive companies. Rather than gaining market share by means of this price competition it appears that the drive companies have created a pretty level, but very hard, playing field. Furthermore, the lack of profitability by disk drive companies and their supporting component suppliers will make it very difficult to invest in the capital equipment needed for areal density advancements that have characterized the industry in the past. As a result financial limitations may curb the growth of drive technology long before technical limitations will.

III. Component Trends

Driving the areal density growth of disk drives is the technology development of the drive components. These components include the magnetic recording head and medium, the channel and other drive electronics, the servo and head actuator system, as well as the disk motor. We will look at developments in these component technologies in the United States and how they will contribute to the growth of drive areal density.

Heads and Head Suspension Assemblies

MR heads came to dominate magnetic disk recording in the early 1990's. Since then the technology has evolved considerably and the increasing sensitivity of magneto-resistive heads plays a large part in the overall areal density growth of the magnetic recording industry.

It is probably natural then that the dominant independent head supplier, Read-Rite, has been a key player in areal density demonstrations over the last two years in conjunction with magnetic medium suppliers HMT and Komag. Other American companies also active in recent areal density demonstrations include Seagate and IBM. Table 1 shows the major recording technology demonstrations over the last two years. All except for the 10/2000 Read Rite/Samsung demonstration are with longitudinal recording. Note that Hitachi and Fujitsu have also made major areal density demonstrations in 2000 and earlier but the table only shows USA demonstrations. Also note that the IBM 100 Gb/in2 demonstration is not a true demonstration like the other cases since it was not done under dynamic recording conditions and the read head width was unrealistically wide.

Table 1. **Recording Technology Demonstrations in the United States**

Month/Year	Company	Gb/in^2	kTPI	kBPI	Mb/s	Comments

8/1998[3]	IBM	12	34	350	120	
9/1998[4]	Read-Rite/ Komag/ HMT	13.5	31.3	427	195	
2/1999[3]	Seagate	16	43	380	214	
5/1999[4]	Read-Rite/ Komag/ HMT	20.9	43.5	480	175	
8/1999[4]	Read-Rite/ Komag/ HMT	26.5	52.6	504	230	
10/1999[3]	IBM	35.3	67.3	522	144	
11/1999[4]	Read-Rite/ Komag/ HMT	36	70.4	511	173	
3/2000[3]	Seagate	45	70	640	211	
3/2000[4]	Read-Rite/ Komag/ HMT	50.2	90.9	552	140	
4/2000[5]	Read-Rite/HMT/ Guzik			380	1000	Data Rate Demonstration
9/2000[6]	IBM	103	256	406	NA	FIB Head Write, Read with Wide GMR , static test, 20 Gb/in^2 medium
10/2000[7]	Read-Rite/Samsung	60	80	750	300	Perpendicular Recording
10/2000[8]	Read-Rite/Komag/ HTI	63.2	105.3	600	160	Dual-Stage Actuator

Let's look in greater detail at the data from the Read-Rite/Komag/HMT demonstration of 50.2 Gb/in^2. 747 off-track tests show 18% off-track capability at 90.9 kTPI. Bathtub curves with recording over old data showed better than 10^{-7} bit error rate (BER) at 50.2 Gb/in^2 recording. Focused ion beam (FIB) etching was used to define the narrow head track width needed. The write track width was 0.28 micron, read width was 0.21 micron, medium coercivity (H_c) was 3670 Oe, medium M_rt was 0.43, medium K_uV/kT was 80 and the magnetic recording showed excellent thermal stability (<0.5% per decade). The bit aspect ratio for this demonstration was 6:1[4].

As areal densities increase toward 100 Gb/in^2 and above head technology will continue to evolve. Read transducers will continue to get more sensitive with GMR sensitivities ($\Delta R/R$) up to 15-30% using ever more complex and sophisticated structures[9]. Ultimately even greater sensitivity will be required. The most promising technology for greater sensitivity is TMR (Tunneling Magneto-Resistance) in which the current being sensed flows normal to the plane of the film across a very thin dielectric (oxide) layer. Such a device can have a $\Delta R/R$ up to about 40% allowing good SNR for narrower track widths. It appears that a TMR structure with a low enough resistance requires a very thin aluminum oxide film (<0.7 nm), across which electrons of the proper spin orientation can tunnel [10]. To date it has been difficult to create uniform pore-free aluminum oxide films of this thickness and as a consequence functioning devices of the required resistance have not yet been reported.

Write heads for higher areal densities have their own issues. Creation of the narrow write poles for the high areal density demonstrations have required very slow etching processes such as FIB. These techniques are far too slow and thus too expensive for production heads. Significant improvements in the rapid and inexpensive etching of write poles will be required for production of heads supporting these areal densities.

As the areal density increases there is a tendency to increase the magnetic medium coercivity in order to prevent the onset of magnetic thermal instability that can cause spontaneous magnetic erasure of the medium. Higher media coercivity requires higher moment write pole materials in order to avoid head saturation during writing. Most of the areal density demonstrations have required magnetic coercivities less than 4500 Oe. However if medium coercivities exceed 6000 Oe it will become very difficult to prevent head saturation with all known soft magnetic materials. Writing on such high coercivity material may require hybrid magnetic writing techniques such as thermally assisted writing where a heat source such as a laser is applied to the medium during writing to heat the magnetic material close to the Curie temperature where a reasonable write field can reverse the magnetism and write bits on the medium. Incorporation of laser heating into magnetic recording heads will further complicate the write/read head structure. Another approach for writing and reading high coercivity media is that taken by R. Carley et. al using a single pole head for writing on a perpendicular magnetic recording medium (recorded magnetization of the medium oriented normal to the plane) and an MFM probe with a soft magnetic material for bringing the magnetic fields from the medium down to the MR sensor[11].

As the read head structures are made more sensitive the thickness of the films used decreases and the sensitivity of the head to damage from electrostatic discharge (ESD) becomes greater. Figure 3 shows the trends in ESD sensitivity over the next few years[12]. As the head becomes more sensitive the efforts taken toward elimination of ESD will become more severe. It is likely that head factories of the future will have very little manual operations in order to avoid accidental ESD damage. This will lead to a greater amount of automation in the production of heads and consequently a greater capital expenditure to create such ESD neutral manufacturing facilities.

The October 2000 areal density demonstration by Read-Rite, Komag and Hutchinson involved the use of secondary actuators imbedded in the head suspension. Figure 4 shows the type of dual stage actuator suspensions from Hutchinson Technology that were used in the 63 Gb/in^2 demonstration[13]. Figure 5 indicates that by 2002 leading edge (highest areal density) drive products will require dual stage actuator suspensions and even low end drives will have dual stage actuator suspensions by 2004[12].

Media

As important in achieving higher areal density as the heads are the magnetic recording media. Magnetic recording media faces its own challenges. Chief among these challenges is thermal stability of the magnetic regions, which constitute the recorded information. The thermal stability of magnetic recording media is a function of the anisotropy energy directed along the recording direction, the volume of the grains in the magnetic recording media assuming good magnetic isolation, the demagnetization field in the medium and the ambient temperature. These relationships are summarized in equation (1) for acceptable levels of thermal stability. K_u is the anisotropy energy density, V is the grain volume, k_B is Boltzmann's constant, T is the temperature in Kelvin, H_d is the demagnetizing field and H_k is the anisotropy field.

(1)

$$\frac{K_u V}{k_B T}\left(1-\frac{H_d}{H_k}\right)^2 \geq 60$$

The coercivity of the magnetic recording medium is a function of the anisotropy energy plus the orientation of the magnetic medium if any. A preferred magnetic orientation along the direction of the magnetic recording enhances the thermal stability of the recording. For this reason longitudinal magnetic recording media will probably continue to have very fine circumferential texture lines to create some magnetic orientation along the texture direction even when the head no longer takes off and lands on the magnetic recording media.

The coercivity used in magnetic areal density demonstrations have followed a more or less linear trend from about 3000 Oe at 10 Gb/in^2 to the target NSIC coercivity for 100 Gb/in^2, 5000 Oe[14]. Much higher than this and conventional write head materials saturate before reaching sufficient field to write on the magnetic medium. Beyond 100 Gb/ in^2 hybrid writing techniques such as thermally assisted writing and perpendicular recording described earlier might be used to record on higher coercivity recording media.

Magnetic recording media continues to use cobalt alloys. These alloys are becoming very complex, composed of five or more elements that serve many purposed among which are: control of grain size, prevention of exchange coupling between the grains, increase of magnetocrystalline anisotropy, and corrosion protection. Furthermore these magnetic recording layers may be split into multiple layers to control medium transition noise and magnetic properties through the film thickness or as in the case of the recent synthetic antiferromagnetic media (described later) or earlier keepered media [15] to reduce the effects of thermal decay. Further complicating the production of magnetic recording media are the various under layers serving various purposes such as surface passivation and magnetic layer epitaxial and crystalline topography development. Figure 6 shows a typical magnetic recording medium in 2000 with several magnetic layers and various under layers [16]. On top of the magnetic layers is a carbon layer and a dipped fluorocarbon lubricant layer which protect the magnetic media from wear and to some extent, corrosion.

The signal to noise (SNR) of the reproduced signal is proportional to the number of grains in the recorded region. Thus as the areal density increases the size of the grains must decrease in order to maintain the SNR. However, as the grain size decreases the incidence of thermal decay increases. In order to reduce the grain size to improve SNR without sacrificing thermal stability of the medium the grain size distribution must be made narrower since the smallest grains will be the first to reverse from thermal decay. For this reason a great deal of effort has gone into controlling the grain size distribution of magnetic recording media. Figure 7 shows expectations for the number of grains per bit as the areal density increases as well as the bit aspect ratio (which is the TPI/BPI)[17]. Table 2 shows the result of this effort. As the areal density has increased the mean grain size has decreased and the particle size distribution has narrowed to improve the SNR for smaller bits and to minimize the number of very small grains in the recorded bit [13].

Table 2. **Grain Size Distribution vs. Areal Density**

Areal Density	Mean Diameter (nm)	Standard Deviation/mean
6	14.9	0.32
10	12.7	0.31
16	11.3	0.27
24	10.3	0.24
40	9.3	0.23

Magnetic spacing loss is one of the most important parameters in accomplishing high areal densities since this is an exponential loss factor. Magnetic spacing is the effective distance between the magnetic recording head and medium including such factors as flying height of the head over the disk, recession of the head pole tip, thickness of the diamond like carbon (DLC) film on the head surface and the thickness of the carbon and lubricant overcoats on the disk surface. The thickness of the medium also effectively adds to this magnetic spacing, which is another important reason in keeping the magnetic medium thickness relatively thin (15-25 nm is the common range for thin film medium magnetic layer thickness at this time).

Figure 8[13] shows expected trends for the various sources of magnetic spacing and the resulting total magnetic spacing as a function of areal density out to 100 Gb/in^2. The expectation is that total magnetic spacing will be about 5 nm for 100 Gb/in^2 recording. This requires very tight constraints on overcoats, pole tip recession and head flying height. Because of the financial constraints on disk drive and component companies it is likely that this will be done using incremental upgrades in existing medium sputtering equipment.

At the InterMag conference in May 2000 both Fujitsu and IBM announced the creation of magnetic recording media that had a synthetic antiferromagnetic structure similar to that used to create bias in GMR heads [18]. Since then other companies such as Komag have also made this media and verified its added thermal stability. Figure 9 shows the basic structure of this recording medium.

In synthetic antiferromagnetic magnetic recording media cobalt alloy magnetic layers are separated by a very thin layer of a material that promotes antiferromagnetic exchange between the two magnetic layers (such as Ru). This antiferromagnetic layer causes the lower magnetic layer to have a magnetic orientation that opposes that of the upper magnetic layer (which is recorded on by the recording head). Thus when information is recorded by the write poles on the magnetic layer closer to the head the antiferromagnetic intermediary layer causes the lower magnetic layer to be recorded in the opposite orientation. As a consequence the effective magnetic recording medium volume is equivalent to the combination of both magnetic layers and so has greater thermal stability and yet is almost as easy to write on as the magnetic layer which is closer to the head. The effective M_rt of a two magnetic layer synthetic antiferromagnetic medium is shown in (2).

(2) $M_rt \text{ (effective)} = \left| M_{r1}t_1 - M_{r2}t_2 \right|$

If needed this can be repeated to create a synthetic antiferromagnetic structure that is several layers thick such as shown in Figure 9, with a resulting M_rt that is the sum of the signed M_rt of the composite layers. Although it appears that this is a very effective technique to avoid the issues of thermal medium stability the synthetic antiferromagnetic Ru layer must be very thin (typically <1.0 nm) in order to create antiferromagnetic coupling between the layers. This Ru layer thickness is very similar to that required for the oxide layer in a TMR head and is difficult to attain. It is hard to achieve uniformly thin films across an area as large as a magnetic disk.

As the push for higher densities continues above 100 Gb/in^2 there is pressure to create uniform grains in the recording material and smaller sized nominal grains, even if this requires very different technology to create it than is used in current magnetic recording media. In March of 2000 IBM announced that they had succeeded in making a particulate recording medium that consists of very fine (4 nm) grains of FePt with extremely uniform spacing between the grains[19]. Figure 10 compares this particulate recording medium with 35 Gb/in^2 demonstration thin film magnetic recording medium. It is quite clear that the FePt particulate medium has finer and more uniformly sized grains compared to the CoPtCrB thin film medium.

The particulate medium is made by coating the synthesized particles with oleic acid and then performing a high temperature anneal that decomposes the organic material into a carbonaceous coating surrounding the resulting face-centered tetragonal FePt particles. Magnetic recording results with a 120 nm particle assembly, M_rt = 10 memu/cm^2, and H_c = 1800 Oe FePt particulate medium show useful recording up to 2000 fc/mm (50,800 fc/in). With a 5 nm particle M_rt of 0.5 memu/cm2, H_c of 5000 Oe 38,000 fc/mm (966,720 fc/in) recording should be possible, which would enable very high BPI recording. With 100 nm wide tracks 250 Gb/in^2 would be possible and with 25 nm wide tracks 1 Tb/in^2 (single particle recording) would be possible. The IBM researchers believe that even 130 Tb/in^2 thermally stable single particle recording may be possible with small enough particles.

Many other approaches are being explored to create isolated magnetic particle recording systems. These are often referred to as patterned media. Patterned media approaches include stamping out disks with defined tracks and magnetic regions or creating such defined magnetic regions by photolithographic techniques or various etching techniques. Any patterned magnetic recording medium will require significant changes in magnetic media manufacturing techniques and will doubtless require significant capital investments.

In 1999 Roger Wood's projected a 1 Tb/in^2 perpendicular magnetic recording system[20]. Perpendicular recording is another approach to achieving such high areal densities. Between all of these approaches to media and the fast pace of head development it appears very likely that technology solutions exist to extend "conventional" magnetic recording to much higher densities than 100 Gb/in^2. However technologies will have to be perfected and capital investments will have to be made for this to be possible.

Channel and Electronics

Higher areal densities as well as the requirements for enterprise storage systems drive the data rate requirements for magnetic recording. For a given disk diameter and RPM as the areal density increases the required data rate must increase to keep pace. With the current trend in data rate it appears that 2000 MB/s will be available in drives by 2002[14].

Another way to increase the data rate of the drive is to read data on and off the disk surfaces in parallel. This would require at least separate data channels for the heads on each surface and so would involve extra cost but there may be some applications where the extra data speed would be welcome.

Dedicating a preamp to each head and mounting it on the head suspension close to the head is one way to increase the SNR as well as reducing time delays due to wire lead impendence. Ultimately with greater head integration (for instance putting a micro actuator on the head itself) it may be possible to put the preamp directly on the head bringing the lead distance from the head transducer to a minimum. It is likely such technologies will only be used with much smaller head sliders having lower mass such as the IDEMA femto standard slider or even smaller[21].

Despite improvements in SNR possible through isolated particle media and preamp placement; as areal density increases there will ultimately be pressure to make bits even smaller, to the point where current ECC, such as Reed-Solomon codes will have problems recovering data. At that point more sophisticated channel codes may be needed such as those used to recover data from far-off and noisy satellite transmissions. In 1998 Roger Wood estimated that with 4 grains/channel-bit the resulting SNR would be 6 dB and for a 512 byte block a single BCH(4956, 4096)) code with 21% overhead correcting t=66 errors results in about one failure per 10^{15} bits read[22].

Disk and Head Actuator Motor

Increasing drive performance is very important for network storage applications. As a consequence enterprise-class disk drives are under pressure to increase their access speed, the speed at which data can be recovered from the disk. The access speed is the sum of the seek time for the head to come on track and the rotational latency time required for the proper information to be found and read-back to begin. Total access time has decreased from about 20 ms in 1990 to about 9 ms in 2000[23].

Rotational latency is mostly determined by the rotational speed of the data track being read. The RPM of disk drives has been increasing steadily with time for all drive categories. Very few drives now ship with 3600-RPM rotational speed that once was common. The majority of mobile drives have 4,200 RPM; desktop drives about 70% 5,400 RPM and 23% 7,200 RPM; enterprise drives are about 66% 10,000 RPM, 34% 7,200 RPM, and 0.4% 15,000 RPM (all these 15k RPM drives are from Seagate as of November 2000). Figure 11 shows history and projections of drive RPM for enterprise disk drive (which have the highest performance demand). 15,000 RPM drives should be available from multiple vendors by 2001 and the first >20,000 RPM may show up in 2002.

As the RPM increases it will be difficult to stay with ball bearing disk motors because of problems with heat dissipation and wear. The disk diameter is also likely to decrease. The Seagate 15k RPM drive uses 2.5-inch disks and fluid bearings.

Seek time is determined by the performance of the actuator and servo system in bringing the head on track. There are improvements in servo algorithms being worked on such as incorporation of neural network logic into the servo system[24]. There may be some demand in the future for disk drives which use multiple actuators to decrease the seek time.

IV. Form Factor Trends and New Uses for Disk Drives

As the areal density increases and as disk drive companies learn to make very inexpensive disk drives, new form factors and applications for disk drives come into being. Figure 12 shows the total disk capacity vs. time for 95-mm, 65-mm and the new 27.4-mm form factor disks assuming the annual areal density increase is 100%. This graph shows some pretty large capacities for 95-mm drives (100 GB for one disk by 2002) and very impressive sizes for the small 27.4-mm disk (4 GB for one disk by 2002).

The very smallest disk drives (27.4-mm) may find uses in all types of mobile storage devices such as digital cameras, MP3 music players, mobile phones with GPS systems, and wearable computers. A small, high capacity disk drive may be very important for portable device speech recognition systems since the file sizes required are so large (>200 MB). Larger sized disk drives (mostly 95-mm) are being used in Personal Video Recorders (PVRs), automobile navigation systems, airline entertainment systems, gaming systems, and music storage and distribution. Figure 13 shows projections for the growth of non-computer vs. computer based disk drive sales [25].

V. Drive Projections

Based on discussions at the October 2000 IIST Lake Arrowhead Workshop [26] Table 3 shows projections for enterprise disk drive specifications for 2002.

Table 3. **2002 Enterprise Drive Projections**

Parameter	Mainstream	High Performance	Data Tub
Disk Diameter (mm)	84	65	130
RPM	10000	22000	3600
Capacity, GB/disk	76	45	181
Areal Density, Gbits/sq.in.	75	75	75
TPI, kTPI	93.7	93.7	93.7
BPI, kBPI	800	800	800
Bit Aspect Ratio (BPI/TPI)	8.5	8.5	8.5
Track Pitch, u"	10.7	10.7	10.7
Track Pitch, um	0.27	0.27	0.27
Data Rate Mb/s Media	1036	1768	579
Number of Disks (Typ)	6	4	6
Number of Heads (Typ)	12	8	12
On-Line Capacity (GB, Typ)	456	180	1086
Ave Seek Times (ms)	5.0	2.0	10.0
Ave Rotational Latency (ms)	3.00	1.50	8.33
Substrate	50 mil Al/Glass	--------------------	----------------->
Suspension	Micro actuator	--------------------	----------------->
Actuator	Single Stage	Dual Stage	Single Stage
Pre-Amp Max Data Rate (Mb/s)	1382	4716	772
Spindle Motor	FDB	FDB	Ball or FDB
Watts Avg (Op)	15	<17	<15
Operating Shock (Gs)	65	65	
Acoustics, Bel (Typical/Max)	<3.5	<4.0	<3.0
MTBF	1,500K	2,500K	1,500K
Interface(s)	Fibre Channel	Fibre Channel	ATA-133
	SCSI	SCSI	SCSI
		Infiniband	Fibre Channel
Onboard Optimization	No	Yes	No

The enterprise drives in Table 3 can be divided into three broad classes of drive. The first class is a conventional enterprise drive with 456 GB capacity. The second class of product is a very high performance product with 180 GB capacity, 22,000 RPM, very high data rate due to parallel disk data transfer, very high access time due to dual actuators and with on-board intelligence which defragments the disk and organizes the data for easy access of frequently used data. The last product class is referred to as a data tub. The data tub provides maximum capacity on a single drive for the lowest cost per GB. This product may replace some tape systems since it has somewhat better performance than tape and offers random access to stored information.

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