Systems and Attributes: Future Trends

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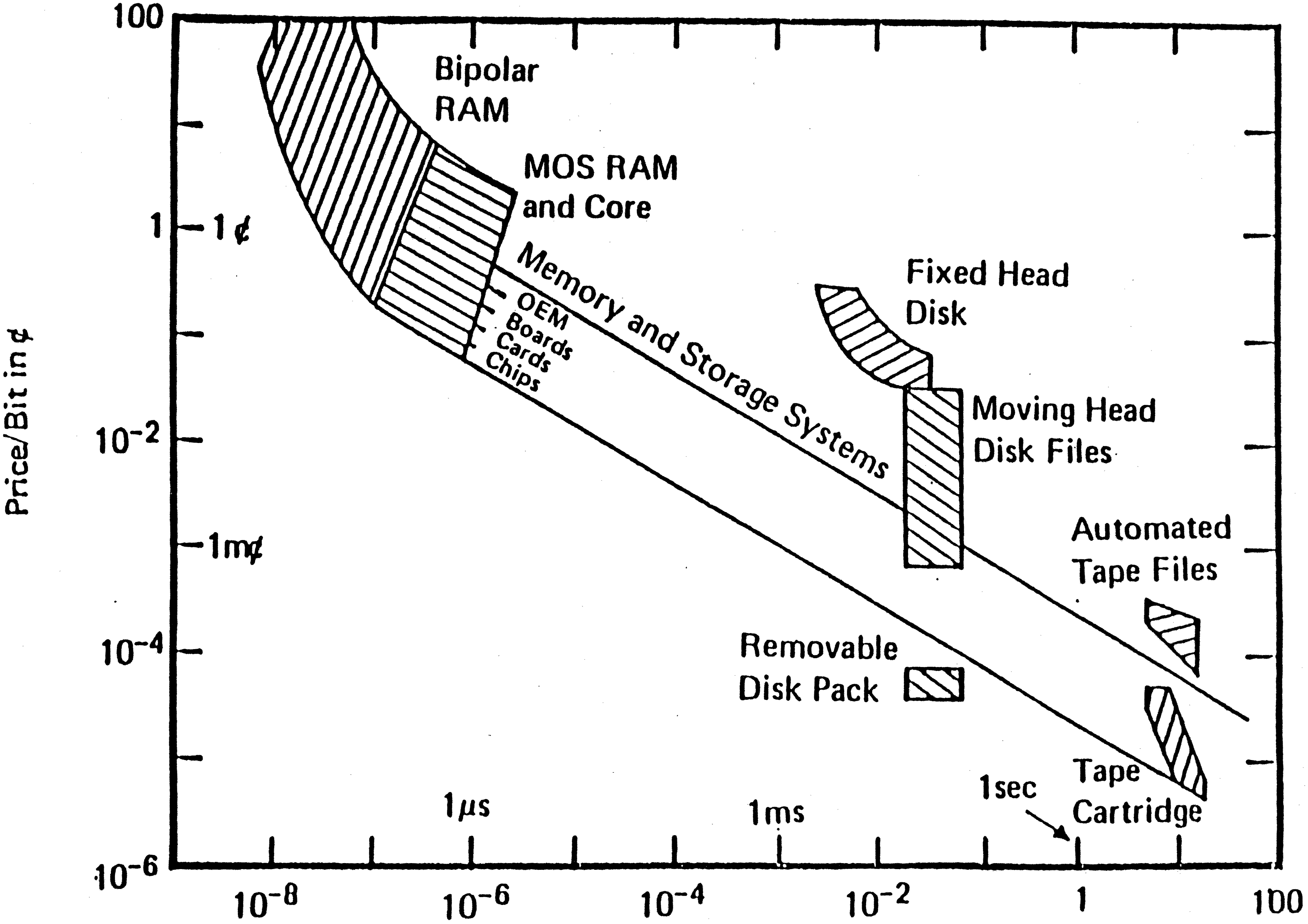
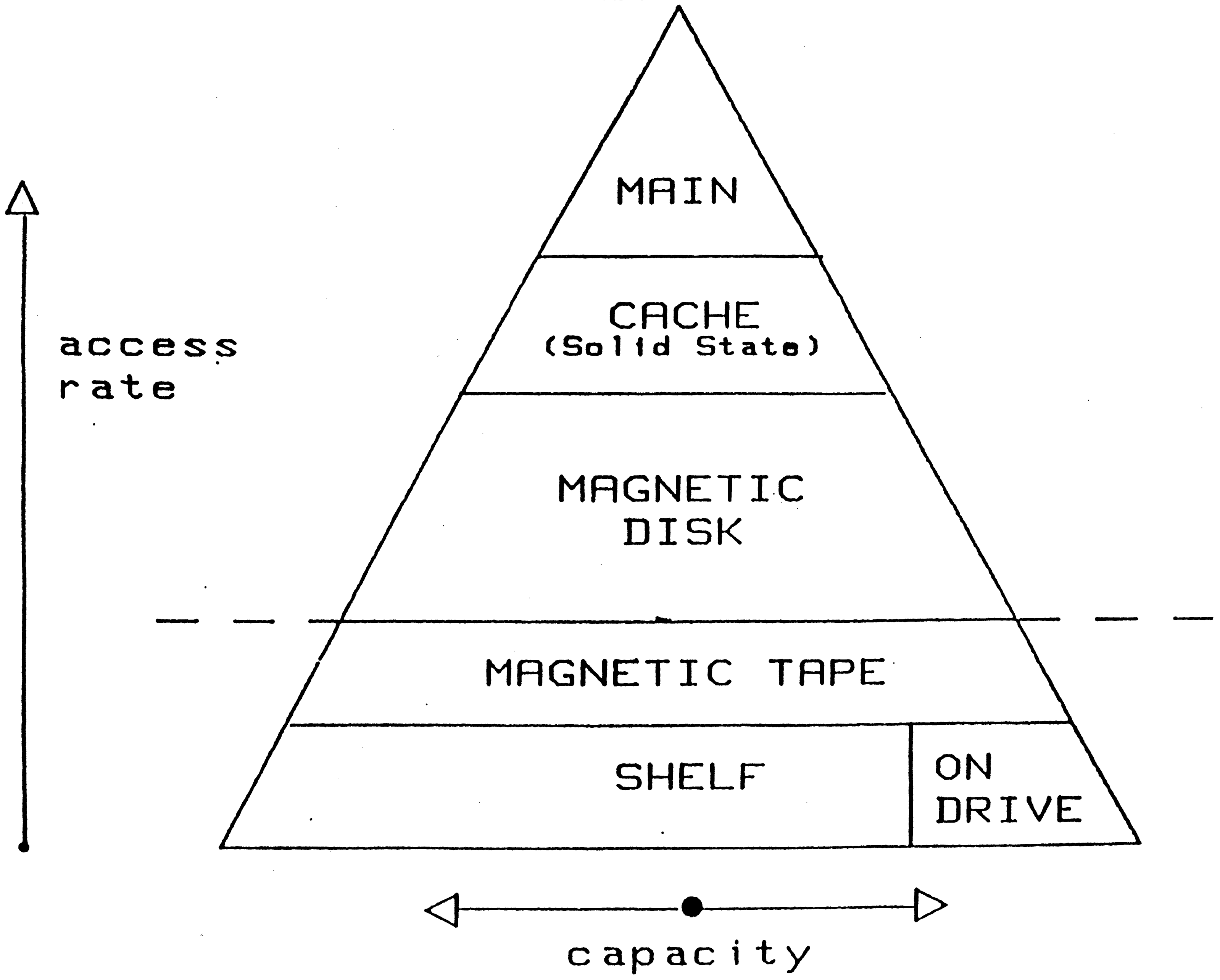
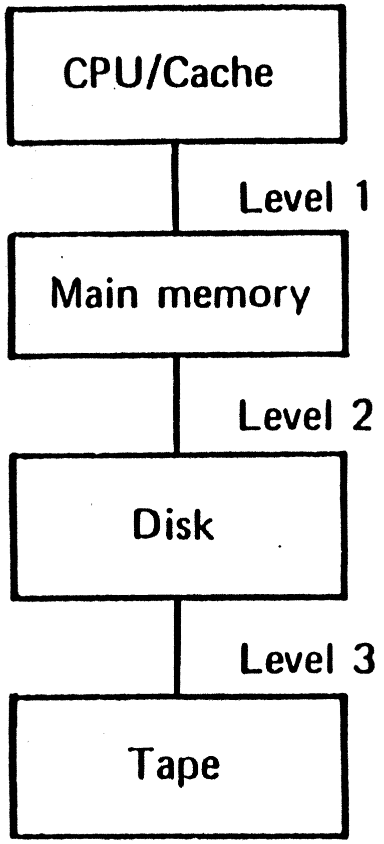


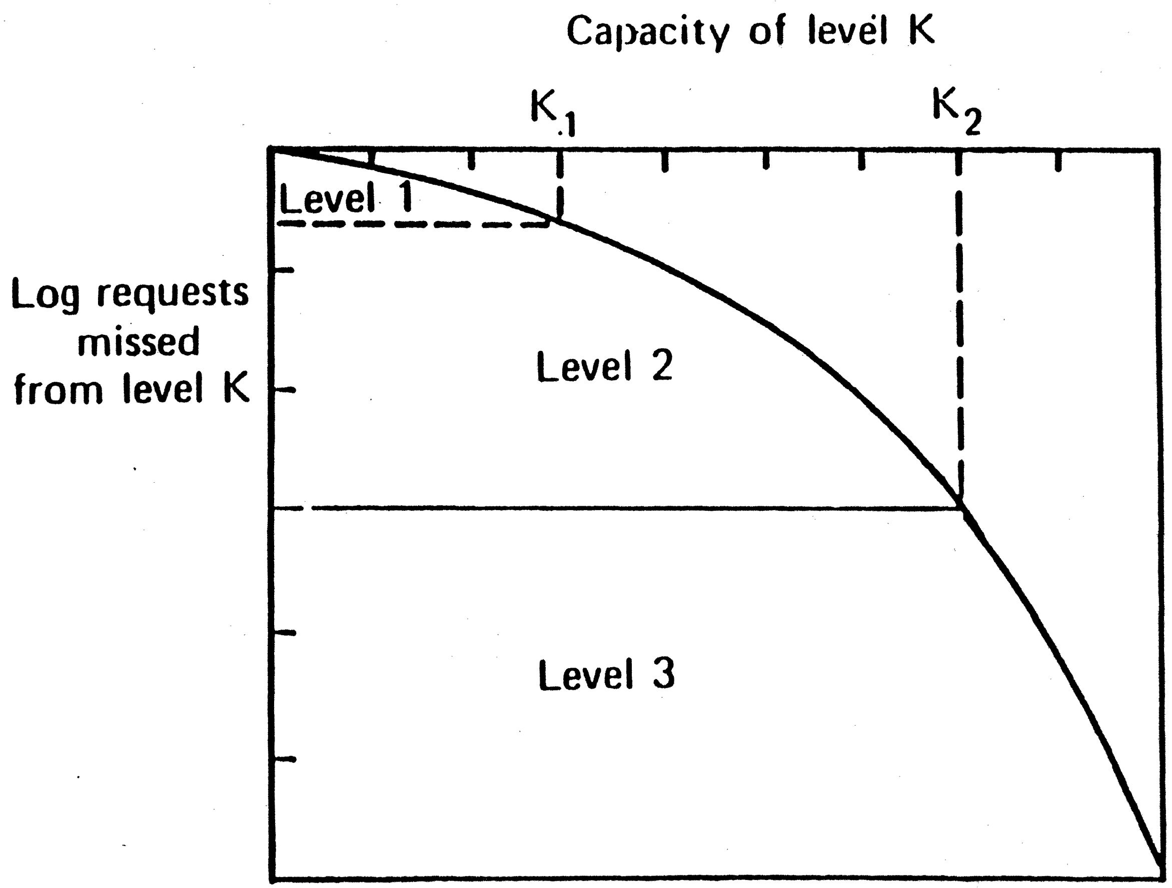
Price/Bit in ¢
100
1
1¢
10^{-2}
1m¢
10^{-4}
10^{-6}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
100
1µs
1ms
1sec
Bipolar RAM
MOS RAM and Core
Memory and Storage Systems
OEM
Boards
Cards
Chips
Fixed Head Disk
Moving Head Disk Files
Automated Tape Files
Removable Disk Pack
Tape Cartridge

STORAGE HIERARCHY



3 - Level Hierarchy



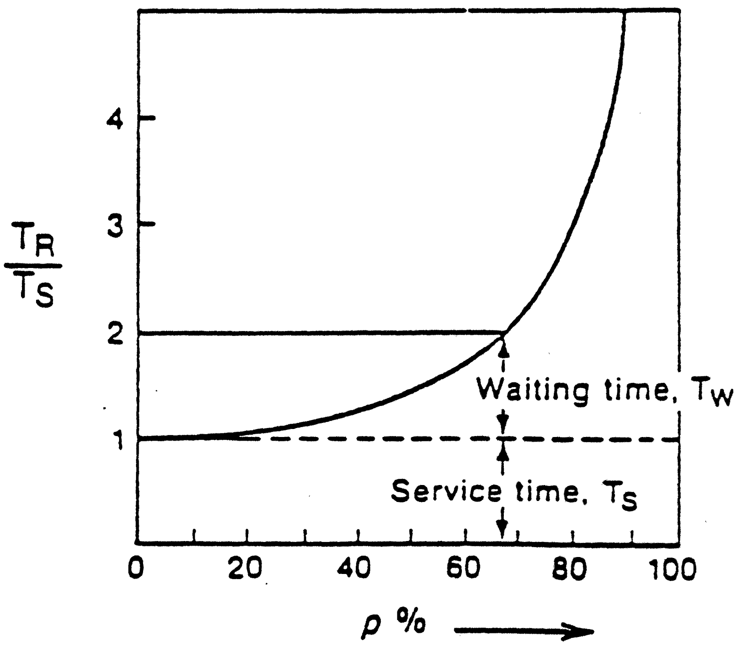


File Transfer Rate

- Service Time : $T_S = \overset{\text{ACCESS}}{T_A} + \overset{\text{LATENCY}}{T_L} + T_F$
- Response Time: $T_R = T_S + T_W$

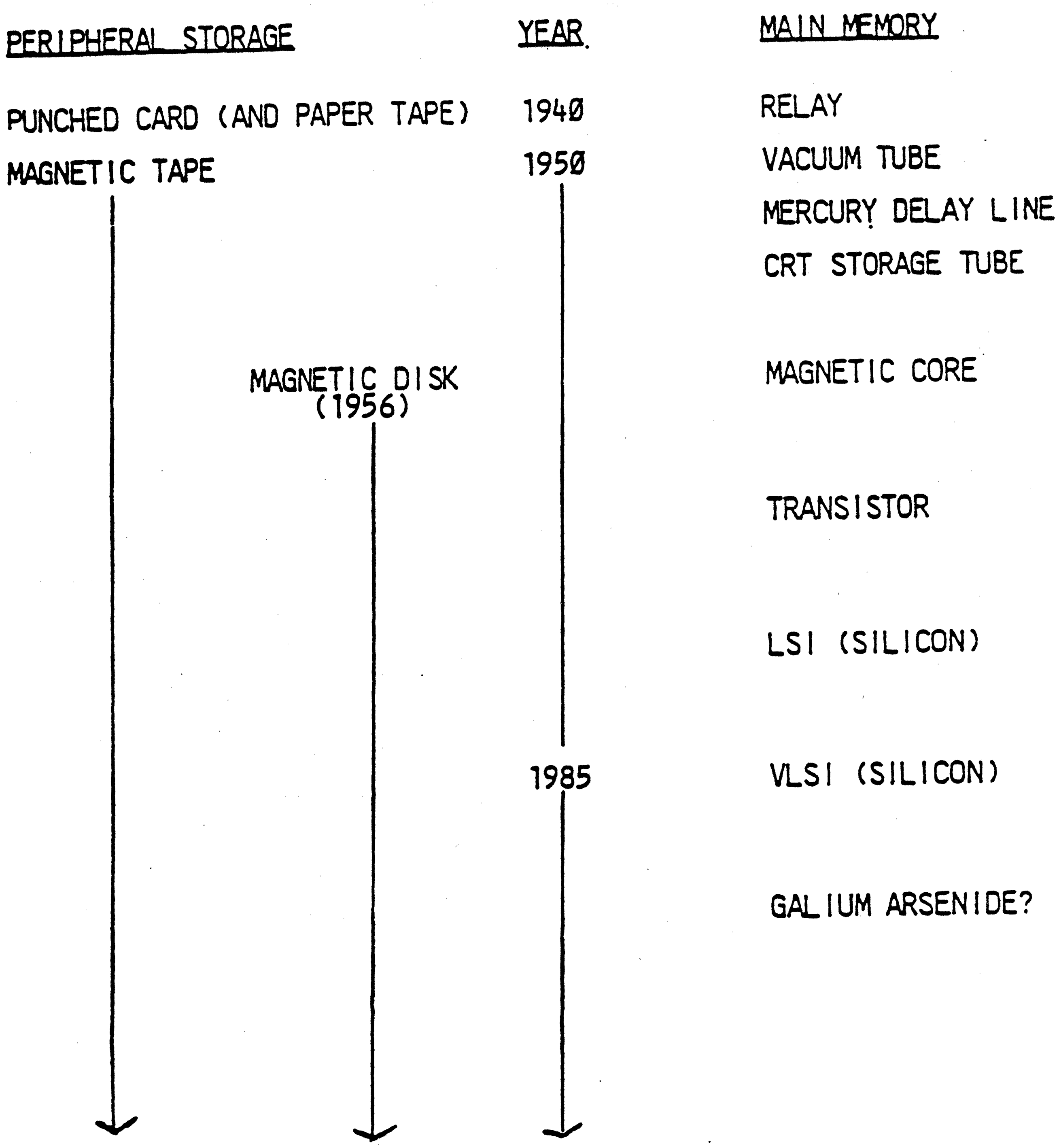
$$\frac{T_R}{T_S} = \frac{1}{2} \left[\frac{2 - \rho}{1 - \rho} \right]$$

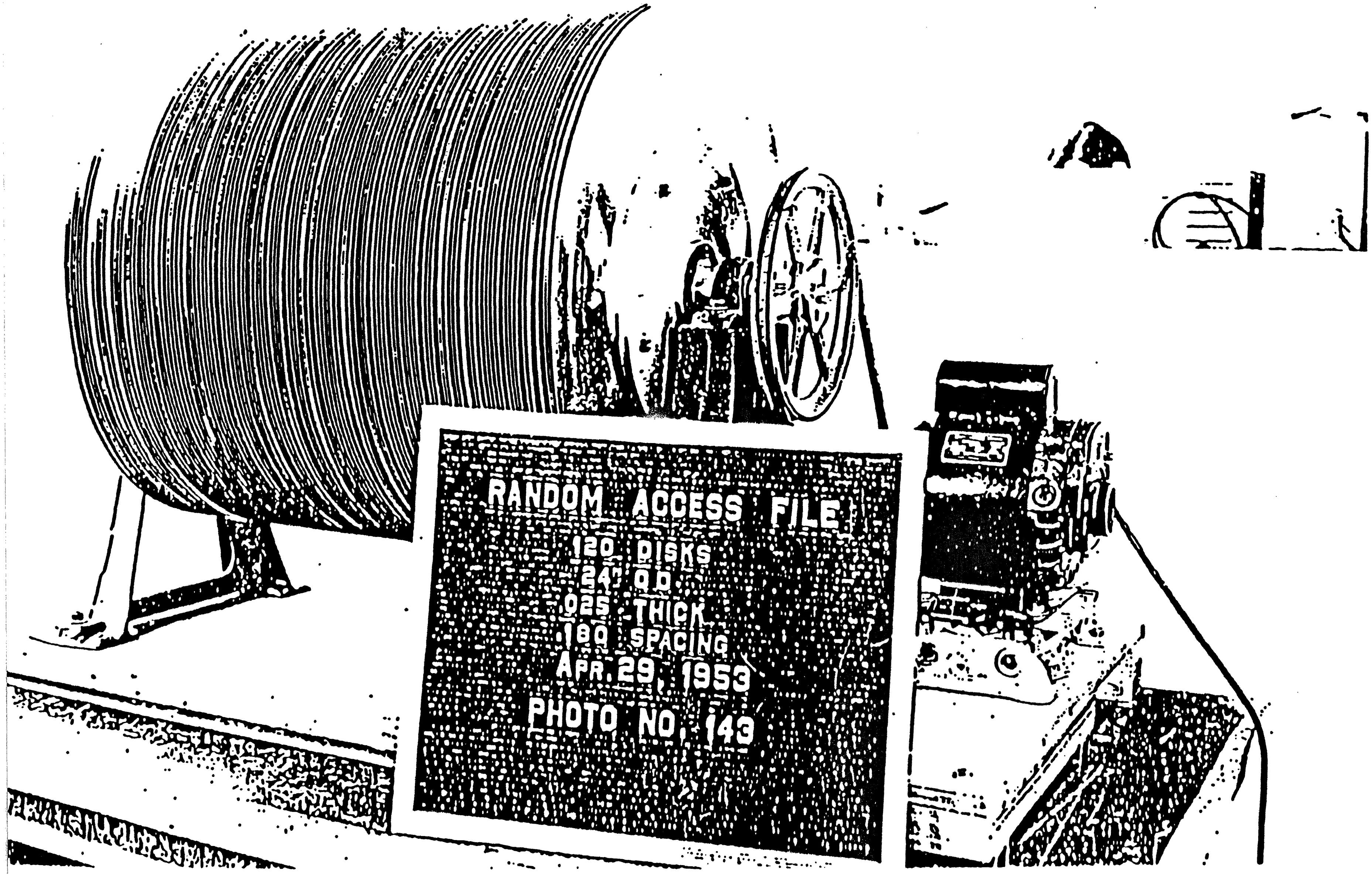
ρ = Actuator Utilization Duty Cycle



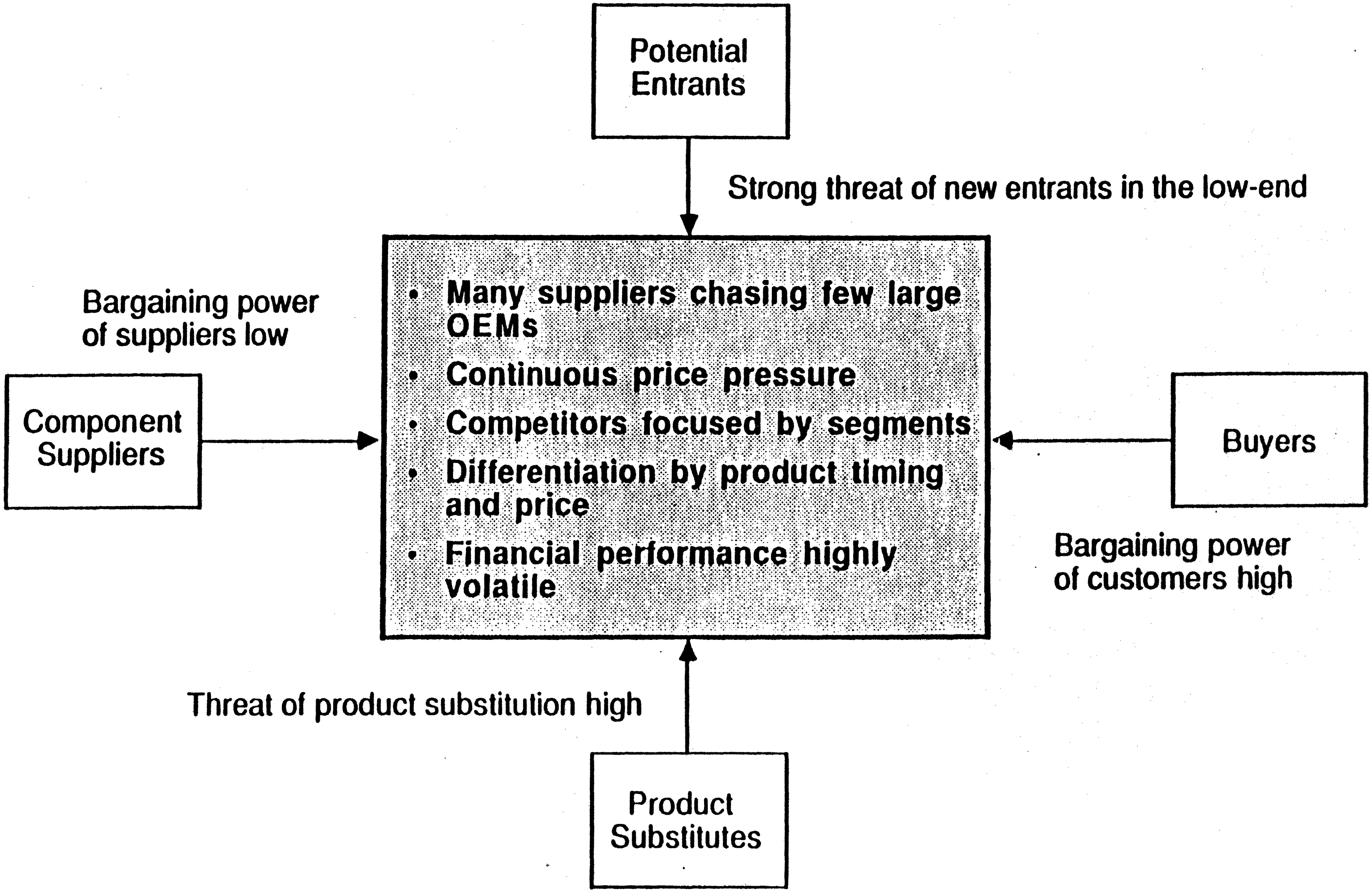
- Increased capacity per actuator leads to increased actuator utilization and an access bottleneck

EVOLUTION OF MEMORY AND STORAGE TECHNOLOGY




RANDOM ACCESS FILE
120 DISKS
24" OD
.025 THICK
.180 SPACING
APR. 29, 1953
PHOTO NO. 143

INTENSE RIVALRY AMONG COMPETITORS IN THE INDUSTRY



Potential Entrants

Strong threat of new entrants in the low-end

Bargaining power of suppliers low

Component Suppliers

- Many suppliers chasing few large OEMs
- Continuous price pressure
- Competitors focused by segments
- Differentiation by product timing and price
- Financial performance highly volatile

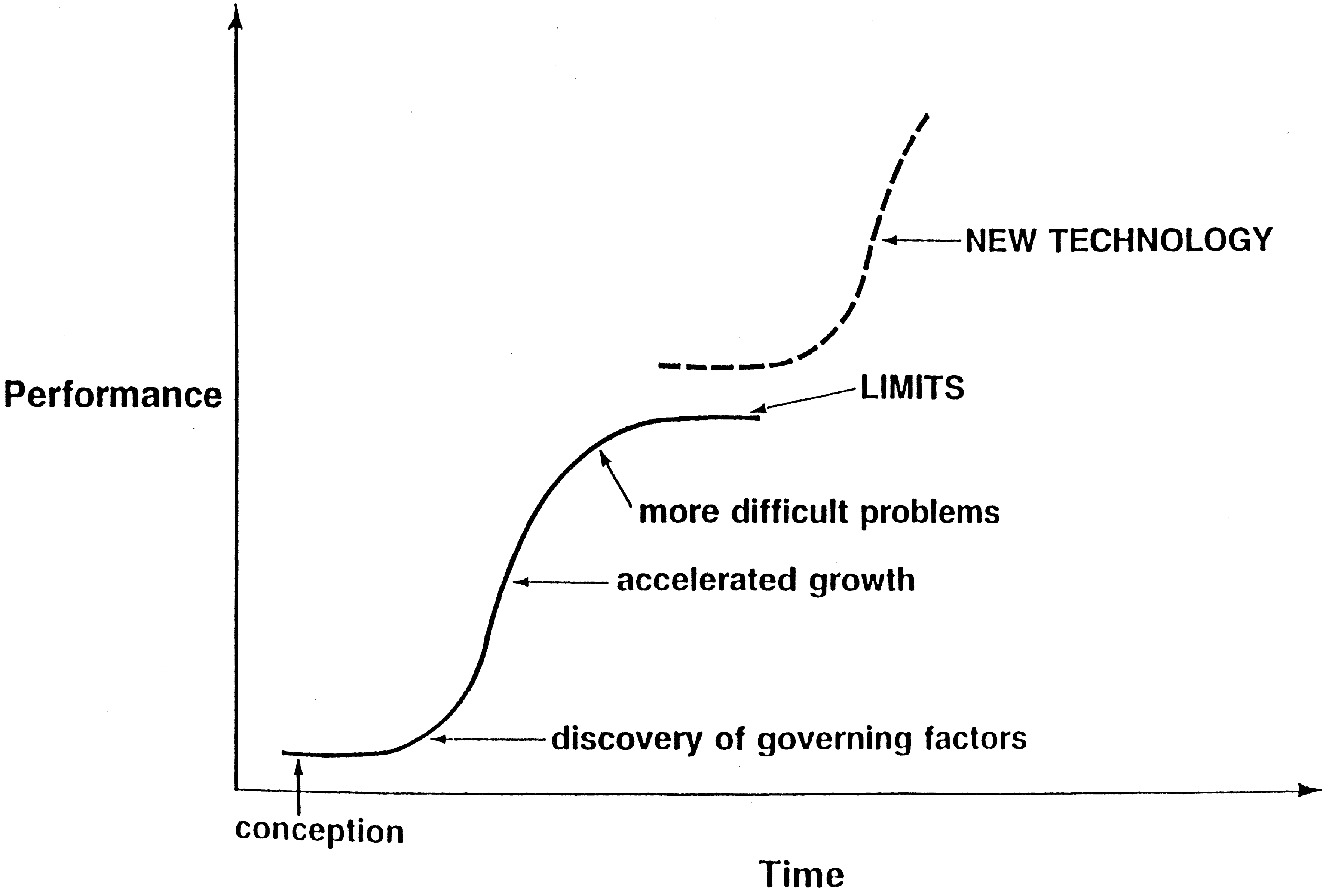
Buyers

Bargaining power of customers high

Threat of product substitution high

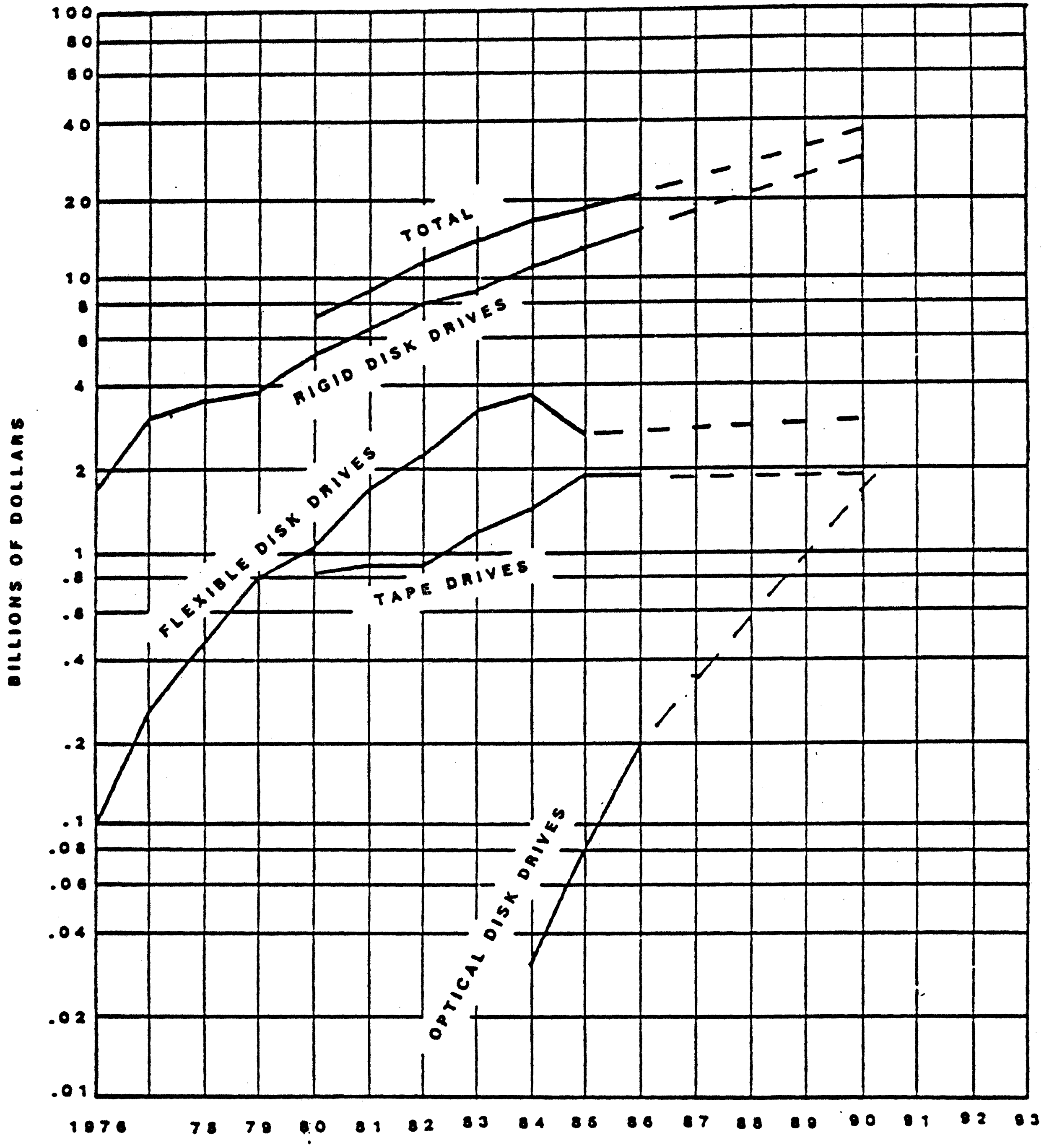
Product Substitutes

Technology Development



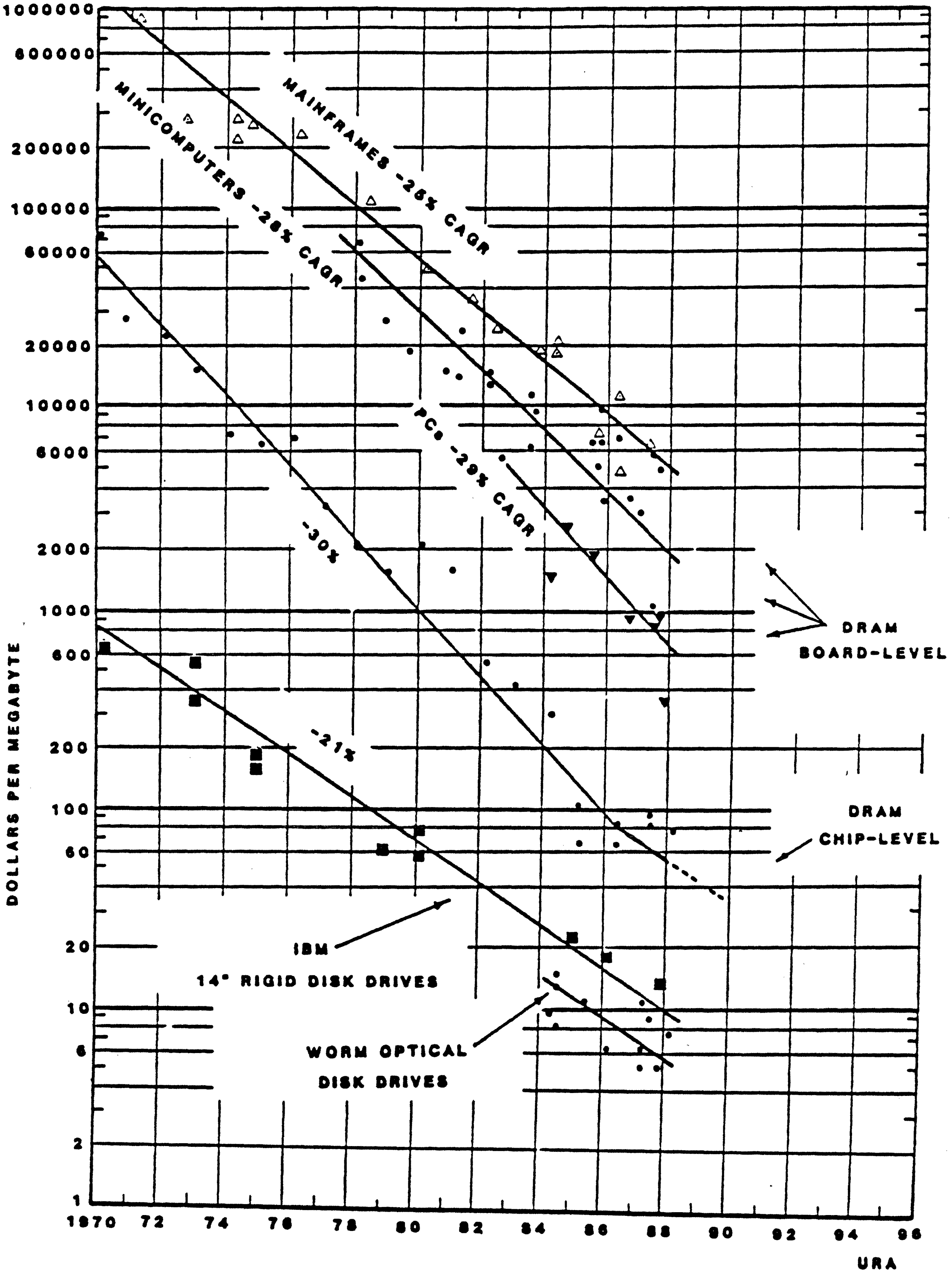
WORLDWIDE REVENUES - MASS STORAGE MARKET

REVENUE BASED UPON FIRST PUBLIC SALE



SOURCE: DISK/TREND

MAIN MEMORY & STORAGE PRICE HISTORY



URA
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RIGID DISK TRENDS

Year	Device	Bits/In	Track/In	Bits/In^2	In Micro Inches		
					Spacing	Gap	Thickness
1956	IBM 350	100	20	2000	1000	800	1200
1961	IBM 1301	500	50	25000	500	500	500
1964	IBM 2311	1100	100	110000	125	200	250
1965	IBM 2314	2200	100	220000	85	105	85
1970	IBM 3330	4040	192	775680	50	100	41
1973	IBM 3340	5600	300	1.68×10^6	17	60	41
1975	IBM 3350	6425	476	3.06×10^6	17	60	41
1978	STC 8650	6425	952	6.12×10^6	17	60	40
1979	IBM 3370	12134	635	7.71×10^6	15	24	35
1980	IBM 3380	15000	801	1.20×10^7	11	24	26
1981	NTT Patty	13970	1092	1.53×10^7	8	32	7
1984	NTT Patty	25400	1800	4.57×10^7	6	20	7
1985	IBM 3380(E)	15000+	∼1400	2.30×10^7	12	--	OXIDE
1987	IBM 3380(J/K)	15000+	2089	3.12×10^7	12	--	OXIDE

Magnetic Tape Technology History

Year	MFG/Model	Recording Method	Tracks Per Inch	Flux Density, FCI	Recording Density,BPI	Head to Tape Speed,IPS	Data Xfer Rate,KBS	Media Type	Capacity, MBytes
1952	IBM 726	NRZI	14	100	100	75.0	7.5	Open Reel	2
1957	IBM 729	NRZI	14	200, 556	200,556	112.5	62.5	Open Reel	12
1961	IBM 729	NRZI	14	800	800	112.5	90.0	Open Reel	17
1965	IBM 2401	PE	18	3,200	1,600	112.5	180.0	Open Reel	44
1970	IBM 3420-7	PE	18	3,200	1,600	200.0	320.0	Open Reel	44
1972	STC 3480	PE	18	3,200	1,600	250.0	400.0	Open Reel	44
1973	IBM 3420-8 (GCR)	4/5 RLL NRZI	18	9,042	6,250	200.0	1,250.0	Open Reel	167
1979	IBM 8809	PE	18	3,200	1,600	100.0	160.0	Open Reel	44
1984	IBM 3480	8/9 RLL DD NRZI	36	24,689	18,935	78.8	3,000.0	3480 Cart.	200
1987	EXB-8200	8/10 RLL NRZI	819	54,000	43,200	150.0	1,500.0	8mm Cart.	2,332

Head-Medium Interface

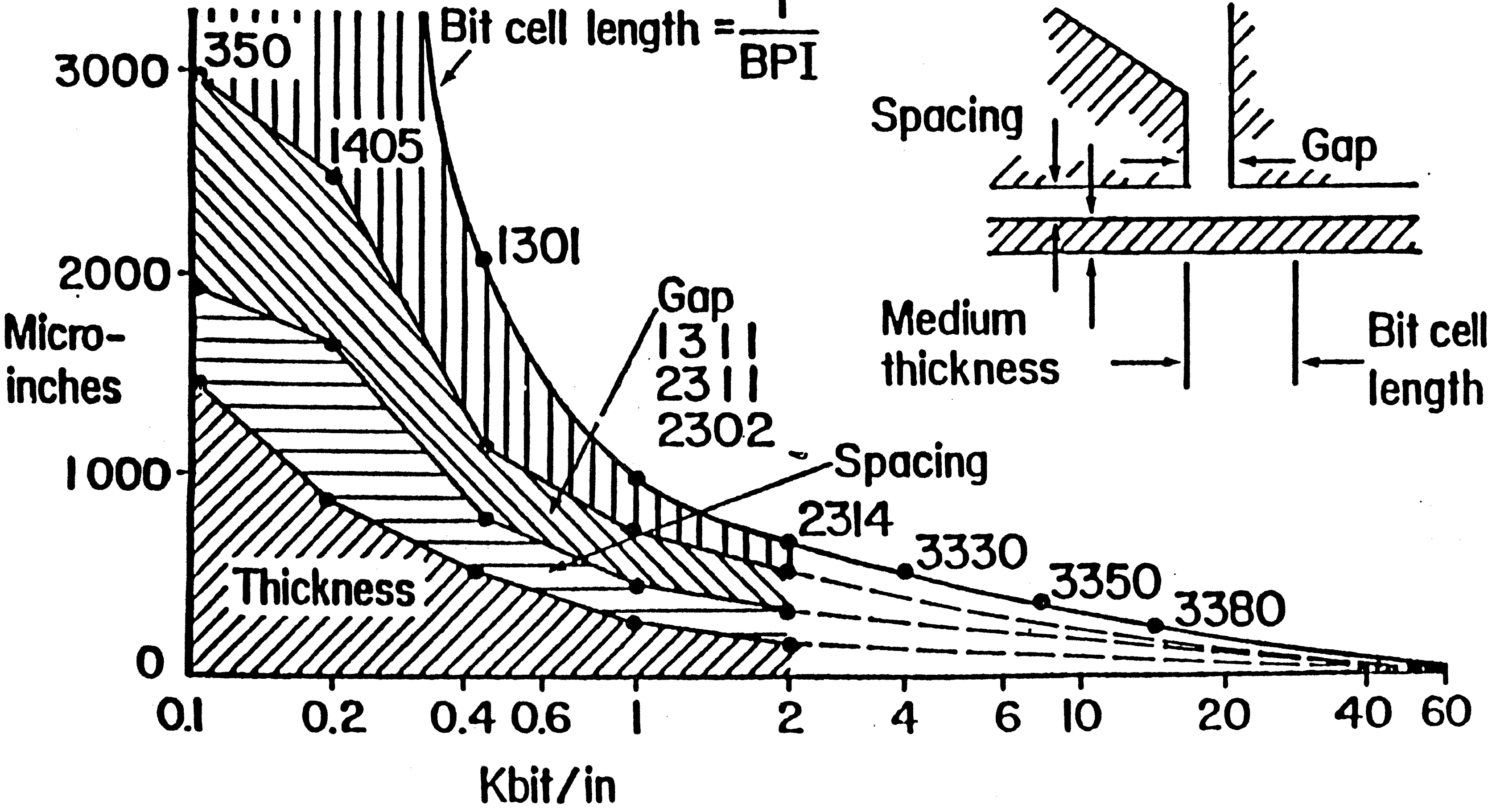
- How close is contact — or how do you define zero?
  (from laws of scaling are relentlessly driven towards 0)

  On Tape
    Assume contact and set limit on number of passes

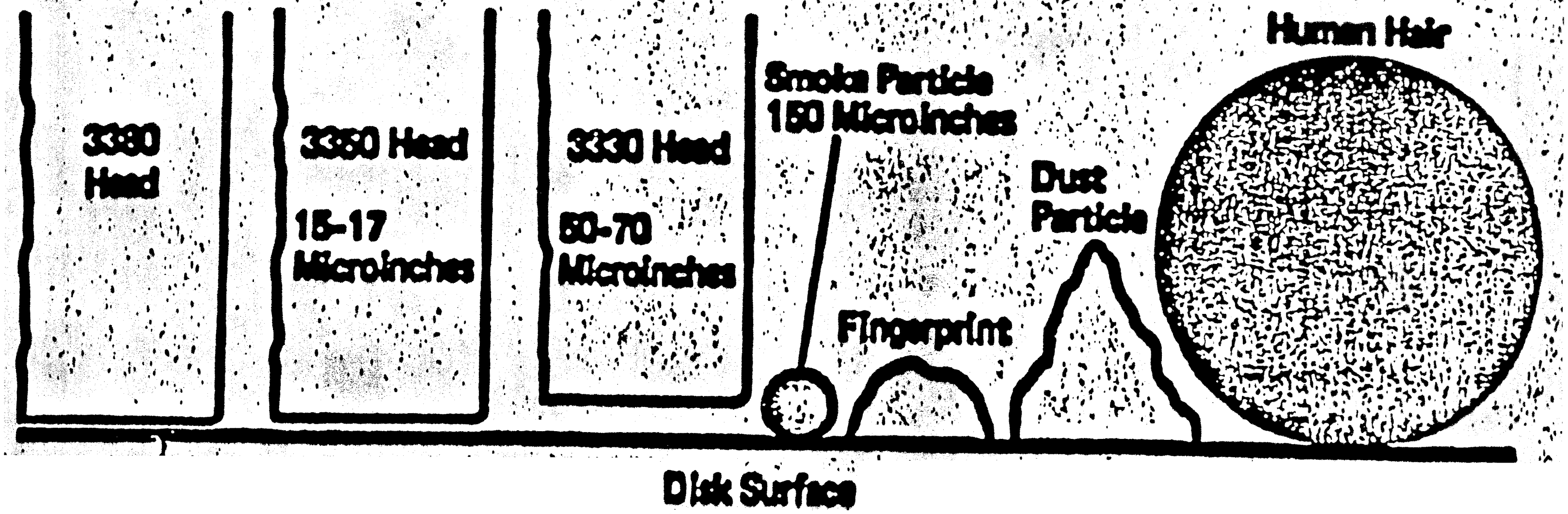
  On Disk
    Assume no contact and expect unlimited number of passes

- Is there a spacing limit at which the disk assumption needs to be tested against design options and actual applications?

Bit cell length is related to physical recording parameters



Head Flying Height



MAGNETIC HEAD TECHNOLOGY

Magnetic heads are an integral part of an air bearing slider which requires mechanical finishing to precise tolerances.

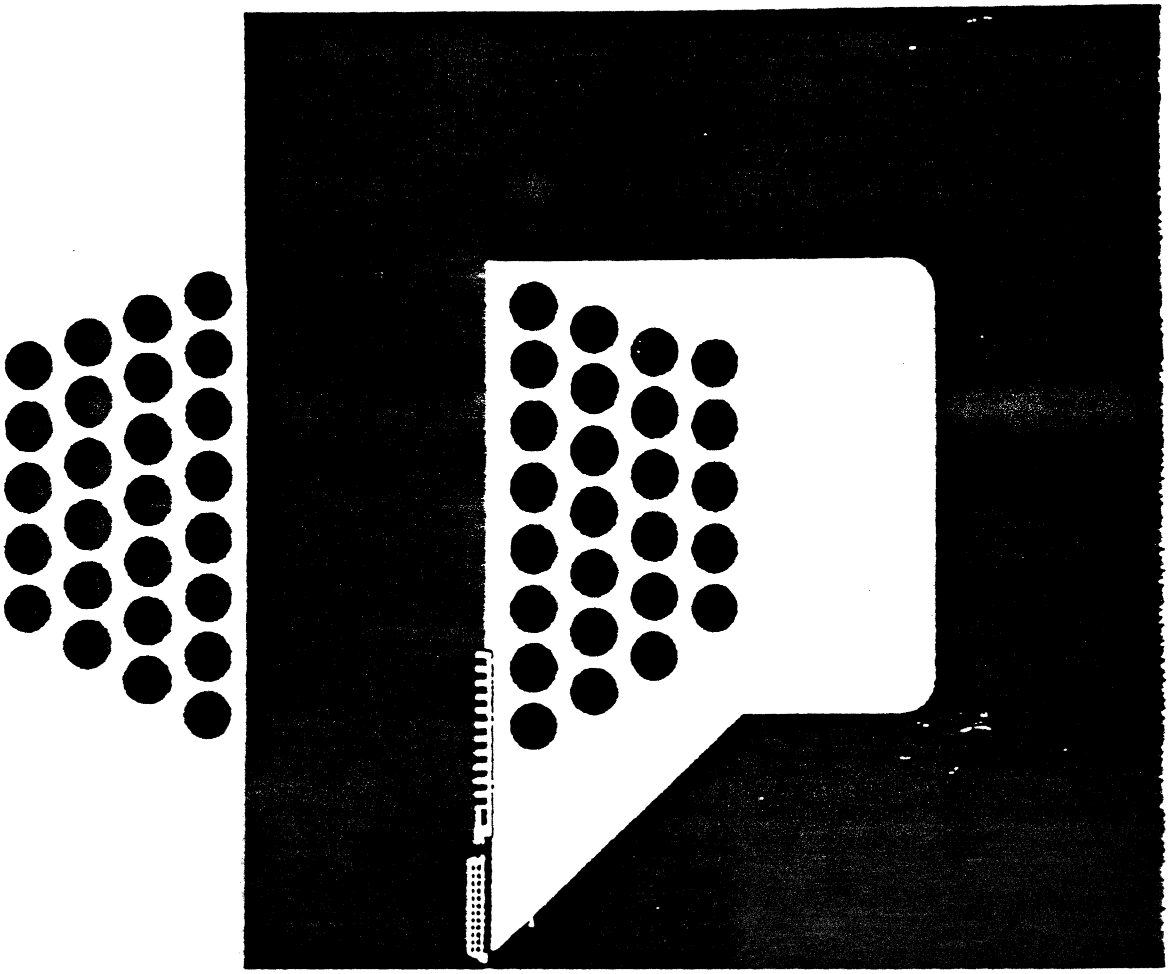
There is (today) only one operational magnetic element per slider.

thus

Batch fabrication using thin film techniques differs greatly from semi-conductor manufacturing, although both involve photolithography.

Heads

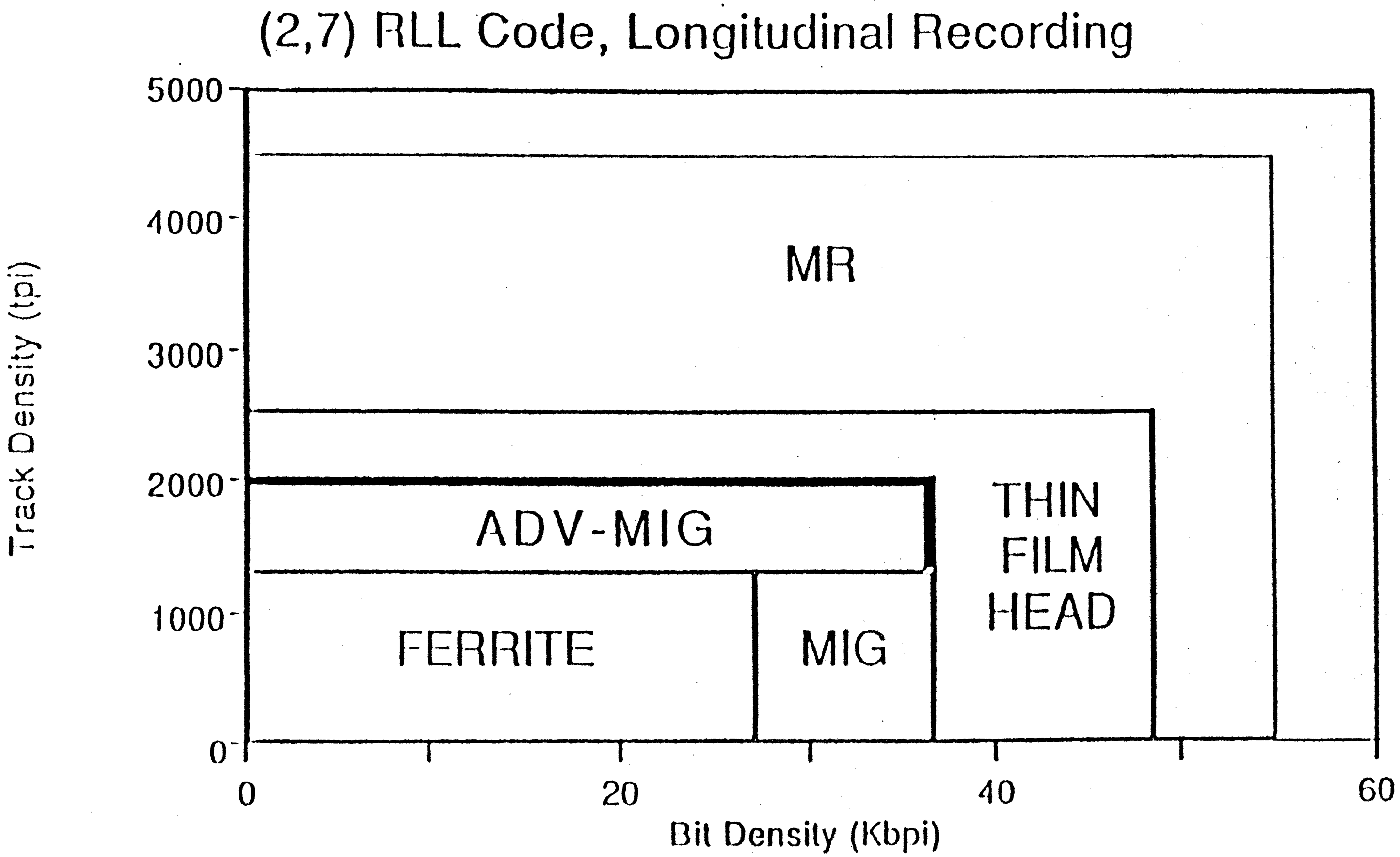
- Monolithic Ferrite
- Composite
- Metal in Gap (MIG)
- Film Inductive
- Magneto Resistive
- Film Probe (Vertical Recording)



Graphical comparison of ferrite and thin film sensor dimensions, showing a thin film sensor superimposed on a minicomposite wound core (with number of turns approximately equivalent).

Source: M. Aronoff, J. Love: Applied Magnetics, 1987

Head Technology Density Universe

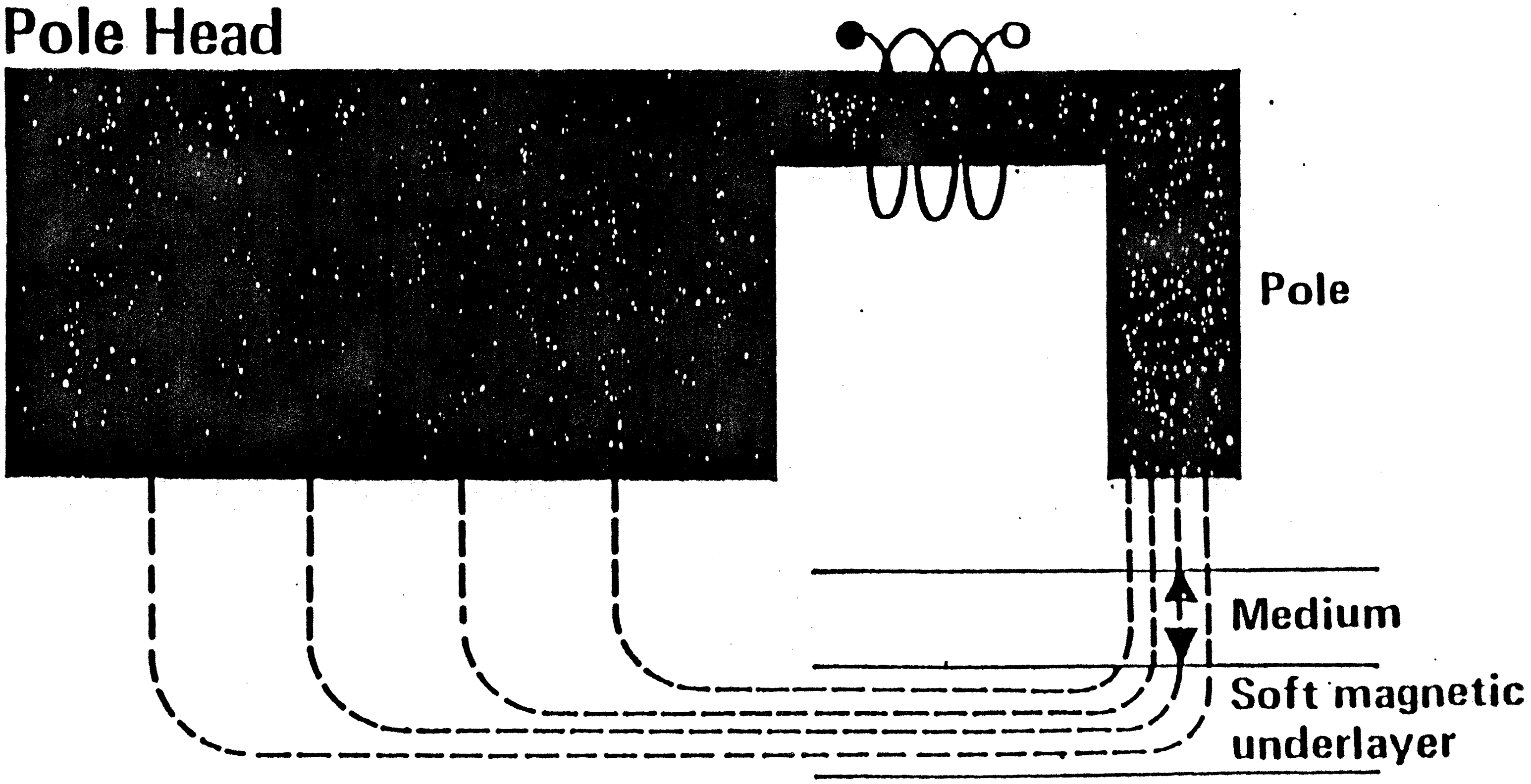


THIN FILM APPROACHES SHOULD EXCEL FOR MULTI-FUNCTION DEVICES

Multi-function heads can
- provide servo info during read/write
- write-wide read-narrow structures to reduce limitations from tracking tolerances
- separately optimize read and write gap lengths (enhance resolution and overwrite)

Example of multi-element: shielded MR head

Vertical



TECHNOLOGY DIRECTIONS IN TAPE MEDIA

- HIGHER COERCIVITY PARTICULATE MEDIA
  - STANDARD IRON OXIDE: 300+ OERSTED
  - CHROMIUM DIOXIDE: 500+ OERSTED
  - COBALT-MODIFIED IRON OXIDE: 700+ OERSTED
  - METAL PARTICLE: 1400+ OERSTED

- FUTURE POTENTIAL FOR BARIUM FERRITE AND METAL THIN FILM TAPE MEDIA

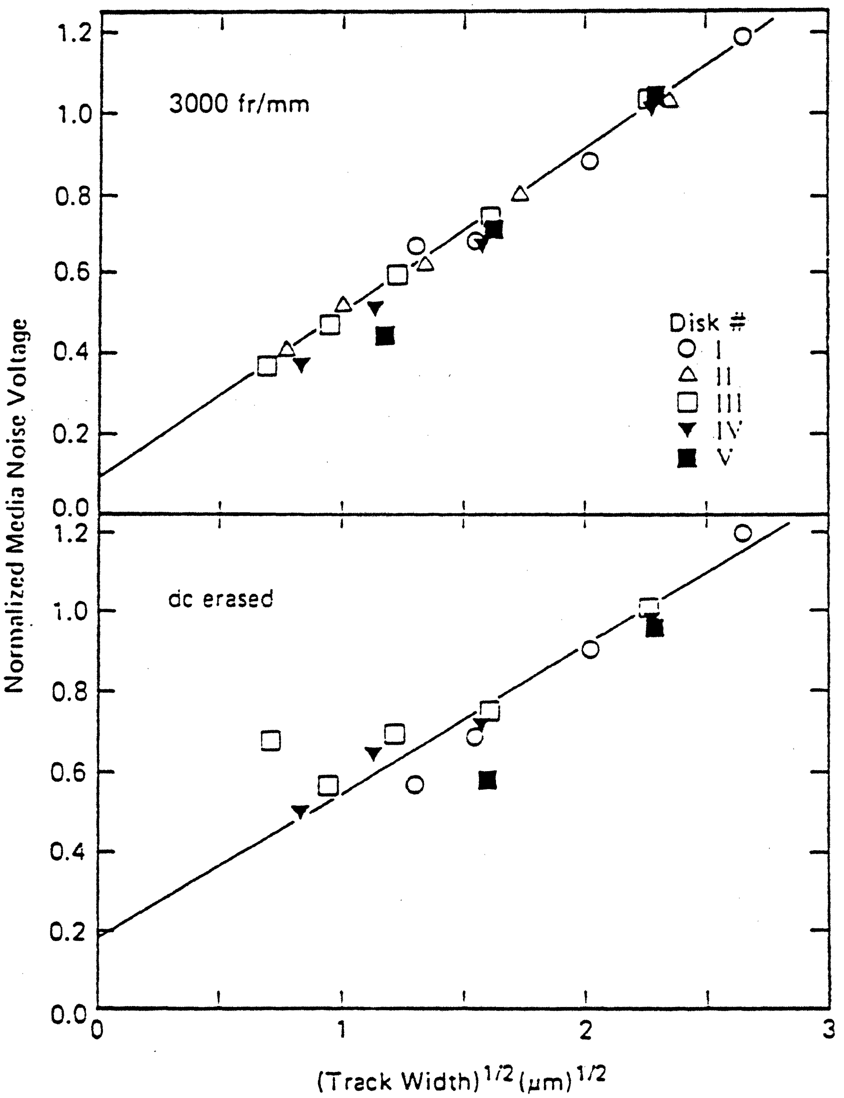


Figure 4. Normalized RMS media noise voltage versus (track width)$^{1/2}$ for five different Co-alloy film disks. Results are given for media that are either dc erased or written with 3000 fr/mm. Similar behavior was found for intermediate written densities. The data for each disk have been normalized to the value interpolated at 5 μm and the solid lines are guides to the eye.

WHERE IS ALL THE STORAGE CAPACITY GOING?

1988 PROJECTIONS FOR OXIDE AND THIN FILM DISKS (5-1/4 & 3-1/2)

OXIDE: 12×10^6

THIN FILM: 16×10^6

TOTAL: 28×10^6 DISKS

AT AN AVERAGE OF 12×10^6 BYTES/DISK, STORAGE CAPACITY SHIPMENTS $> 330 \times 10^6$ MB;

AT AN AVERAGE OF 2000 CHARACTERS/PRINTED PAGE:

1.7×10^{11} PRINTED PAGES OF STORAGE CAPACITY TO BE SHIPPED IN 1988

INTERNATIONAL MAGNETICS CONFERENCE

APRIL 14-17, 1987 TOKYO, JAPAN

NEW EXPERIMENTAL RESULTS:

- HIGHEST OBSERVED BPI: 680 KBPI
  USING IN-CONTACT PERPENDICULAR RECORDING
- NARROWEST WRITTEN TRACK: 0.5 MICROMETERS
  USING DISCRETE TRACKS ON THIN FILM DISK
- NARROWEST HEAD TRACK WIDTH: 2.7 MICROMETERS
  USING A THIN FILM MR HEAD
- HIGHEST SATURATION FLUX DENSITY HEAD
  MATERIAL: 21000 GAUSS
  USING FeC AND FeNi LAMINATED METAL FILMS

Longitudinal vs. Vertical

Read
- Same loss factors apply

Write
- Transition width set by both
- Head field gradient & medium demagnetization

favors longitudinal favors vertical

Vertical Recording

Is History Passing It By?

- Need high readback resolution to leverage very narrow transition
- Thus potential depends on very small separation

  Best oportunity is then flexible disk
  (ultimately could involve pole type write head)

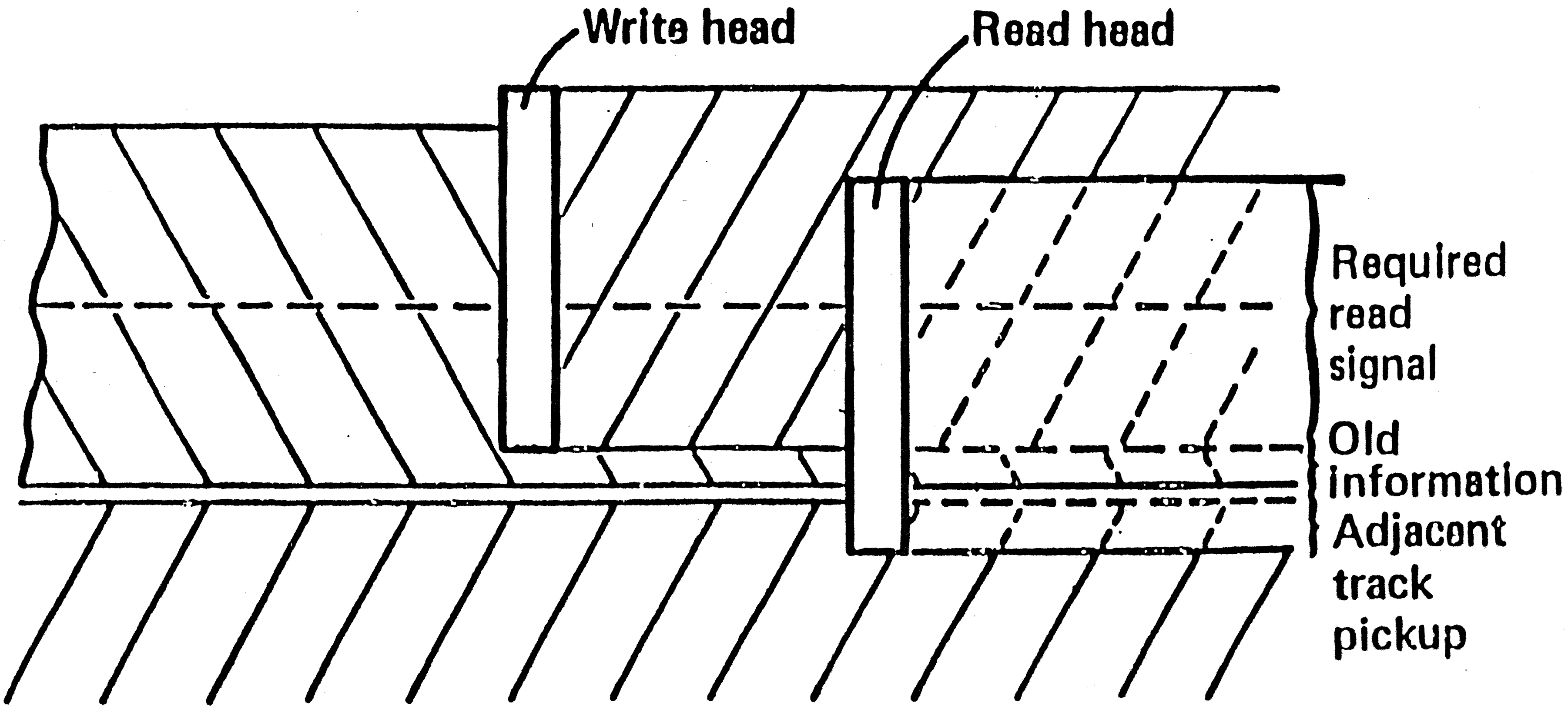
- Major alternative is magneto-optical
  i.e.: high density and removability with no contact
- Vertical recording now seen as only evolutionary extension
  — are still far from limits on conventional mag recording

Heads & Media — Long Term

As **Track Density** Limits Get More Intensive Focus

- Will require "pre-formatted" substrates (a la optical disk)
- Disks in turn will depend upon multi-element transducers
  - To servo during read and write
  - To separately optimize read and write elements
  - To permit erase option to improve overwrite
- will accelerate move to thin film head devices

Read head pickup of old/adjacent track information



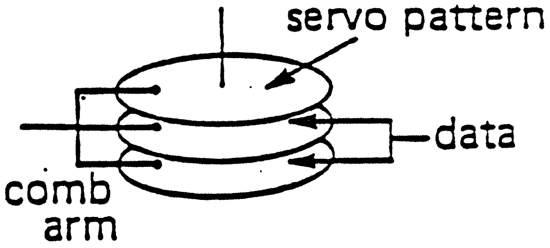
HEAD POSITIONING

Open Loop

low cost

Servo

- dedicated

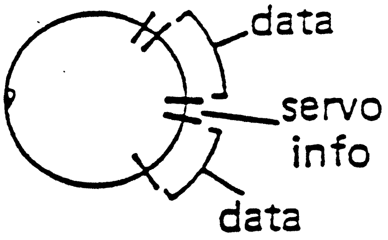


Issue - cascaded mechanical & thermal tolerances

- imbedded

(a) Sector

Issues - open loop when R/W
- real estate
- slew rate
- tolerance to disk defects

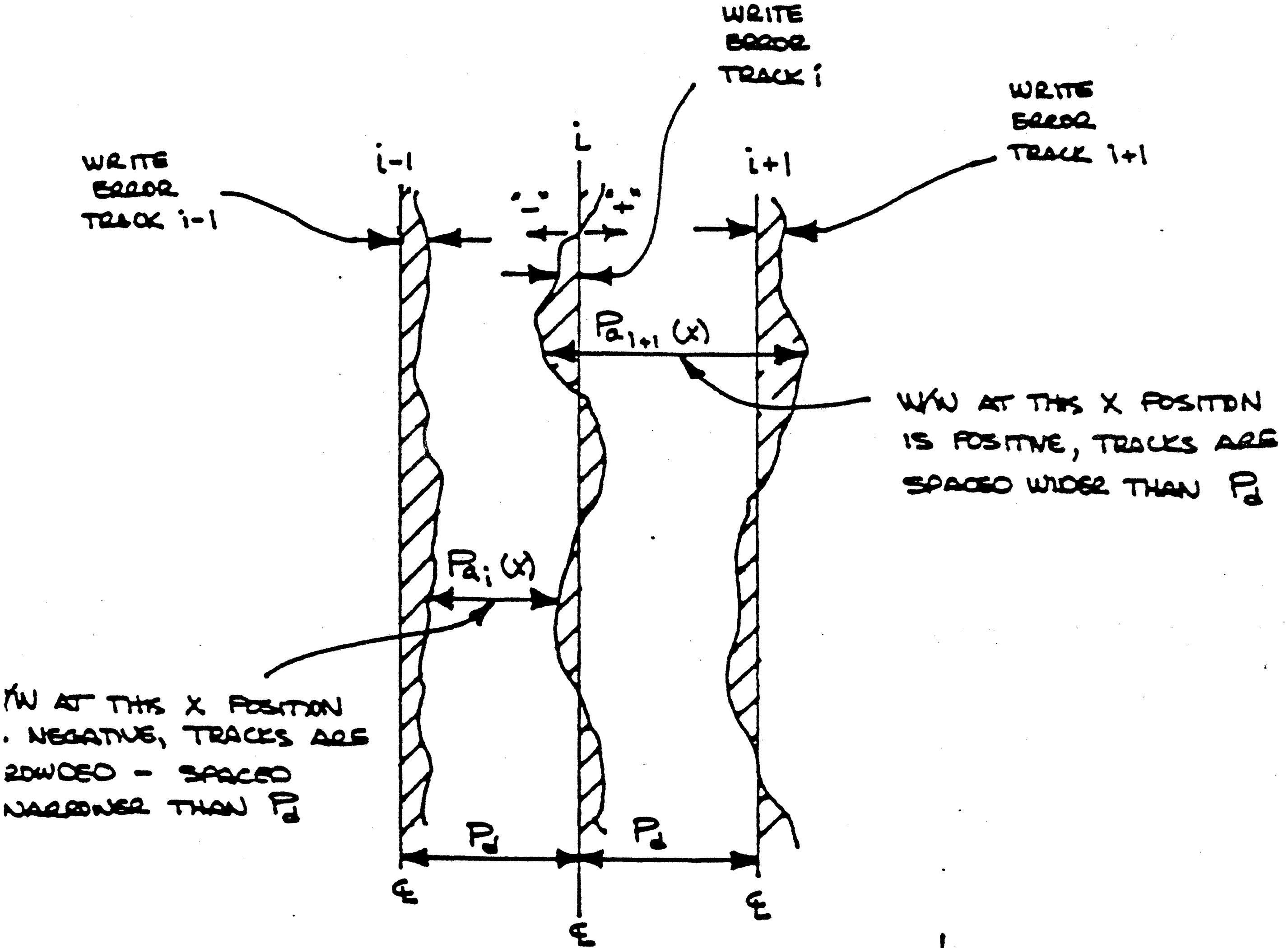


(b) Continuous

Issues - source of PES (position error signal)
- disk fabrication
- sensor
- servo while write

WRITE-TO-WRITE TOLERANCE (W/W)

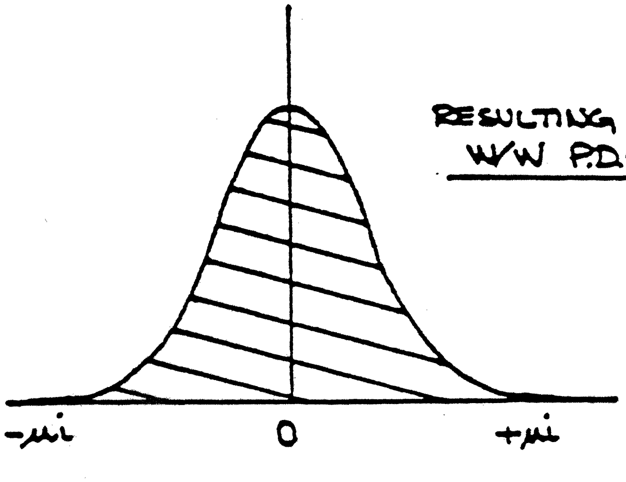
MEASURE OF ADJACENT TRACK CROWDING



P_d - DESIGN TRACK PITCH, 1/TPI ↓X

$P_{a_i}(x)$ - ACTUAL TRACK PITCH BETWEEN TRACKS i AND i-1

$$P_{a_i}(x) = (\text{WRITE ERROR})_{i} - (\text{WRITE ERROR})_{i-1} + P_d$$

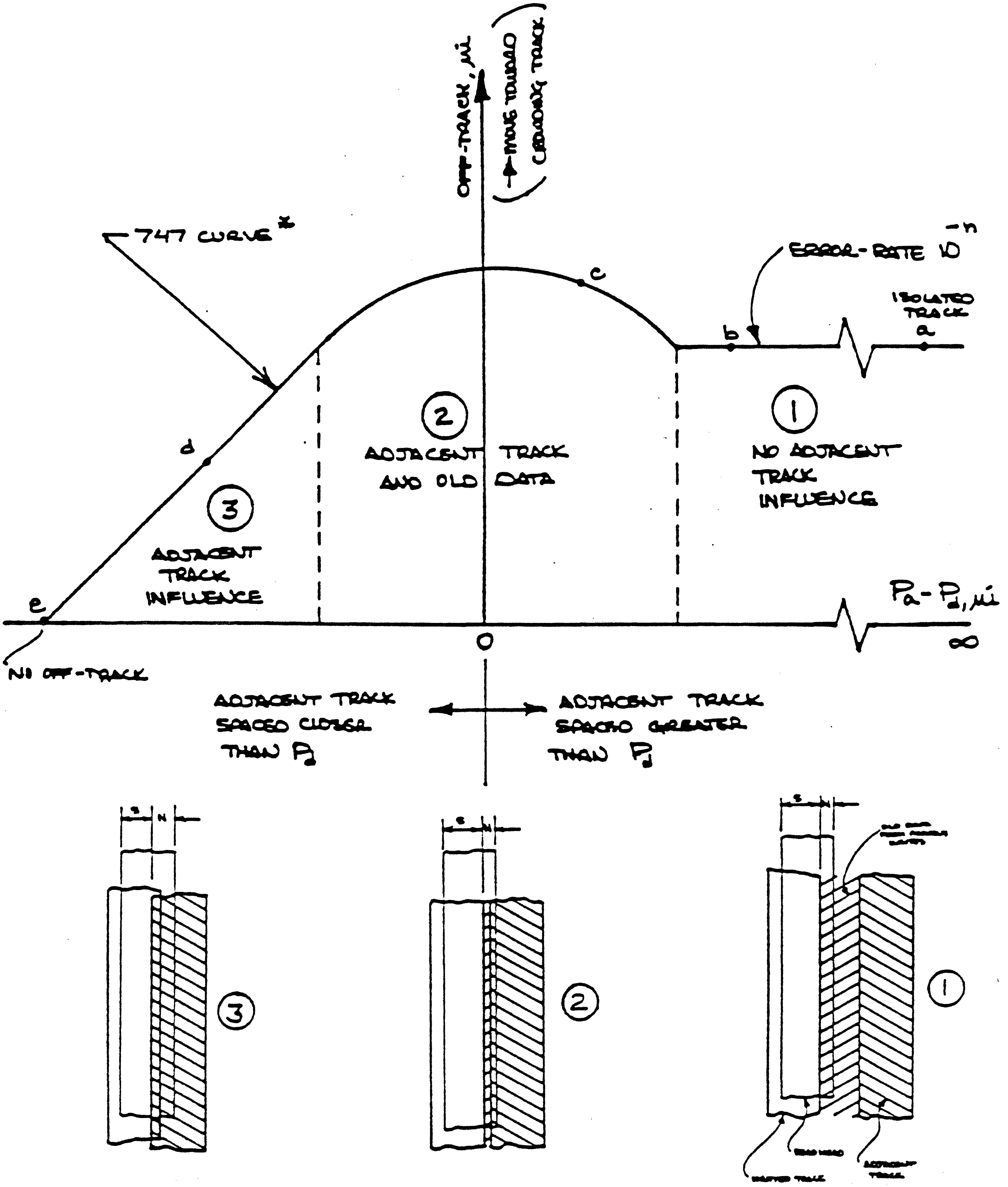


RESULTING W/W P.D.F.

$$(W/W)_i(x) = P_{a_i}(x) - P_d$$

MRH
3-7-88

747 OTC CURVE



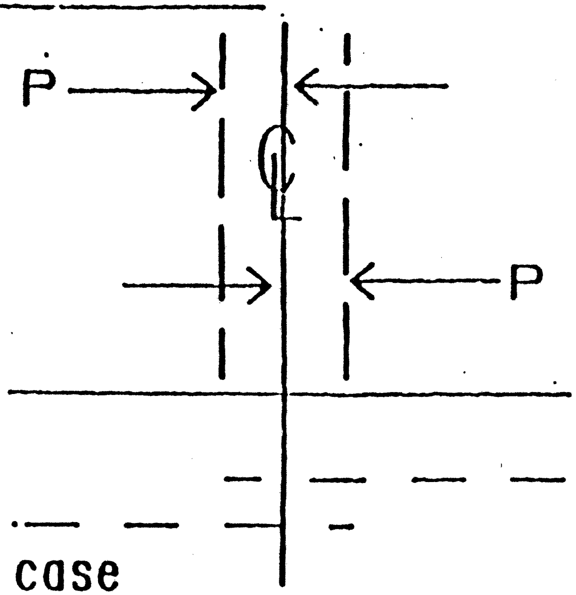
* GUZIK TESTER SOFTWARE GENERATES AUTOMATICALLY

MRH
3-7-88

SINGLE ELEMENT vs WRITE WIDE/READ NARROW

±P = head to medium lateral registration tolerance

SINGLE ELEMENT



worst case

new information α W−2P
adj. track info α P
old information α P
or interference α 2P

for 10 to 1 ratio (signal to interference)

$$\frac{W-2P}{2P} = 10$$

W = 22P (tpi = 1/W)

DUAL ELEMENT

W= write width
R= read width

about track centerline:

W−2P= guaranteed newly written write band

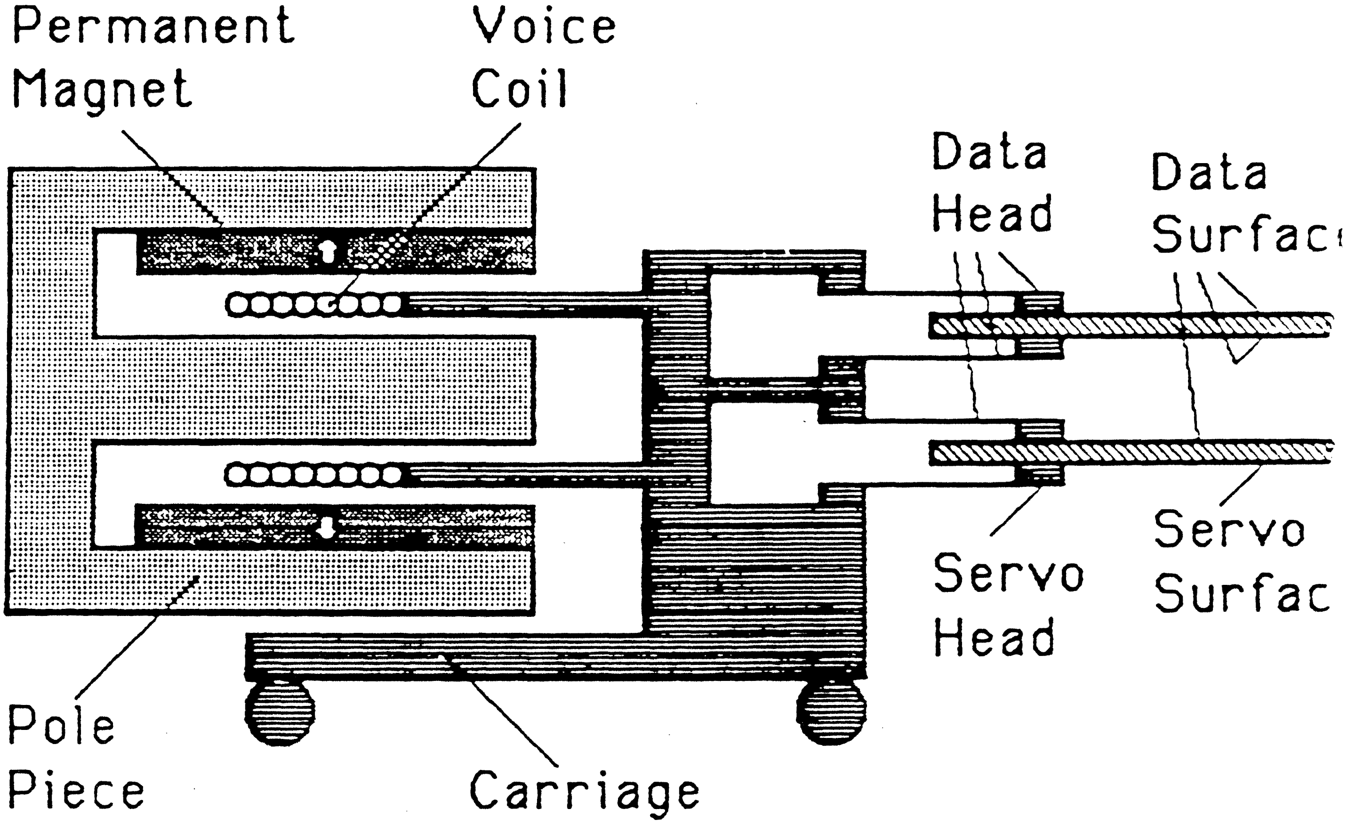
R+2P= width within which reading must occur

For no interference

$R+2P < W-2P$

or $W \geq R+4P$

Closed Loop Actuator - Principle



The carriage is actuated by a linear ("voice coil") motor. The carriage position is sensed from a magnetic servo pattern. Most commonly, the servo pattern is on a dedicated surface, (servo surface) and read by a servo head. The magnetic servo pattern is prerecorded during drive manufacturing.

HIGH PERFORMANCE HEAD POSITIONING SERVO SYSTEM (HPHPSS) BLOCK DIAGRA

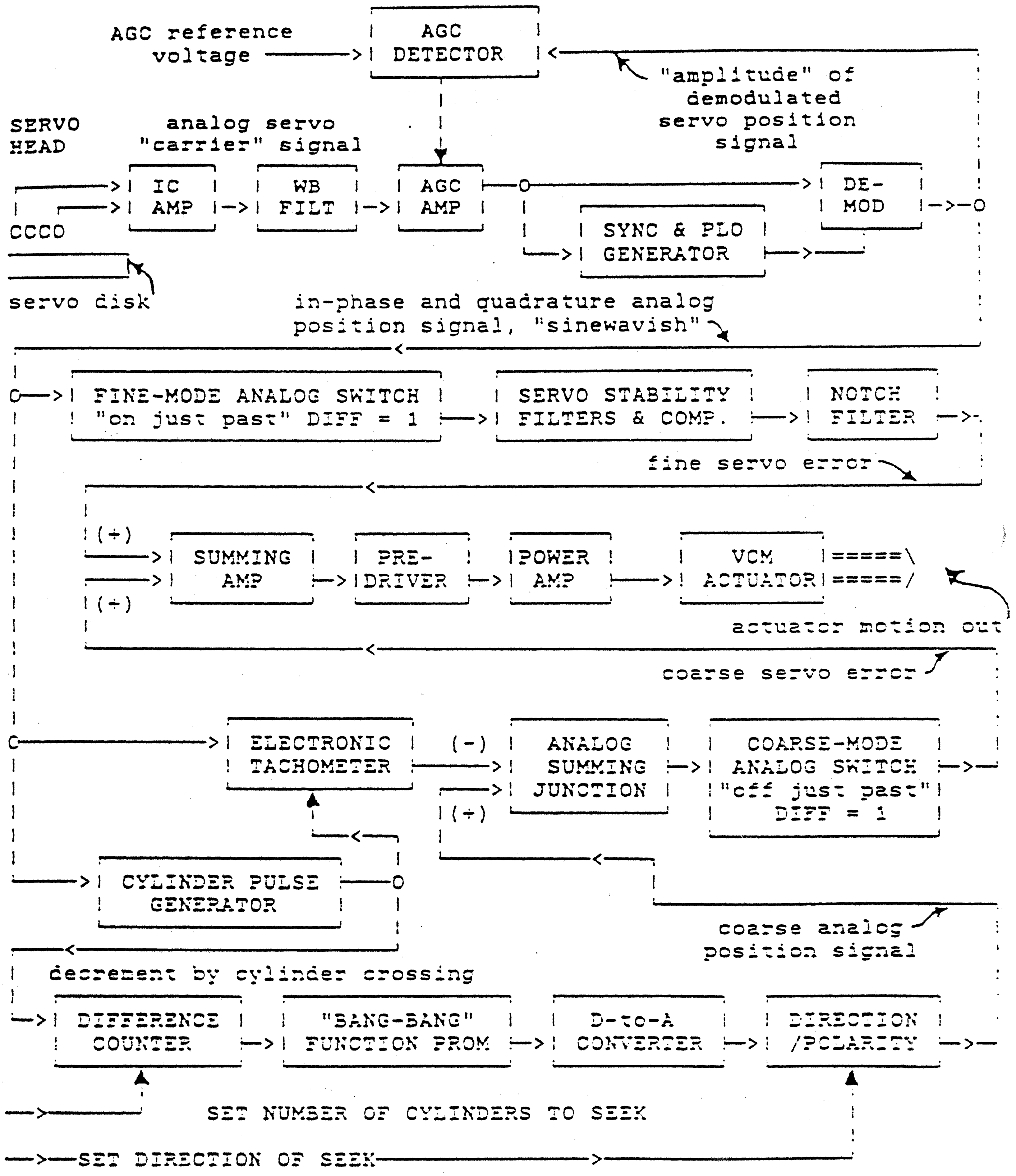
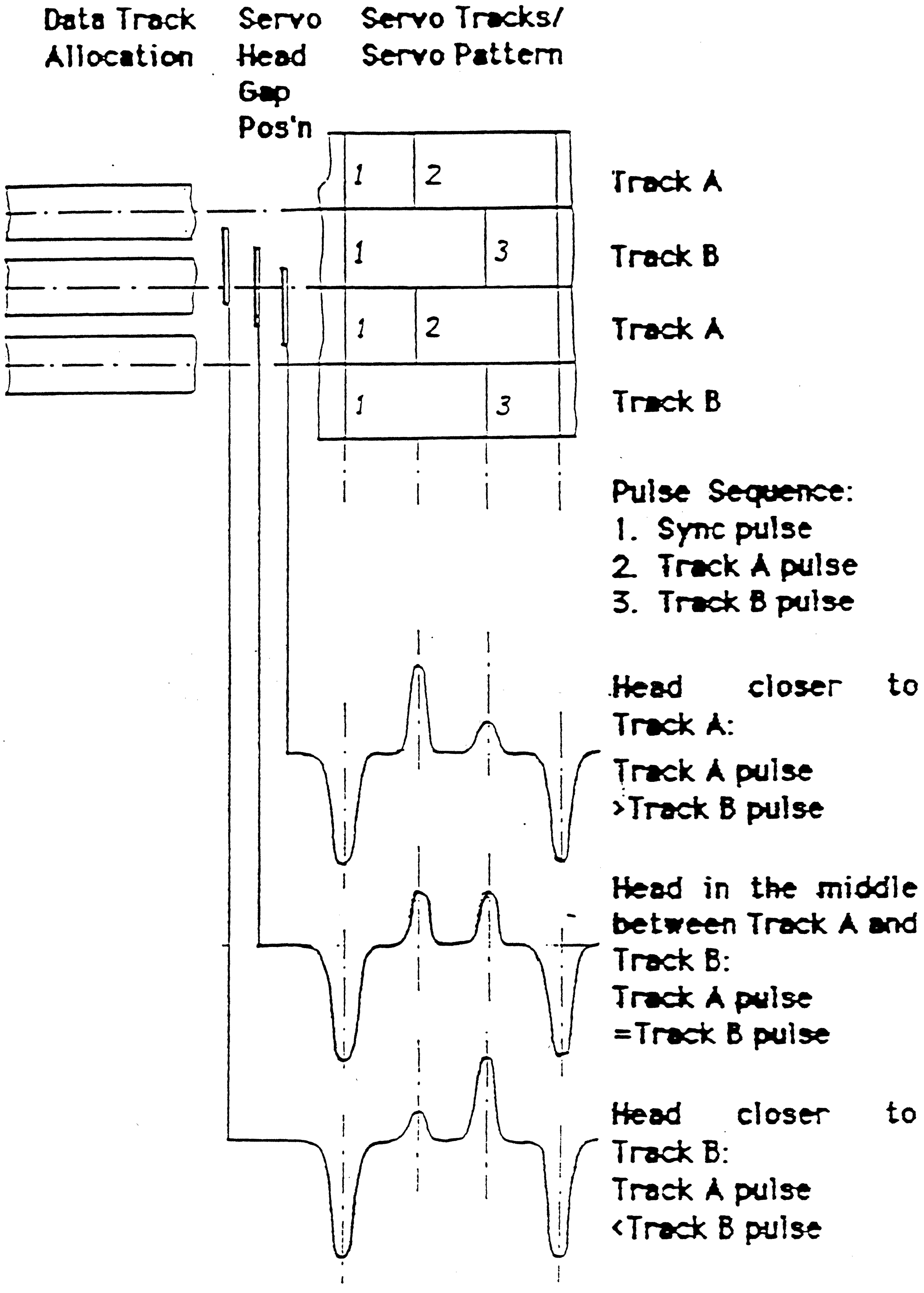


FIGURE E

"Tribit" Servo Pattern



Pulse Sequence:
1. Sync pulse
2. Track A pulse
3. Track B pulse

Head closer to Track A:
Track A pulse
>Track B pulse

Head in the middle between Track A and Track B:
Track A pulse
=Track B pulse

Head closer to Track B:
Track A pulse
<Track B pulse

ENCODER AND WEDGE/TRACK

+ PROS;
  - SIMPLE SERVO WRITER
  - LOW OVERALL COST
  - LOW OVERHEAD
  - TRANSPARENT TO CONTROLLER - FREE FORM FORMATTING
+ CONS;
  - LOW BANDWIDTH FEEDBACK FROM DISK (ONCE AROUND)
  - CORRECTS FOR LONG TERM EFFECTS ONLY
  - HIGHER INERTIA OF ARM STACK (ACCESS TIME CONSIDERATION)
  - LIMITED TPI UPPER LIMIT

OPTICAL ENCODER-WEDGE SERVO OVERVIEW

- SEEKING IS PERFORMED BY CLOSING A SERVO LOOP AROUND AN OPTICAL ENCODER MOUNTED BETWEEN THE HEAD ARM AND DRIVE BASE.

- DURING READ/WRITE POSITIONING THE HEAD ARM IS SERVOED USING THE OPTICAL ENCODER FOR PRIMARY POSTION FEEDBACK.

- ALSO DURING READ/WRITE THE TRACK CENTER REFERENCE FOR THE OPTICAL ENCODER SERVO IS DETERMINED BY A ONCE PER REVOLUTION SERVO WEDGE ON A DATA SURFACE.

- DURING SEEKING THE SERVO WEDGE CANNOT BE READ WITHOUT A LATENCY SEEK TIME PENALTY. THIS IS SOLVED BY A THERMAL PREDICTION ALGORITHM.

- SERVOWRITING OF THE WEDGE SERVO IS PERFORMED UPON A SEALED DRIVE WITH THE OPTICAL ENCODER AS THE POSITION REFERENCE.

3/24/88 JNH

EMBEDDED

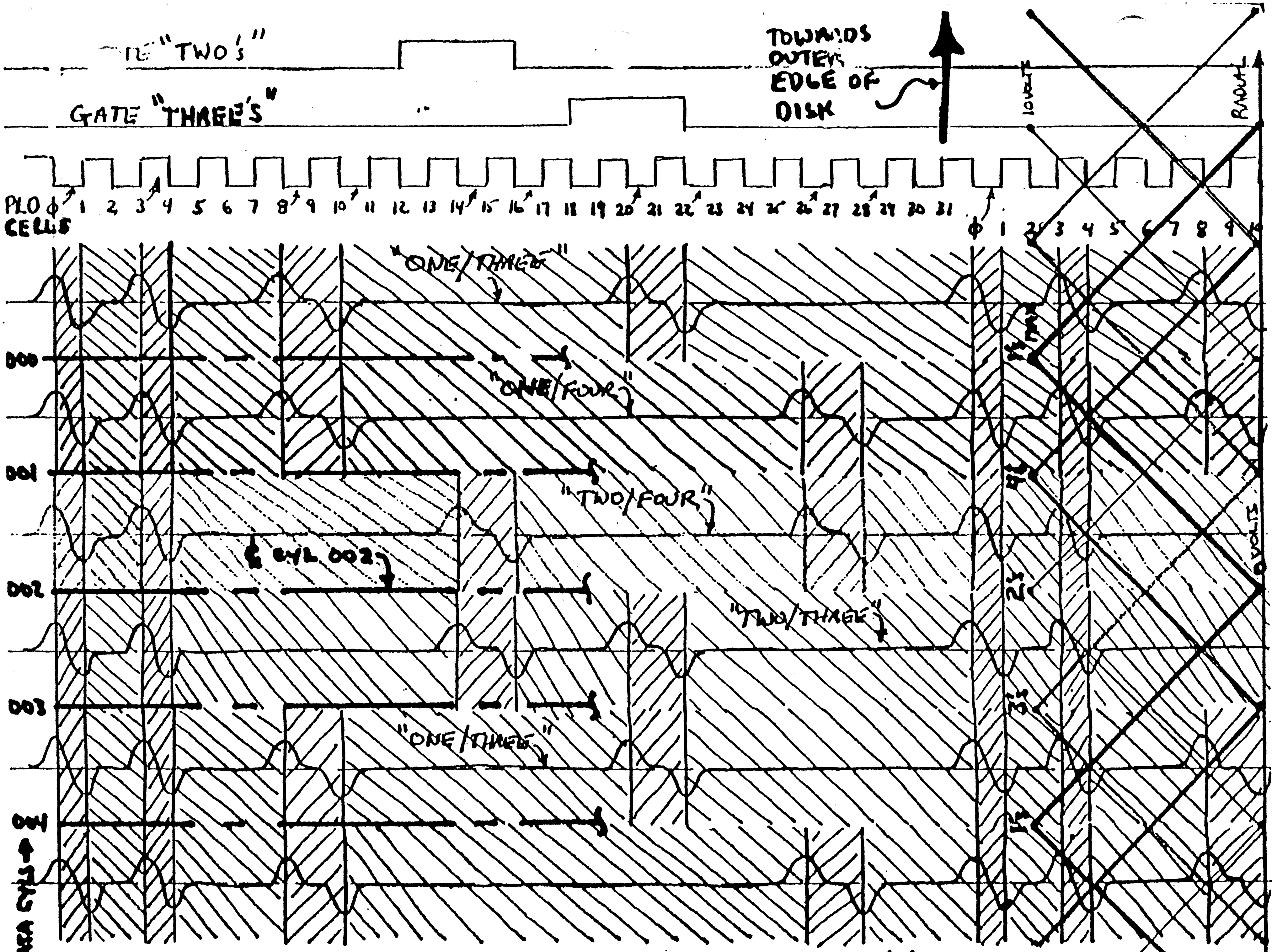
- + PROS;
  - FEEDBACK FROM DATA HEADS
  - REMOVES THERMAL TILT VARIATIONS
  - LOWER OVERHEAD
- + CONS;
  - "NON ZERO" HEAD SWITCH TIME
  - LOWER BANDWIDTH SERVO SYSTEM
  - HARD SECTORED - LESS TRACK FORMAT FLEXIBILITY
  - INCOMPATIBLE WITH DEVICE LEVEL INTERFACES
  - SETTLING TIME

DEDICATED AND EMBEDDED

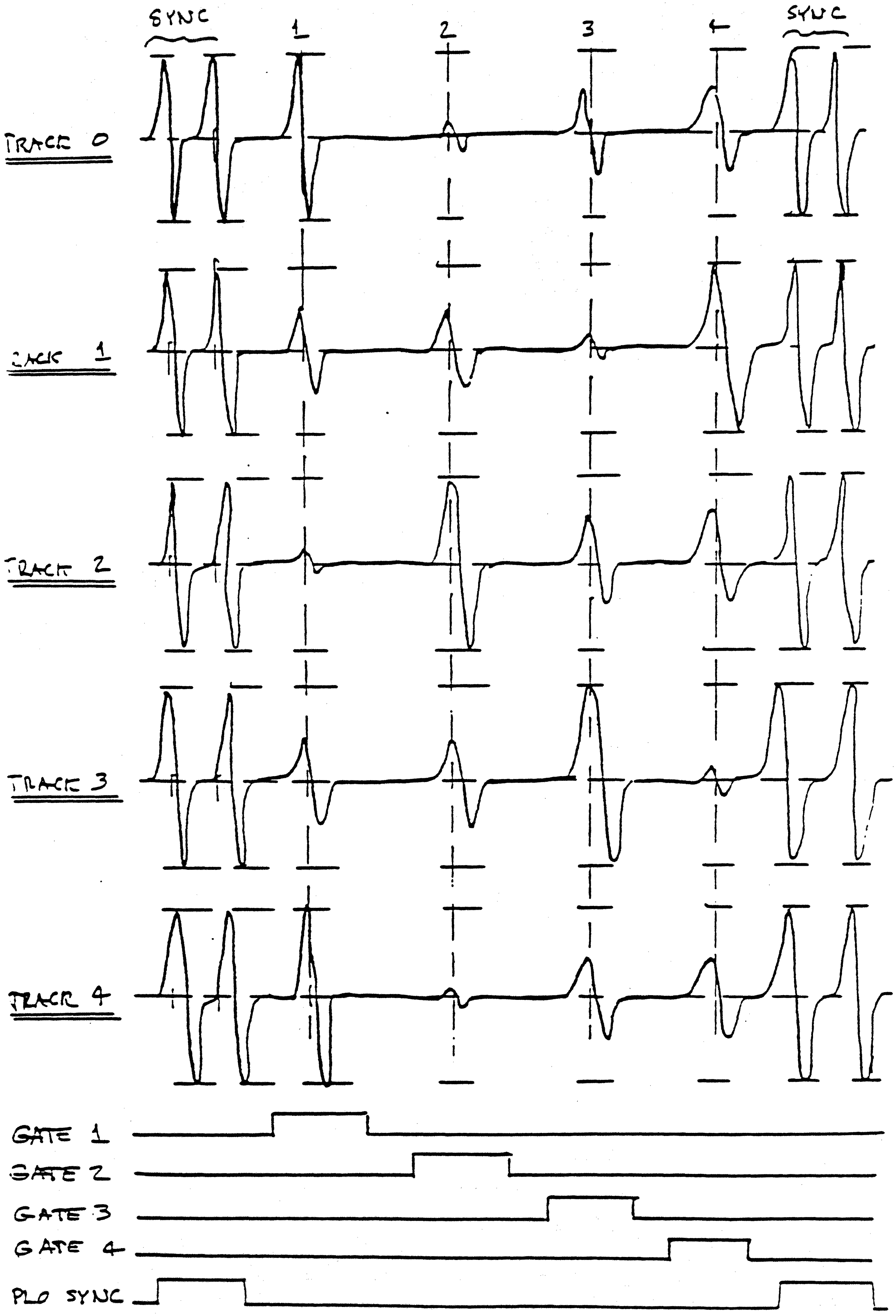
- PROS;
  - BEST OF BOTH WORLDS
  - WIDE BANDWIDTH FROM DEDICATED SURFACE
  - FEEDBACK FROM DATA HEADS
  - HIGHEST TPI POTENTIAL
- CONS;
  - "NON ZERO" HEAD SWITCH
  - HARD SECTORED - LESS TRACK FORMAT FLEXIBILITY
  - INCOMPATIBLE WITH DEVICE LEVEL INTERFACES
  - HIGHEST OVERALL COST
  - HIGHER OVERHEAD

DEDICATED SURFACE

+ PROS;
  - FEEDBACK FROM DISK STACK
  - WIDE SERVO BANDWIDTH
  - CORRECTS RUNOUT
  - BETTER SHOCK AND VIBRATION IMMUNITY
  - WELL DOCUMENTED APPROACH
  - MORE PRECISE SERVOWRITING
  - TRANSPARENT TO CONTROLLER - FREE FORM FORMATTING
+ CONS;
  - FEEDBACK FROM SERVO HEAD ONLY
  - NOT EFFECTIVE FOR DIFFERENTIAL DISK SLIP
  - SERVO TO DATA SURFACE RELATIONSHIP DESIGNED IN (COST OF MECHANICS)
  - EXPENSIVE SERVOWRITERS
  - % OF OVERHEAD INCREASES WITH SMALLER FORM FACTORS



F.J. SORDELLO PAGE 65 FIGURE 26 5/1/86


SYNC
1
2
3
4
SYNC
TRACK 0
TRACK 1
TRACK 2
TRACK 3
TRACK 4
GATE 1
GATE 2
GATE 3
GATE 4
PLO SYNC

Several thousands of servo bytes are recorded around the total circumference of the disk.

The PLO is synchronized to the disk by these first synchronizing sets, with transitions occurring at the beginning of "cells" 0, 1, 3, and 4. After these synchronizing sets, a total of four, different, repeating, radial position information-bearing recorded-"cell" patterns are shown:

"ONE/THREE" = OT = TRANSITIONS AT BEGINNING OF "CELLS" 8, 10, 20, 22.

"ONE/FOUR" = OF = " " " " " 8, 10, 26, 28.

"TWO/FOUR" = TF = " " " " " 14, 16, 26, 28.

"TWO/THREE" = TT = " " " " " 14, 16, 20, 22.

"ONE/THREE" = OT = " " " " " 8, 10, 20, 22.

The individual servo tracks are recorded at the track density that the disk product will use for customer data tracks (here = 1400 TPI) at the factory by an expensive, instrument-quality, servo writer. The servo-head in the disk drive product has **TWICE** the core width of the data head such that it reads **TWO** servo tracks simultaneously! The servo head, being twice the recorded servo pattern's track width, assures smoother and more continuous increases and decreases of the sensed amplitude of di-pulses as the servo head moves across the disk's radius. Servo pattern di-pulses are amplified and linear-phase, low-pass filtered to maximize signal-to-noise ratio while maintaining di-pulse waveform fidelity. The demodulator can be nothing more than a set of four (or eight) gated diode, peak-rectifying, sample-and-hold (S&H) circuits, with controlled held-voltage sag, that obtain and store the di-pulse amplitudes read by the servo head. For the pattern of figure F, a minimum of four S&H circuits are needed, one to be gated-on by timed signals from the synchronized PLO for each dipulse time location within the servo byte. Careful study of the complex servo surface patterns and associated electrical signals of figure F yields the method of generation of the IN-PHASE, and QUADRATURE servo transduction signals for locating data track/cylinder centerlines.

Refer once again to figure F. Assume that the servo head is centered along data cylinder 002. (The terms "Tracks" and "Cylinders" are interchangeable for this analysis: "Cylinders" referring to a plurality of "Tracks" due to a plurality of disks and hence data-surfaces at a servo position null.) At the top of figure F is shown two of the four demodulating gates logically generated by the syncbit-pattern-locked PLO system. Gate "TWO's" turns-on the diode demodulator (see figure G on page 20) that S&H's the radial position-sensitive readback amplitude of di-pulses written at the beginning of PLO count 14. The demodulated servo-head position signal, consisting of the S&H'ed **algebraic sum of the servo- head sensed di-pulse** zero-to-positive-peak amplitudes of servo tracks "TWO/FOUR" and "TWO/THREE", is shown as "2's" varying radially at the right-hand side in figure F. Note its maximum value occurs at the centerline of data cylinder 002.

At the same radial location, the demodulating circuit that is gated by gate "THREE's" will S&H'ed a signal value that is half of the possible peak value, since the servo-head senses a dipulse contribution from only servo pattern track "TWO/THREE" at that time. The S&H'ed output of the demodulator controlled by gate "FOUR's" (not shown) will also be half of the maximum possible amplitude value since the servo-head senses only the contribution from servo track "TWO/FOUR" at gate "FOUR's" time (not shown). Following the same analysis, the output of the demodulator controlled by gate "ONE's" (not shown) is zero volts at the stated servo-head radial position.

Hence the four demodulator outputs ("1's", "3's', "2's", and "4's") vary as a function of servo-surface disk-radius as shown at the right-hand side in figure F.

Refer to figure H on page 21. The IN-PHASE servo position signal is formed by demodulated signals "3's" minus "4's". The QUADRATURE servo position signal is formed by demodulated signals "1's" minus "2's". The reason for the above algebraic combinations is due to the fact that each **demodulated** di-pulse signal or any magnetically recorded, **read-back** and **demodulated** signal tends to have sharper "pointed" maximum values and quite "sloppy" or "rounded" near-zero voltage values. When "locking-on" to cylinder 002, the Fine Mode servo uses IN-PHASE position signal by which a positive voltage causes VCM current to force the VCM towards a lower-numbered cylinder (001) direction, and negative IN-PHASE voltage causing VCM current to force the VCM towards cylinder 003. In order to lock-on to cylinder 001, inverted QUADRATURE position is selected. For cylinder 002, IN-PHASE is selected. For cylinder 003, QUARDRATURE is selected. And, for cylinders 000, or 004, inverted IN-PHASE is selected.

The servo-pattern magnetic flux as a function of radial position that the servo-head senses and the **sum of the demodulated di-pulse amplitudes** at any radius is a constant.(Ideally, it should be constant, but the "sawtooth's rounding especially near zero signal values causes some inconsistencies.) An AGC circuit utilizes this **fairly constant** feature to facilitate amplitude, and hence position gain calibration, such that the overall transduction gain (in volts/inch) is constant. (A magnetically recorded digital signal is amplitude-dependent upon a number of parameters, including relative velocity between the reading-head and disk surface.) The end result is the classical saw-tooth-like position signals as a function of disk radius shown in figure F.

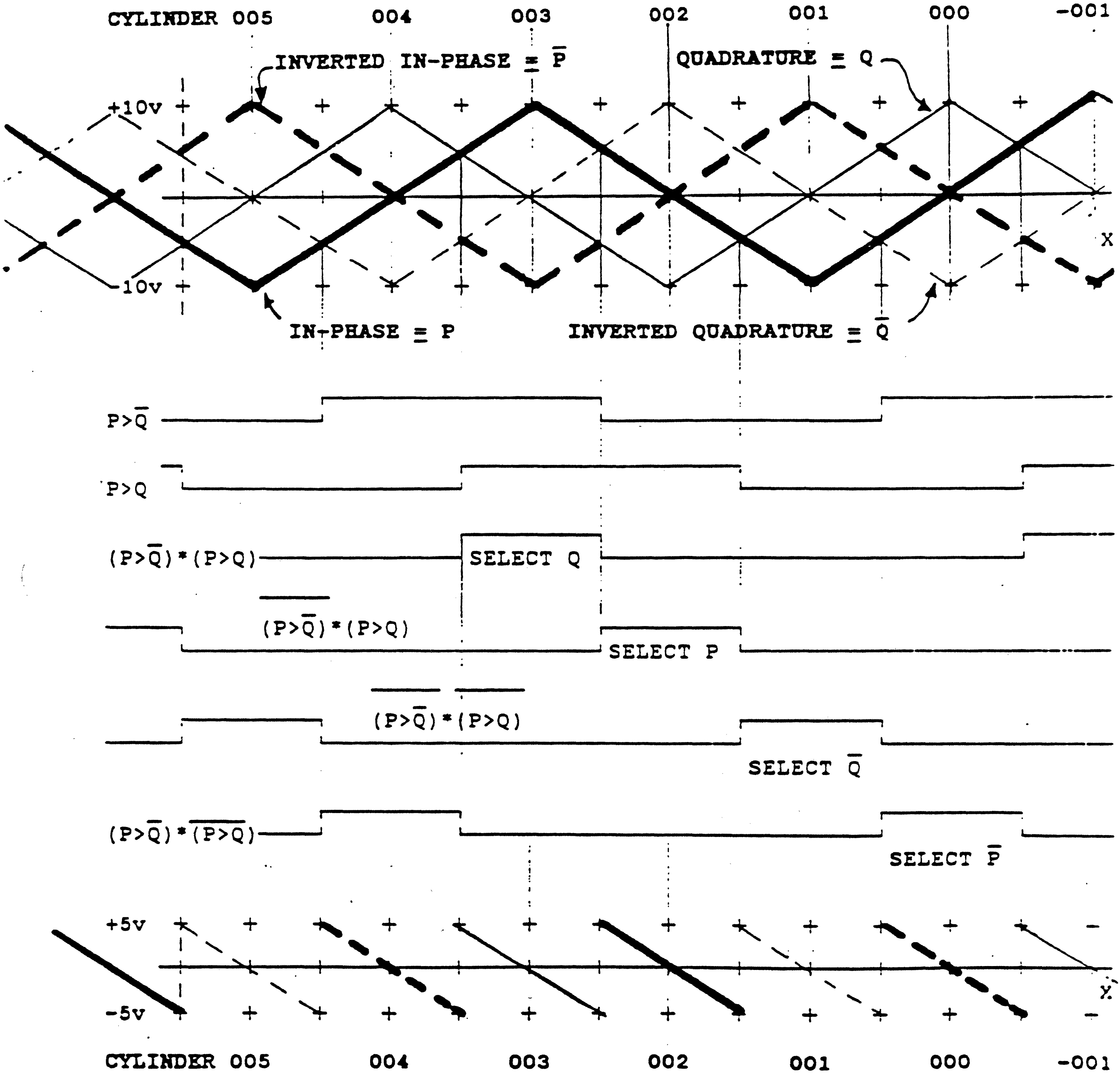
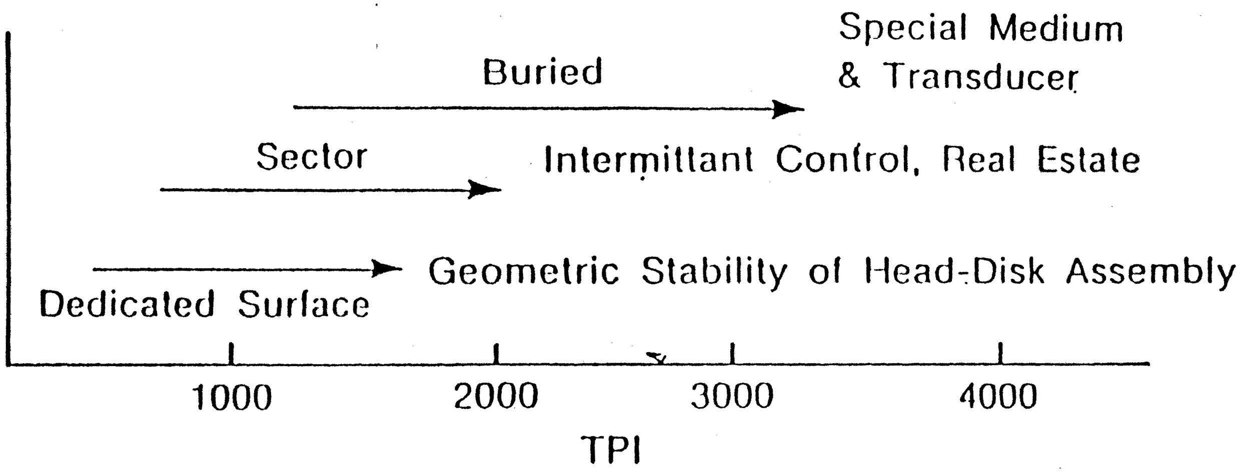
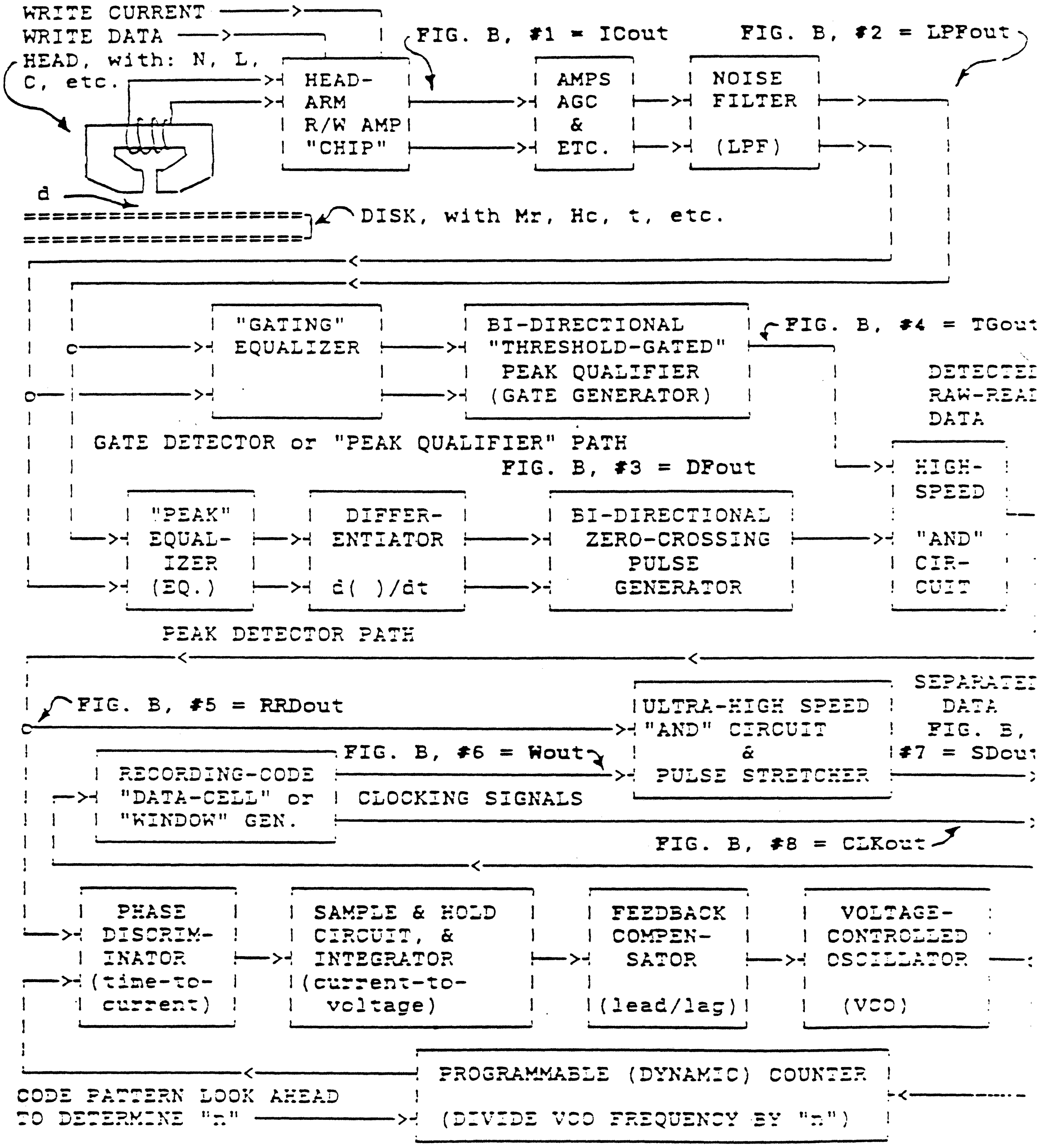


FIGURE H POSITION TRANSDUCER "IN-PHASE", "INVERTED IN-PHASE", "QUADRATURE", AND "INVERTED QUADRATURE" SIGNALS VERSES RADIAL DISK POSITION OR CYLINDER LOCATION; LINEAR REGION SELECTION LOGIC AND CYLINDER COUNTING IN COARSE MODE; AND, SELECTED LINEAR REGION FOR FINE MODE.

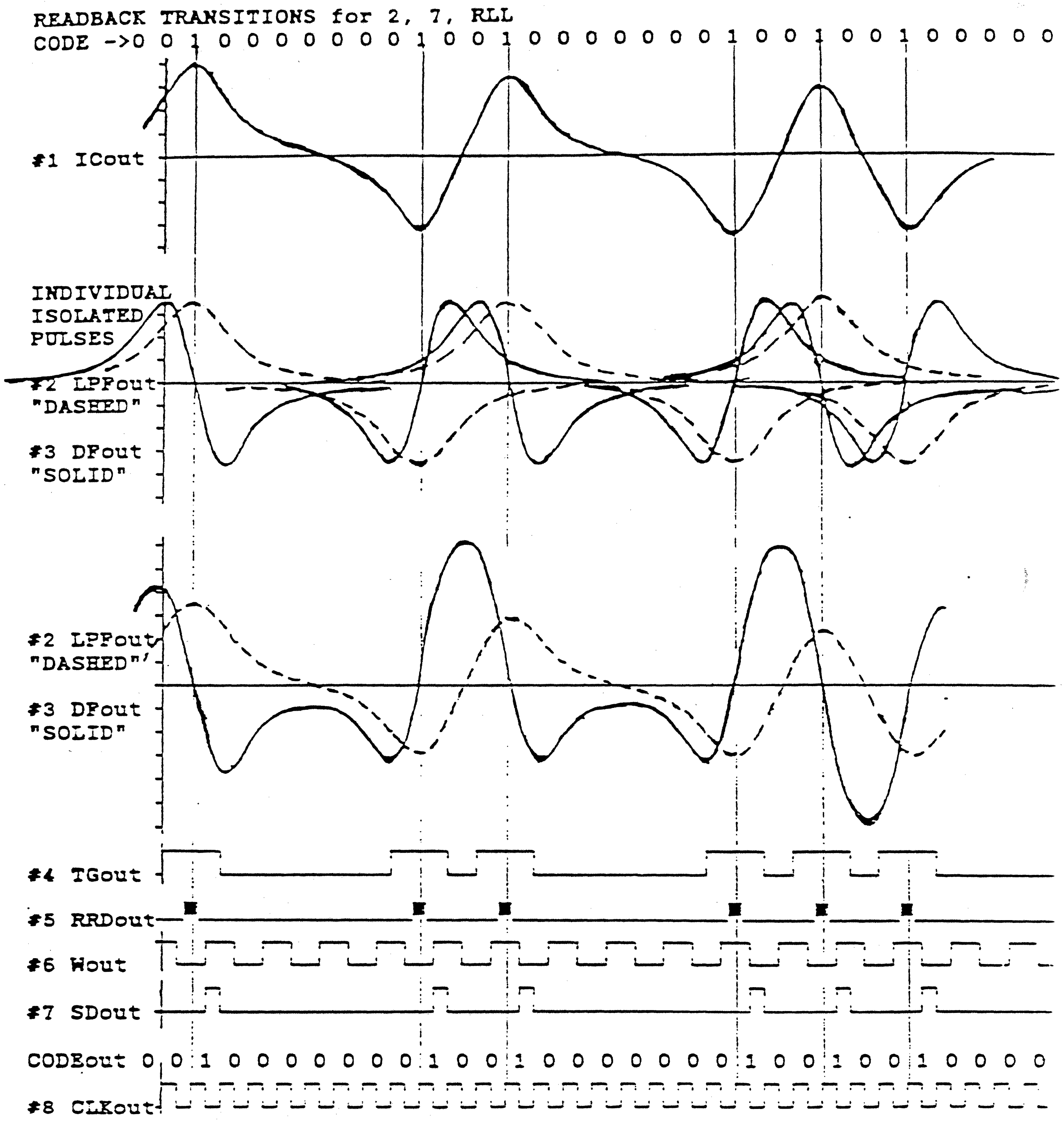
Track Density in Magnetic Storage





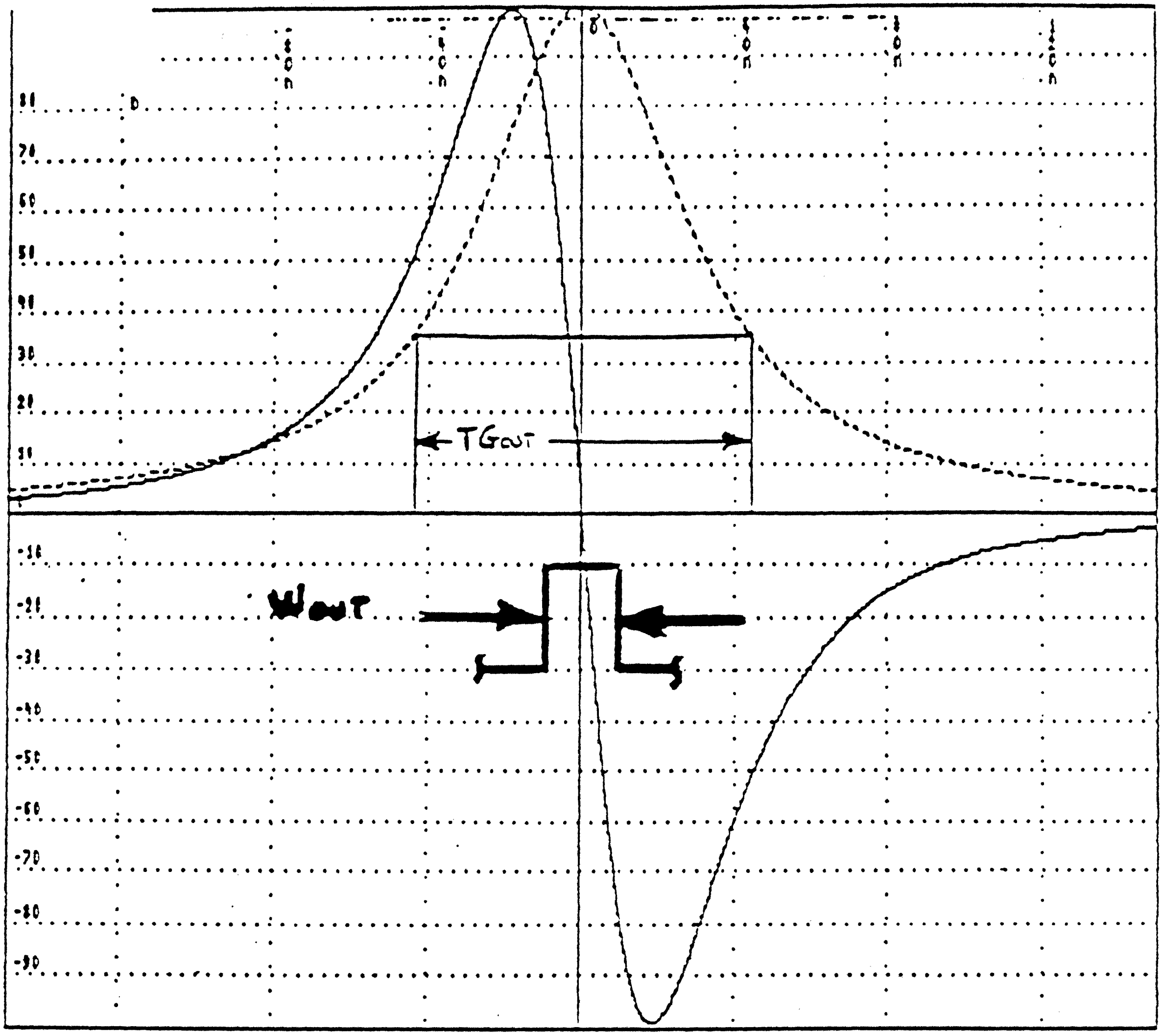
"VFO", "PLL", "PLO", or PHASE-LOCKED DATA SEPARATOR CLOCKING SYSTEM

FIGURE A. TYPICAL HIGH-PERFORMANCE DISK DRIVE RECORDING CHANNEL



FIRGURE B. READBACK SIGNALS AT VARIOUS STAGES WITHIN READ CHANNEL
(All intrinsic circuit delays have been eliminated .)
clairity. For 24 Mbit/sec = 3 Mbyte/sec, one "Wout"
cell (½ complete cycle of "Wout") = 20.833 nanosecond.

LORENTZIAN (Pw50=65nS) RESPONSE Frank J. Sordello 3/4/1988 14:07:58
Left: -150nS, Right: 150nS, Top: 100, Bottom: -100, Time Step:200pS



TGout IS
TRUE WHEN
LPFout IS
± 35 % OF
ITS PEAK
VALUE.

Wout IS
20.8nsec

NORMALIZED LPFout (T50 changes from 55 to 65 nsec in LPF) and RESULTING D
Analysis by Frank J. Sordello. Common Block Zero at: 0Hz; Pole at: 1000MH
The gain is currently set to -146.089db. This has 0db at 3.333MHz.

FIGURE C:. NORMALIZED LPFout & DFout, with TGout & Wout TIME-BOUNDARIES MARKED for ISOLATED READBACK PULSE.

A STUDY OF THE CHARACTERISTICS OF THE VARIOUS READ CHANNEL SIGNALS OF FIGURE B, WHEN THE HEAD SHOWN IN FIGURE A READS A SINGLE RECORDED TRANSITION (AN ISOLATED READBACK PULSE) QUICKLY REVEALS A GREAT DEAL. REFER TO FIGURE C. FIGURE C ALLOWS US TO OBSERVE THE SLOPE OF THE DIFFERENTIATED (AND EQUALIZED) NOISE FILTER OUTPUT. THE ZERO CROSSING OF DFout IS INTENDED TO CORRISPOND EXACTLY TO THE TIME OF OCCURANCE OF THE PEAK OUTPUT OF LPFout. IDEALLY, THE PEAK OUTPUT OF LPFout CORRISPONDS TO THE SPATIAL CENTER OF THE MAGNETIC TRANSITION RECORDED IN THE DISK MEDIUM. (AT LEAST WITHIN THE TOLERANCES OF THE PARAMETERS OF THE MANY ENGINEERING DICIPLINES AND PHENOMENA ASSOCIATED WITH DIGITAL MAGNETIC RECORDING!)

BIT-SHIFT
ON TRACK

	(@ ANY TIME	**@ $x10^{10}$** (6.5*sigma)
NOISE INDUCED **NIB**	0.71	3.25
PATTERN INDUCED **PIB**	2.4	2.4
OVER WRITE **OWIB I**	0.8	0.8
OWIB II	1 -> 3	1 -> 3
ASYMMETRY **ASIB**	0.5 -> 2	0.5 -> 2
SYSTEM NOISE **SNIB**	0.1 -> ?	0.1 -> ?
ADJACENT TRACK **ATIB**	~0	~0
	5.51	8.05
ERROR RATE	10^{10}	10^{10}
MARGIN	4.91	2.37

BIT-SHIFT
ON TRACK and DURING MINOR DEFECT

(DFout slope divided by 0.7)

	@ ANY TIME	**@ $x10^{10}$)** (6.5*sigma)
NIB	1.01	4.64
PIB	3.43	3.43
OWIB I	0.8	0.8
OWIB II	1 -> 3	1 -> 3
ASIB	0.5 -> 2	0.5 -> 2
SNIB	0.14 -> ?	0.14 -> ?
ATIB	~0	~0
	6.88	9.71
ERROR RATE	10^{10}	10^{10}
MARGIN	3.54	0.71

BIT-SHIFT
OFF TRACK

(DFout slope divided by 0.75)

	(@ ANY TIME	**@ $x10^{10}$** (6.5*sigma)
NIB	0.95	4.33
PIB	2.4	2.4
OWIB I	0.8	0.8
OWIB II	1 -> 3	1 -> 3
ASIB	0.5 -> 2	0.5 -> 2
SNIB	0.13 -> ?	0.13 -> ?
ATIB	1.5	1.5
	7.28	10.66
ERROR RATE	10^{10}	10^{9}
MARGIN	3.14	0

BIT-SHIFT
OFF TRACK and DURING MINOR DEFECT

(DFout slope divided by 0.7*0.75)

	@ ANY TIME	**@ $x10^{10}$)** (6.5*sigma)
NIB	1.35	6.19
PIB	3.43	3.43
OWIB I	0.8	0.8
OWIB II	1 -> 3	1 -> 3
ASIB	0.5 -> 2	0.5 -> 2
SNIB	0.19 -> ?	0.19 -> ?
ATIB	2.14	2.14
	9.41	14.25
ERROR RATE	10^{10}	10
MARGIN	1.01	0.

Track Width

- (W = Track width) (s = signal output)
- $s \propto We^{-\pi d(fci)}$
- $tpi \propto \frac{1}{W}$
- track density *versus* linear density

  $bits/in^2 \propto (fci)(tpi) \propto (fci) \times s \times e^{\pi d(fci)}$

  holding s constant, maximize $bits/in^2$ in terms of bpi and tpi

  $$\frac{\partial(bits/in^2)}{\partial fci} = 0 \quad \text{or} \quad fci = \frac{1}{\pi d}$$

  (ignoring noise) operate where a further increase in linear density causes a greater signal loss than an increase in track density would.

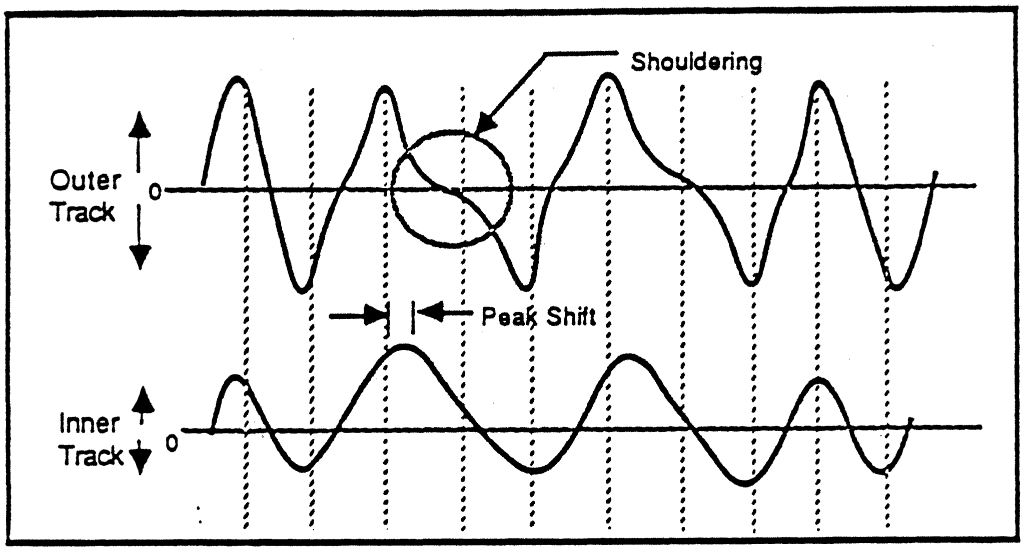


FIGURE 1

TYPICAL HEAD OUTPUT WAVEFORMS

Each peak in the waveforms above represents a recorded "1" bit. To correctly decode this data, a drive must accurately detect the occurrence of a signal peak. Furthermore, each peak must be detected within a period of time referred to as the Data Window to correctly establish the original sequence of "1"s and "0"s.

Because individual flux reversals are relatively far apart on the outer track, there are regions in which the flux is constant. As a consequence the head output signal hovers about zero for an extended time before the next peak is encountered. This is the *"Shouldering"* phenomena visible in the outer track waveform. Shouldering is a problem because it presents a relatively long lived opportunity for even low amplitude *noise* to *falsely trigger* the peak detection circuitry

In contrast, on the inner track, flux reversals are packed so closely together that the head is never exposed to regions where the flux is constant; the signal associated with the inner-most track passing through zero quickly. Shouldering is therefore not a problem on the inner track, however other effects present similar opportunities for noise to cause an error.

Visualizing the shifts in detection that occur due to noise and Peak Shift as a *Statistical Distribution* within the Data Window is the first step in the modeling process. As shown in Figure 2, the perspective gained by this model yields an immediate observation, *the error rate of a drive is the total area of the distribution falling outside the Data Window.*

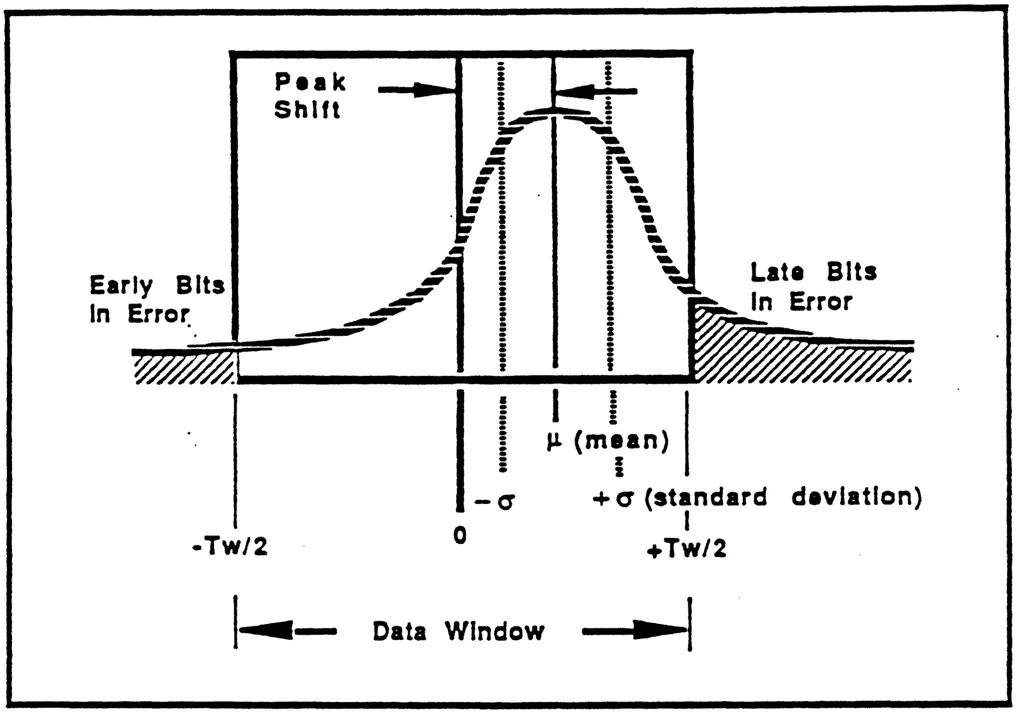


FIGURE 2

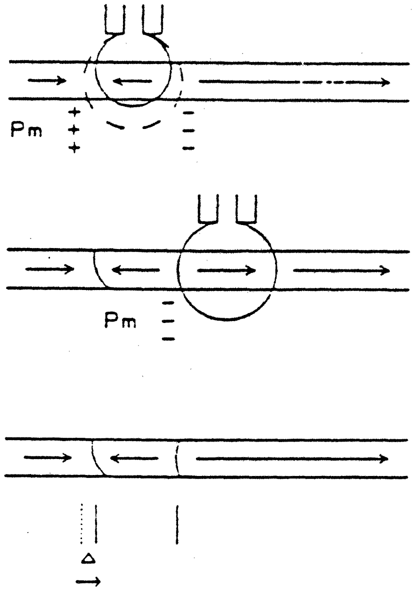
STATISTICAL DISTRIBUTION

The next step in the modeling process is the choice of statistics. Assuming that the shifts in peak detection conform to a *Gaussian* model, makes the task of comparing noise and Peak Shift to the Data Window simple. According to the Gaussian model, the area outside the Data Window is directly related to the ratio of Data window width to the Mean (μ) and Standard Deviation (σ) of the distribution. This is referred to as the *intrinsic error rate* † of the system.

---

† Katz and Campbell, "Effect of Bitshift on Error Rate in Magnetic Recording", IEEE Transactions on Magnetics, Vol. Mag. 15, No. 3, pp 1050-1053, May 1979

WRITE-INDUCED BIT SHIFT



Disk Memory Division
S. Brittenham 7/88

HEWLETT PACKARD

Transitions are written onto the disk by changing the direction of the head field to reverse the media magnetization. In this example, the media is dc-erased and its magnetization is represented by the right-facing arrows. In the upper figure, the head field (dotted circle) is opposite that of the media (left-facing arrow), so the effective writing field is reduced (solid circle). Since the head moves to the right, the field's trailing edge forms the transition; because of the reduced writing field, this transition will be displaced to the right (bottom figure, left-hand transition). In the middle figure, the head has moved to the position of the next transition; the head current has reversed, and its field is now in the same direction as that of the media. The effective writing field is not reduced, so no displacement of the transition occurs.

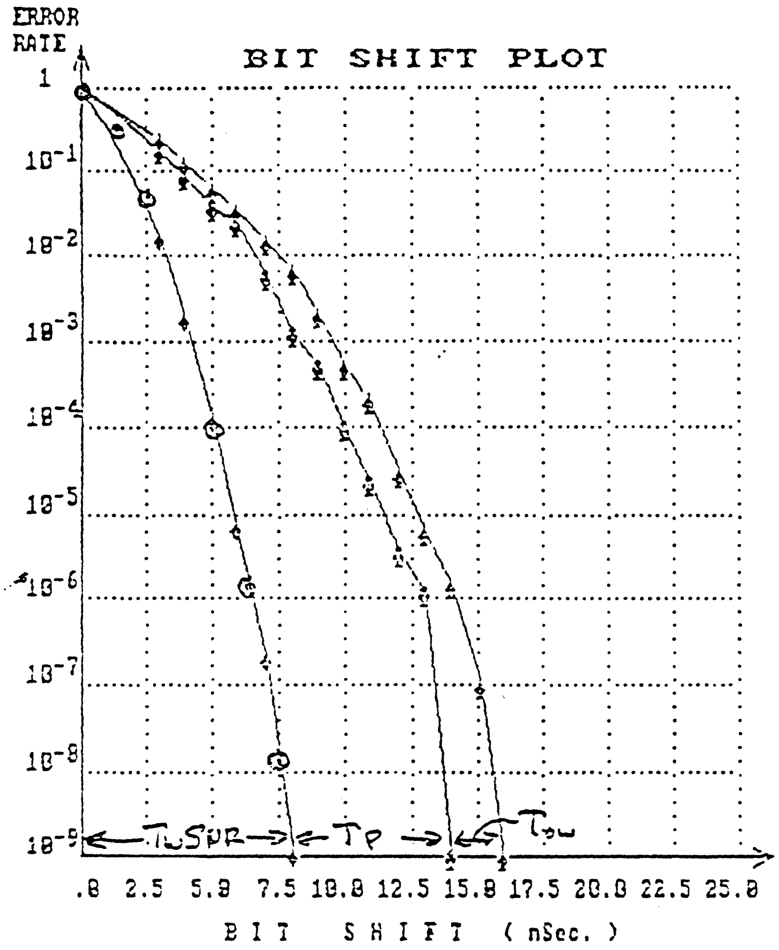
For constant frequency patterns written over dc-erased media, alternate transitions are displaced late in time; the decibel overwrite measurement indirectly quantifies the resulting asymmetry between consecutive time intervals. However, a more direct measure of this effect is obtained through time interval asymmetry measurements.

[A specific implementation of the asymmetry measurement is described in the companion presentation.]

```
                    *** TRACK  ANALYSIS  ***

 ID: [redacted]2/175      10/30/86     12:12:05       TRACK #     0    HEAD #   0
-  -----------------------------------------------------------------------------

       AMPLITUDE        =      .26mV        IF    AMPLITUDE        =     .32mV
 NEGATIVE MODULATION =    -6.65%           POSITIVE MODULATION =     6.31%
 RESOLUTION             =    80.17%          PULSE WIDTH           =  110.87nS
                                             OVERWRITE             =   32.12dB
 ASYMMETRY NEGATIVE    =  -7.06nS           ASYMMETRY POSITIVE    =    4.58nS
```



```
  TRAK HD PTRN ZERO S THRS
♦    0  0 FFFF  8.9 I 49.8
♦    0  0 B6D9 17.7 I 49.8
♦    0  0 B6D9 18.2 I 49.8
```

No erase

+ Erased before B6D9

o—o erfc(z)

$SNR = 17.0 \left(\frac{rms}{rms}\right)$

$f_r = 5$ MHz

$T_p = 0$; $T_{ow} = 0$

$\Big\}$ 1111 pattern

$T_{W\,SNR} \simeq 8.9$ nsec

B6D9: 0110110 peak shift pattern

$T_p \simeq 5.9$ nsec

$T_{ow} \simeq 1.8$ nsec

$T_{w10} \simeq 17$ nsec

```
ID: [redacted]#2/175
 10/30/86      12:13:49
```

$H_c \simeq 1050$ Oe

21 Kfci

$P1|G|P2 = 3.0|0.5|3.0\mu$

10 μ'' fly Height

$\Delta f = 15$ MHz

EMWilliams

READ-RITE Co.

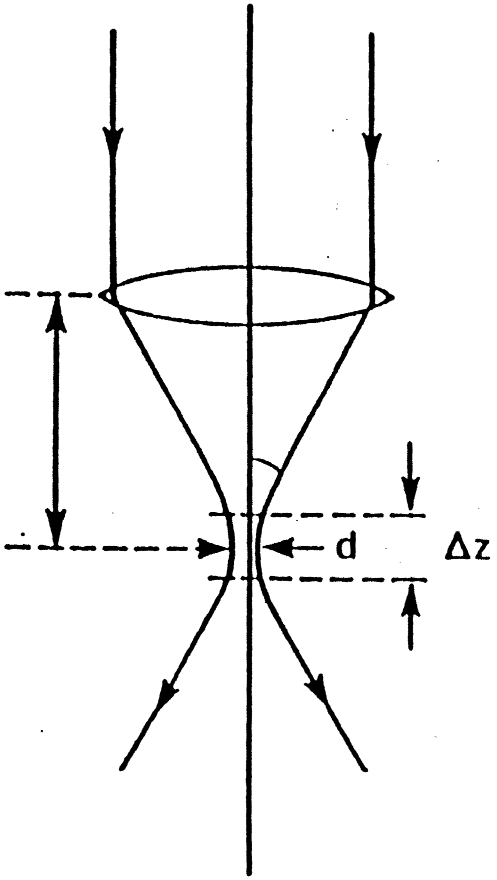
Classification of Optical Data Storage

	Read-Only	Read/Write	
		Write-Once	Erasable
Media Type	Factory replicated plastic disk with embossed surface	Various thin film metal or organic materials	Magneto-optic or phase-change thin film materials
Media Capacity Both Sides 30 cm Disk	1 hr continuous video 100,000 video frames 1 hr digital audio* 2-8 GB Data	2-8 GB Data 20K-100K A4 doc.	1-4 GB Data
Applications	Consumer entertainment Education/training Program distribution Database distribution Videogame ROM	Document storage Archival database (tape replacement) On-line mass storage (juke-box)	High capacity, low cost store for small systems
Media Cost (†)	$2-10/GB	$10-50/GB	$10-50/GB
Drive Cost (†)	$0.5-5K	$5-20K	$5-20K

*12 cm disk, 1 side

† D. Durbeck IEEE MSS (1982)

Optical Read/Write Spot Formation



- Diffraction limited spot-size

$$d \sim \frac{1}{2} \frac{\lambda}{\sin\theta}$$

Typically $d \simeq 1.0\mu$ for $\lambda = 820\text{nm}$

⟹ Power density ~ 10^6 W/cm²!

- Focal length, F ~ 1-2mm

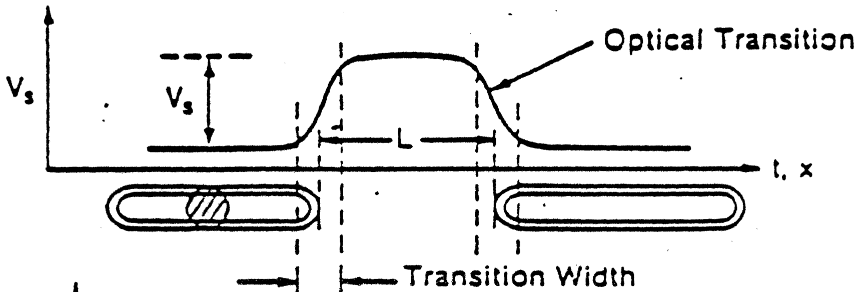
  ⟹ Large Head/Disk separation

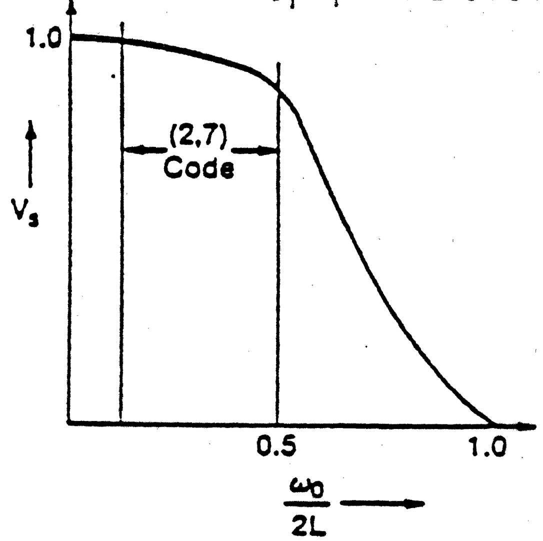
- Depth of focus

$$\Delta z \sim \frac{d}{2 \sin\theta}$$

Typically ±1 μ

Lineal Density - Optical Storage





- Read Beam Diameter (FWHM)

  $$\omega_0 = \frac{0.56\lambda}{NA}$$

- To limit bitshift

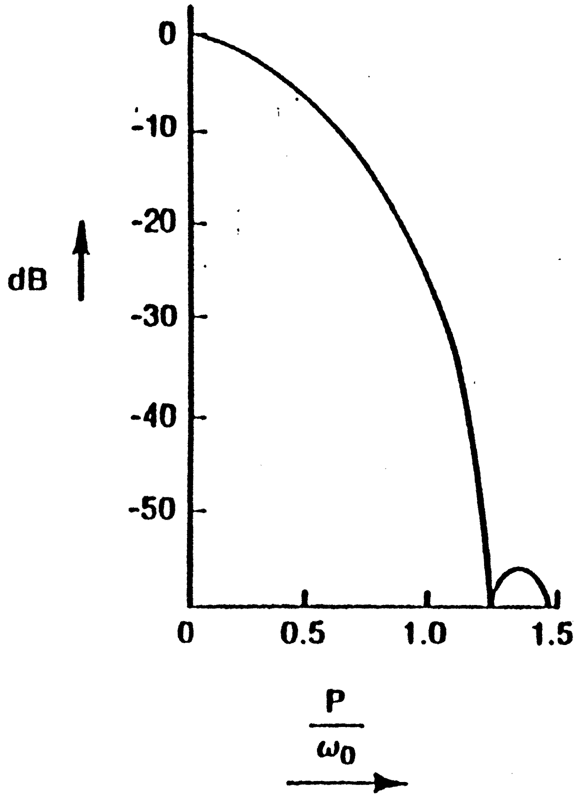
  $L_{min} \sim \omega_0$

- Lineal Density ~ ω_0^{-1} TRPI

- For $\lambda = 820$nm

N.A	TRPI
0.5	27K
0.65	35K

Track Density - Optical Storage



- To Limit Crosstalk

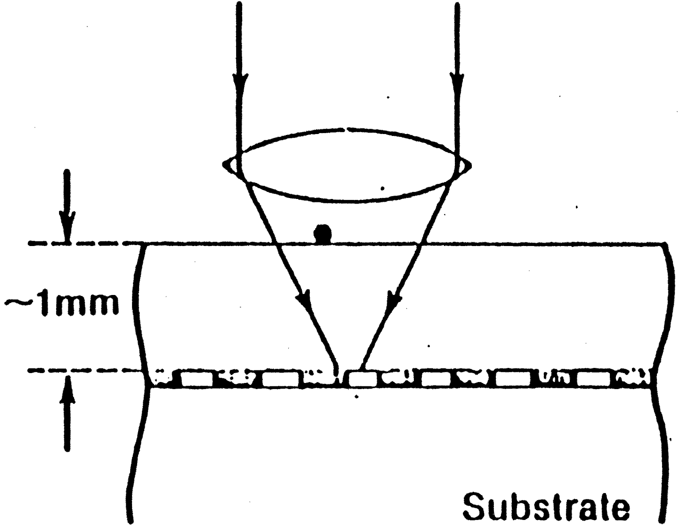
  $\frac{P.}{\omega_0} \sim 1.5$

- $\lambda = 820$nm

NA	TPI
0.5	18K
0.65	24K

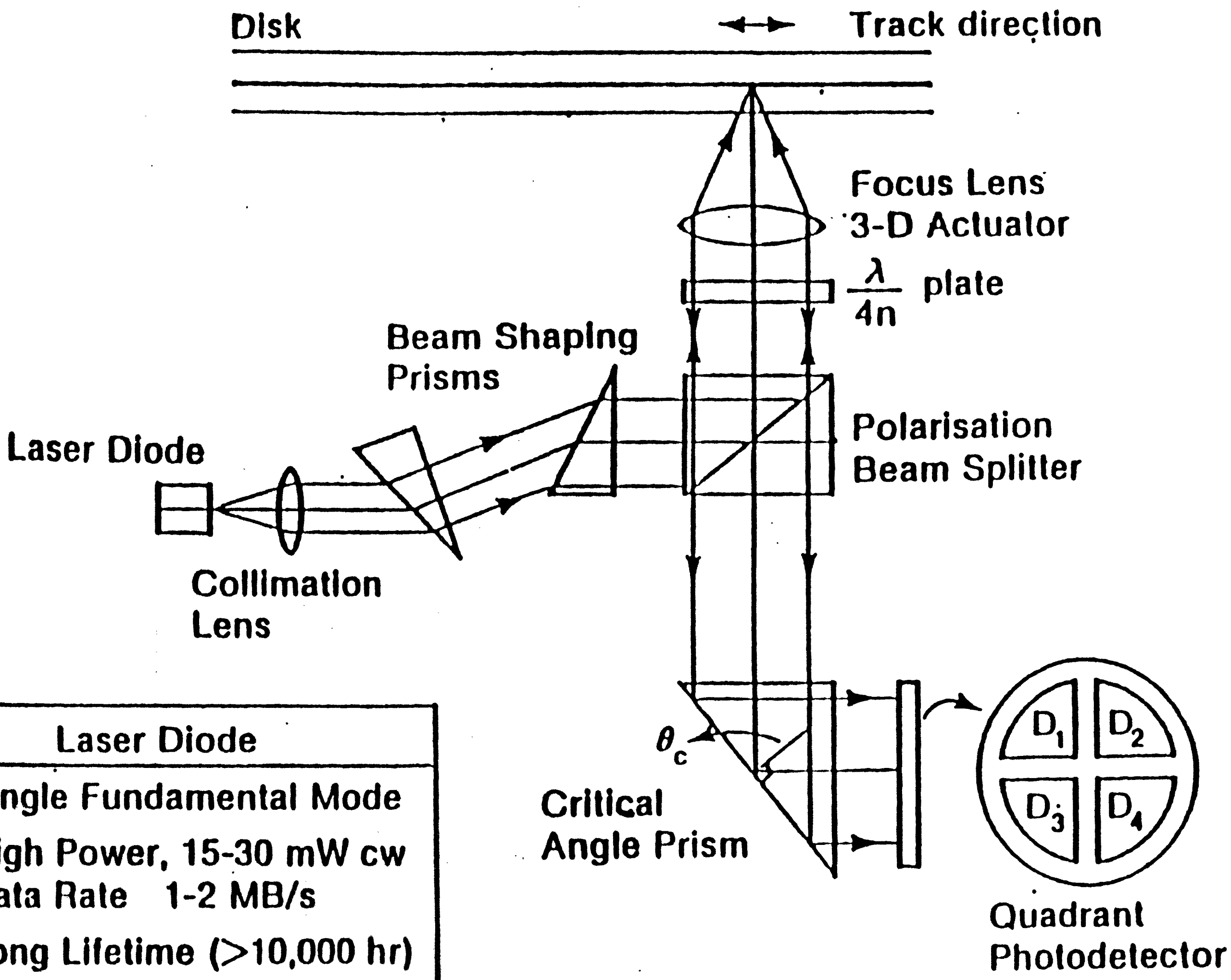
- Residual error limited by:
  - centering error
  - spindle runout
  - gain-bandwidth of servo

Optical Media Encapsulation



- Eliminates defects due to dust particles
- Protects storage layer from environment
- Permits removability of media

Diode Laser Read/Write Systems



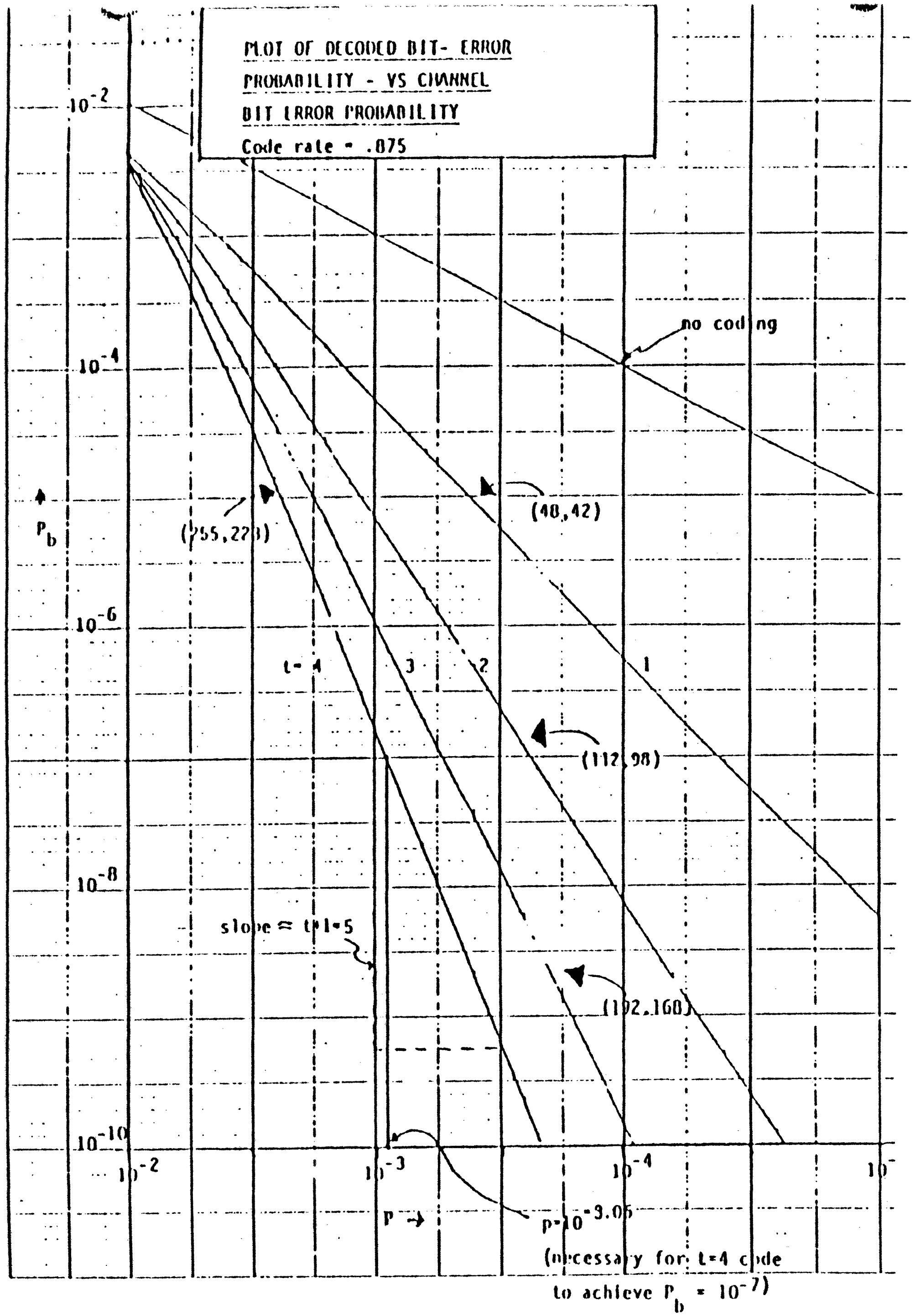
Laser Diode

- Single Fundamental Mode
- High Power, 15-30 mW cw
- Data Rate 1-2 MB/s
- Long Lifetime (>10,000 hr)
- Future — Laser Arrays

Data Signal = $D_1 + D_2 + D_3 + D_4$

Focus Error = $(D_1 + D_2) - (D_3 + D_4)$

Tracking Error = $(D_1 + D_3) - (D_2 + D_4)$



To achieve a desired bit error probability (e.g. $p = 10^{-7}$) an uncoded system requires a certain value of E_b/N_0 (e.g., 11.3 db).

A coded system can achieve the same value of error probability at a lower value of E_b/N_0. The difference between these two values of E_b/N_0 is referred to as the gain of the code.

Example: To achieve a bit error probability of 10^{-7}, the 4-error correcting (255,223) code requires a channel bit error rate of $p = 10^{-3.06}$. This value of p, in turn, requires a signal-to-noise ratio of E_b/N_0 = 7.5 db. Hence

Coding Gain = 11.3 - 7.5 = 3.8db

CODING GAIN OF VARIOUS CODES

($P_b = 10^{-7}$)

R \ t	.875		.75		.5	
	block	conv.*	block	conv.*	block	conv.*
1	1.8 db		1.7	1.3		
2	2.8		2.7	2.6	2.3	
3	3.4	3.3	3.3	3.2	2.7	2.4
4	3.8		3.7	3.6		

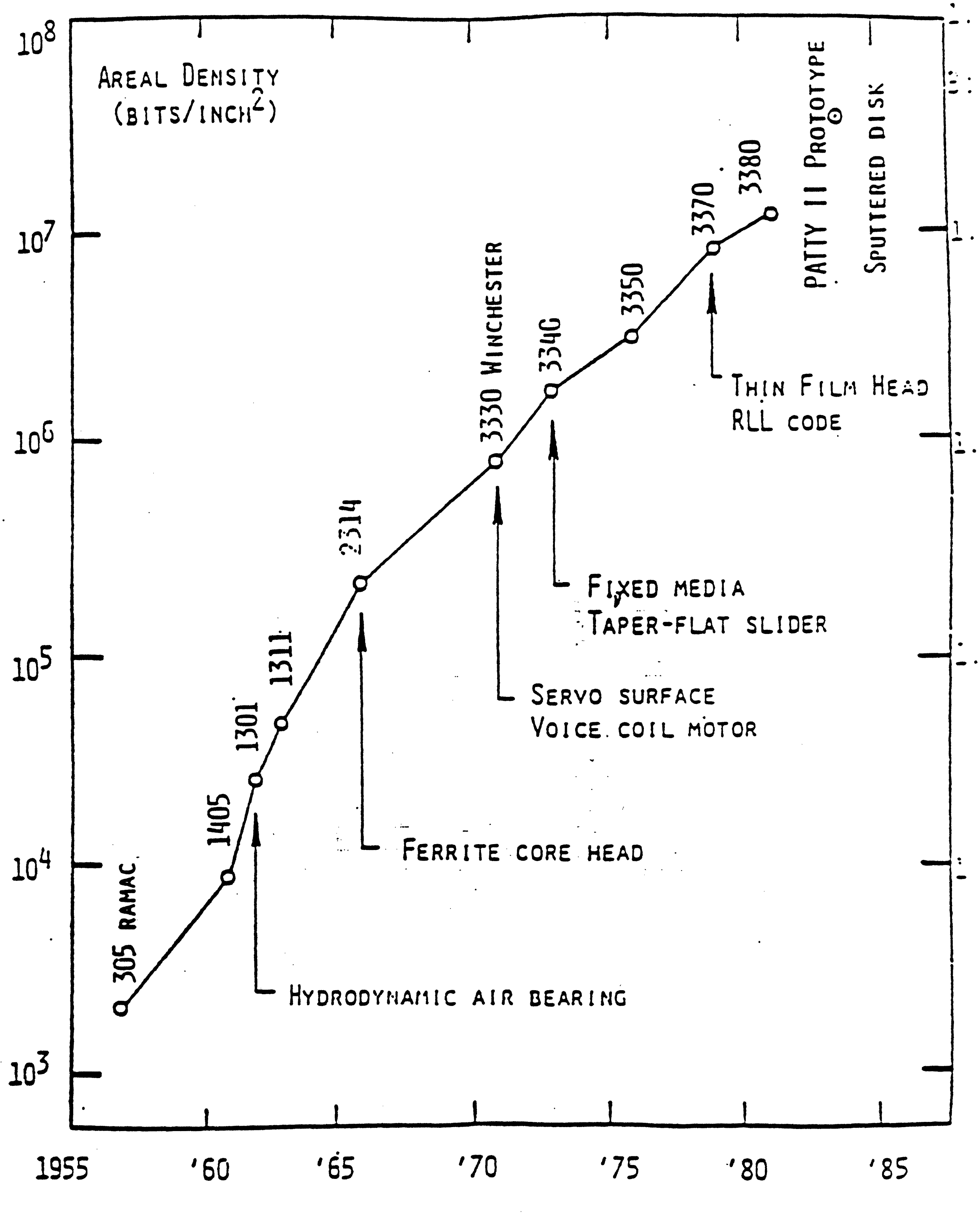
*Convolutional codes are self-orthogonal majority - logic decodable codes.

ECC IN DISK STORAGE DEVICES

YEAR SHIP	DEVICE	DENSITY bpi	DENSITY tpi	DATA CODE	ECC CAPABILITY	
1957	350	100	20	NRZI	PARITY CHECK	
196X	13XX	520	50	NRZI	CRC CHECK	
		1020	50		MULTIPLE ERROR DETECTION	
	23XX	2200	100	FM		
197X	33XX	4000- 15000	200- 800		SINGLE BURST CORRECTION	
					MODIFIED FIRE CODE	
					CORRECT./DETECT.	= OF CHECK BYTES
1971	3330	4040	192	MFM	11 BITS / 22 BITS	7 / RECORD
1973	3340	5636	300	MFM	3 BITS / 11 BITS	6 / RECORD
1976	3350	6425	475	MFM	4 BITS / 10 BITS	6 / RECORD
					MODIFIED REED-SOLOMON CODE	
1979	3370	12134	635	(2,7)	9 BITS / 17 BITS	9 / BLOCK
1980	3375	12134	800	(2,7)	9 BITS / 17 BITS	12 / RECORD
1981	3380	15200	800	(2,7)	17 BITS / 33 BITS	12 / RECORD

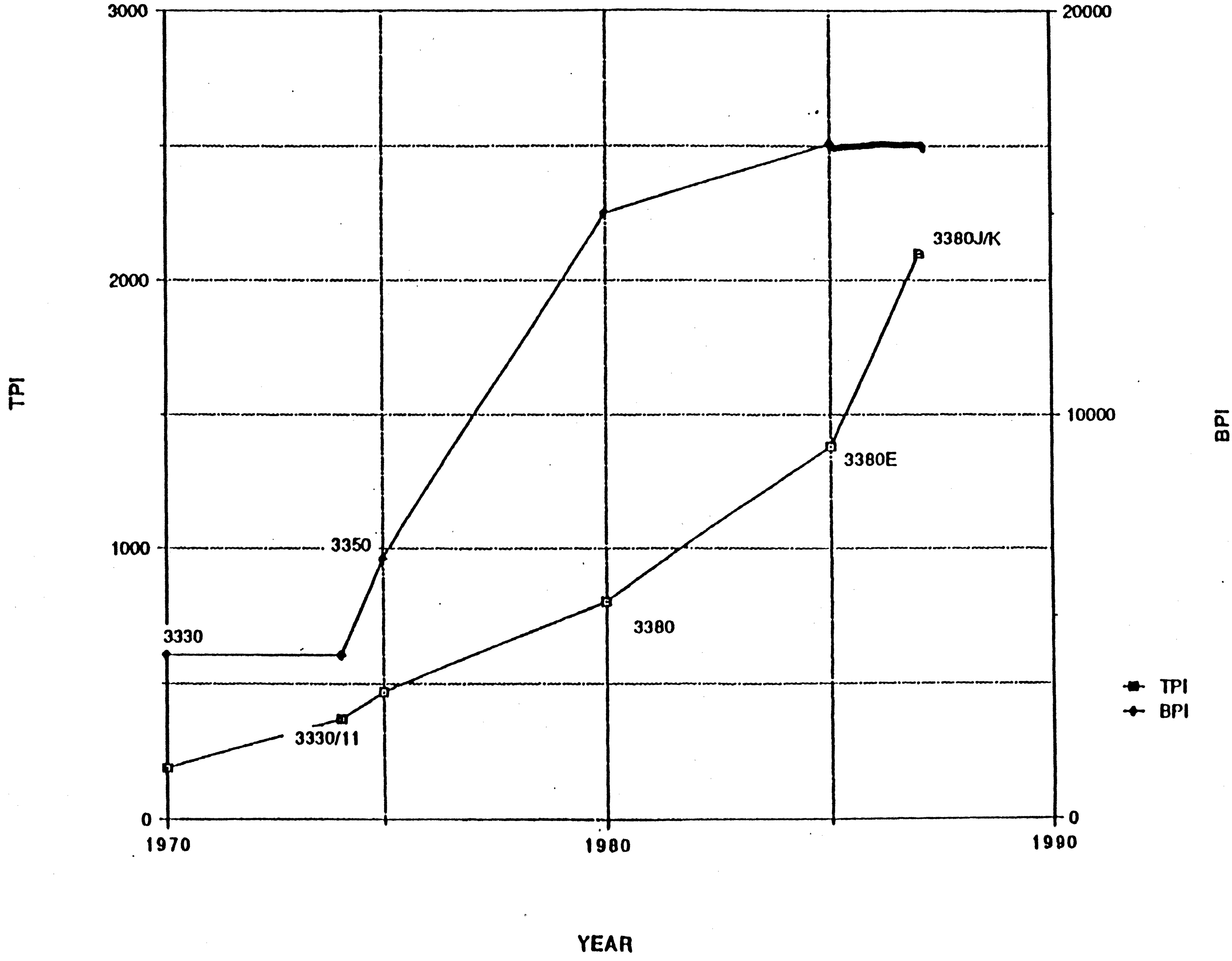
Magnetic Recording as Standard for Judging Alternatives

- Advantages
  - Updating Capability
    Investment in Software
  - Nonvolatile
  - Large Capacity at Lowest Cost per Bit
- Disadvantages
  - Relatively Long Access Time
  - Mechanical Reliability Issues

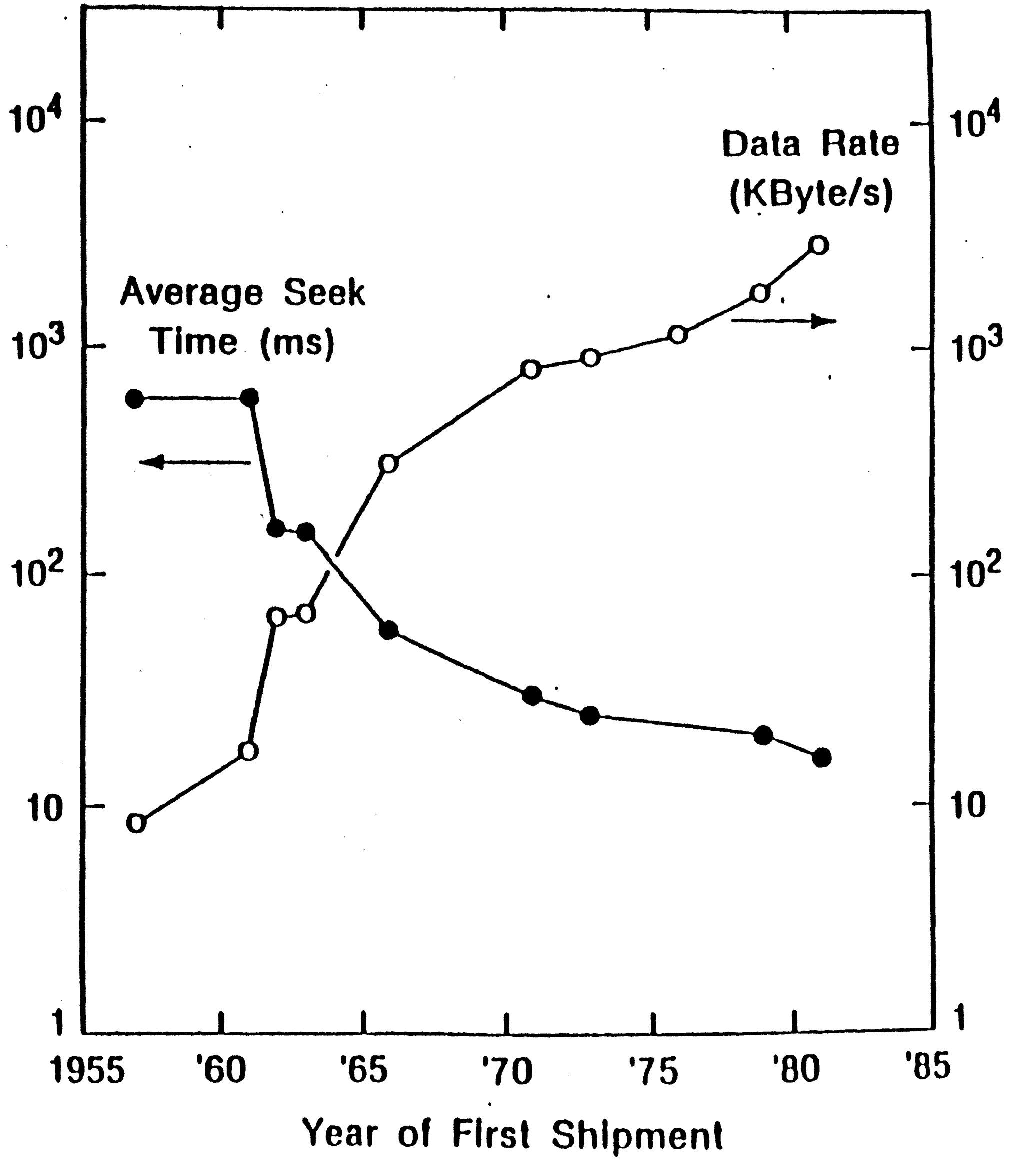


STORAGE DENSITY OF MAGNETIC DISK DRIVES.

HISTORY OF IBM AREAL DENSITY



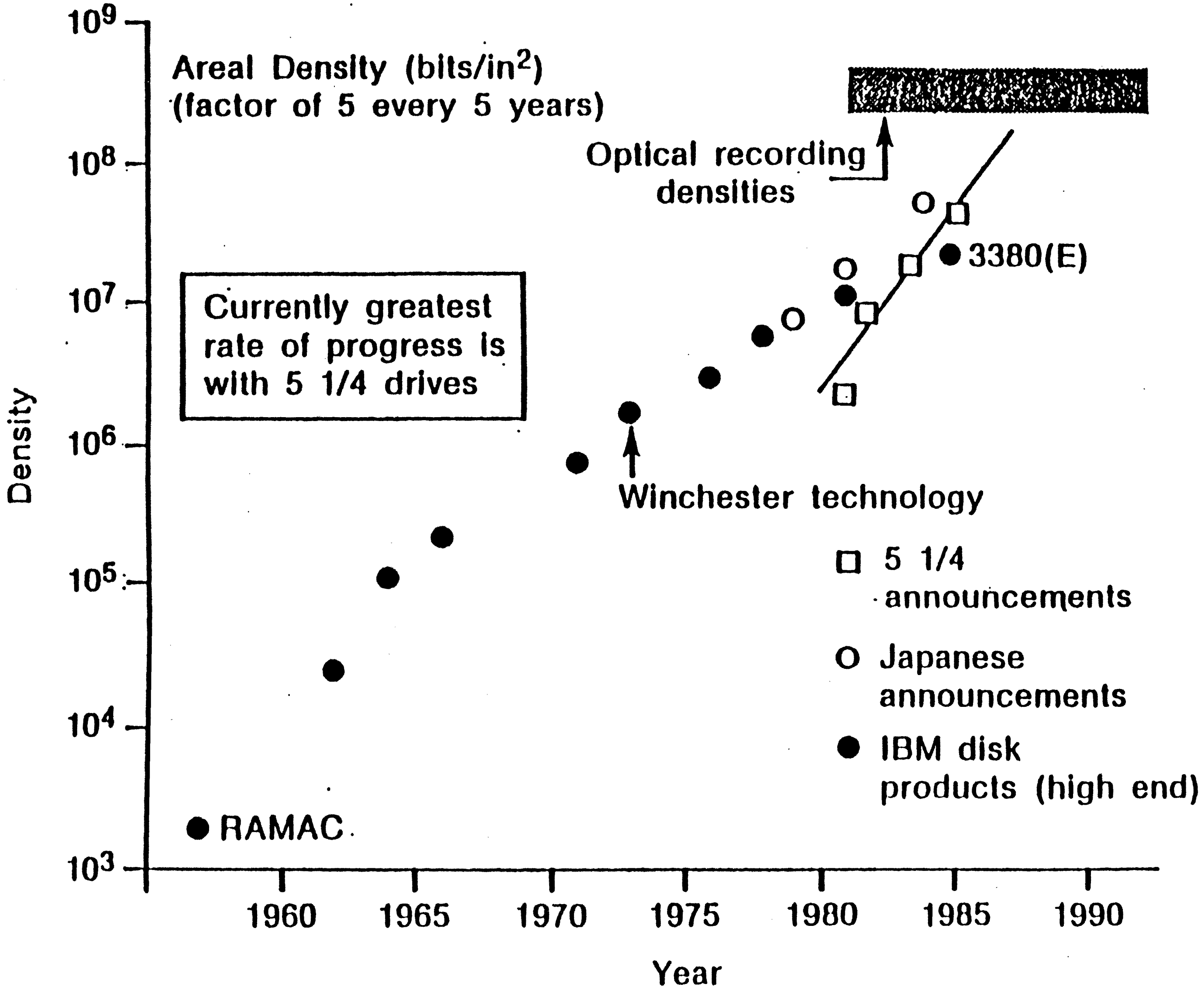
High End Files



Cost of Supporting Mechanics & Electronics vs. Form Factor

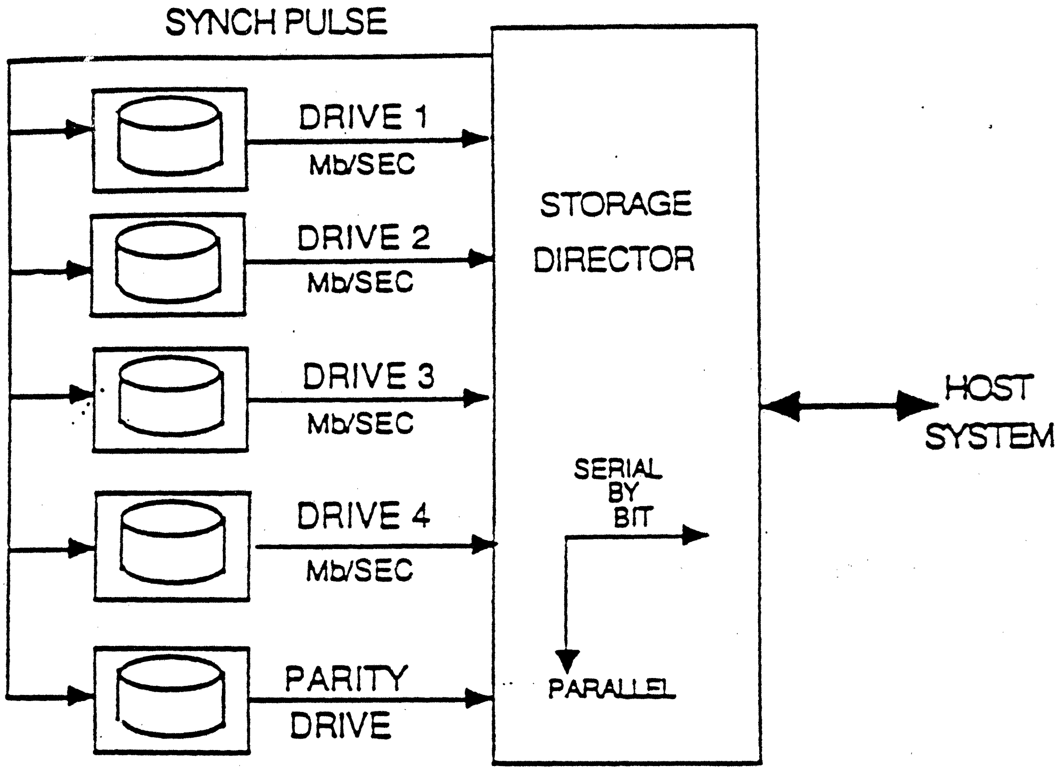
- Standard mechanical parts are cheaper on smaller mechanisms.
- Custom mechanical parts are much cheaper on smaller mechanisms.
- Low cost precision molding is more effective on small parts.
- Actuator & spindle criver electronics are much cheaper on small drives.
- R/W & controller costs drop with transfer rate.
- Package costs much lower on smaller drives.
- Power supply costs much lower on smaller drives.

Magnetic Disk Storage Density



--Challenges In Winchester Technology--

HI-TRANSFER RATE CLUSTER: TYPICAL DRIVE ARRAY (4 OUT OF 5)



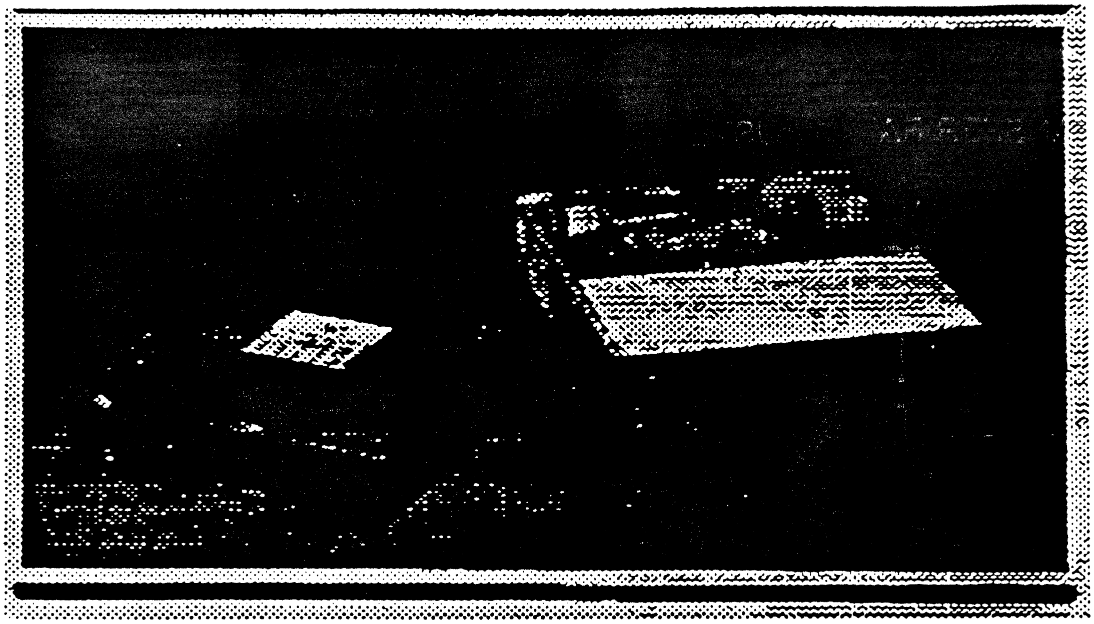
PERFORMANCE CHARACTERISTICS (N SYNCHRONOUS DRIVES)

*ARRAY TRANSFER RATE [MB/SEC] ==> $\frac{\text{(N-1) x DRIVE TRANSFER RATE [Mb/SEC]}}{8}$

*SYSTEM DATA SKEW: (DEVICE INTERFACE)
INDIVIDUAL DRIVE SKEW = +/- 10 uSEC ==> 20 uSEC ARRAY SKEW (W/C)
EACH BUFFER ==> 20 x Mb/SEC = 300 BITS
= 40 BYTES
WITH DEFECT SKIPPING [512 BYTES/SECTOR]
EACH BUFFER (WITH OVERHEAD) = 560 BYTES
(WITH SAFETY FACTOR) = 1 KBYTE

*DATA INTEGRITY
IN-LINE ECC FOR INDIVIDUAL DRIVES (BIT STREAM)
PARITY BIT FOR FAILED OR MISSING DRIVE (PARALLEL STREAM)

*SECURITY FEATURES
AUTOMATIC SCRAMBLING BY BIT FOR EACH SECTOR
OFFLINE DRIVE (STORAGE AND REPAIR) ==> STORED DATA UNINTELLIGIBLE



SQ555

44.3 MBytes

23316 BPI

1086 TPI

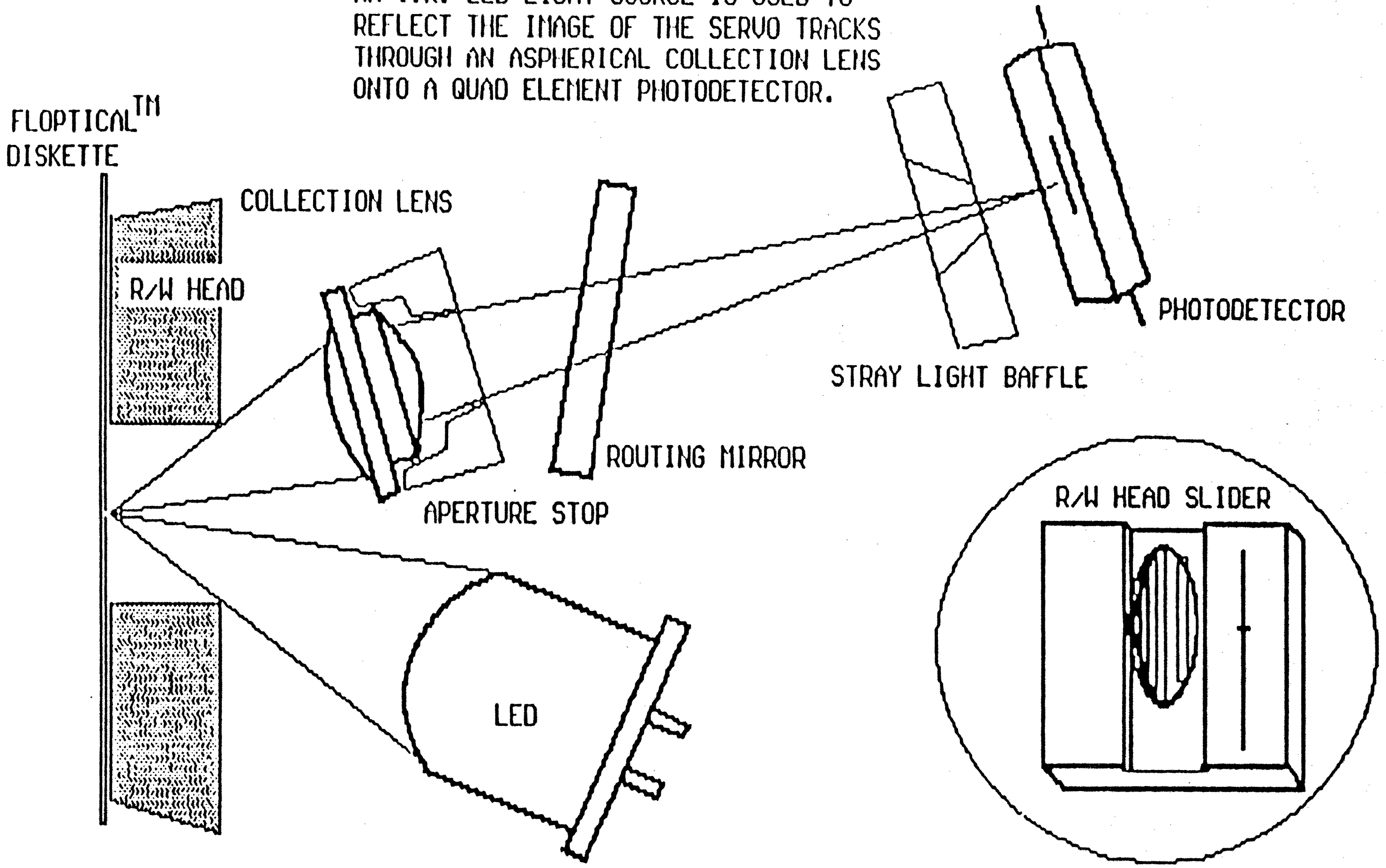
25 Ms Average Access time

1280 Tracks per Surface

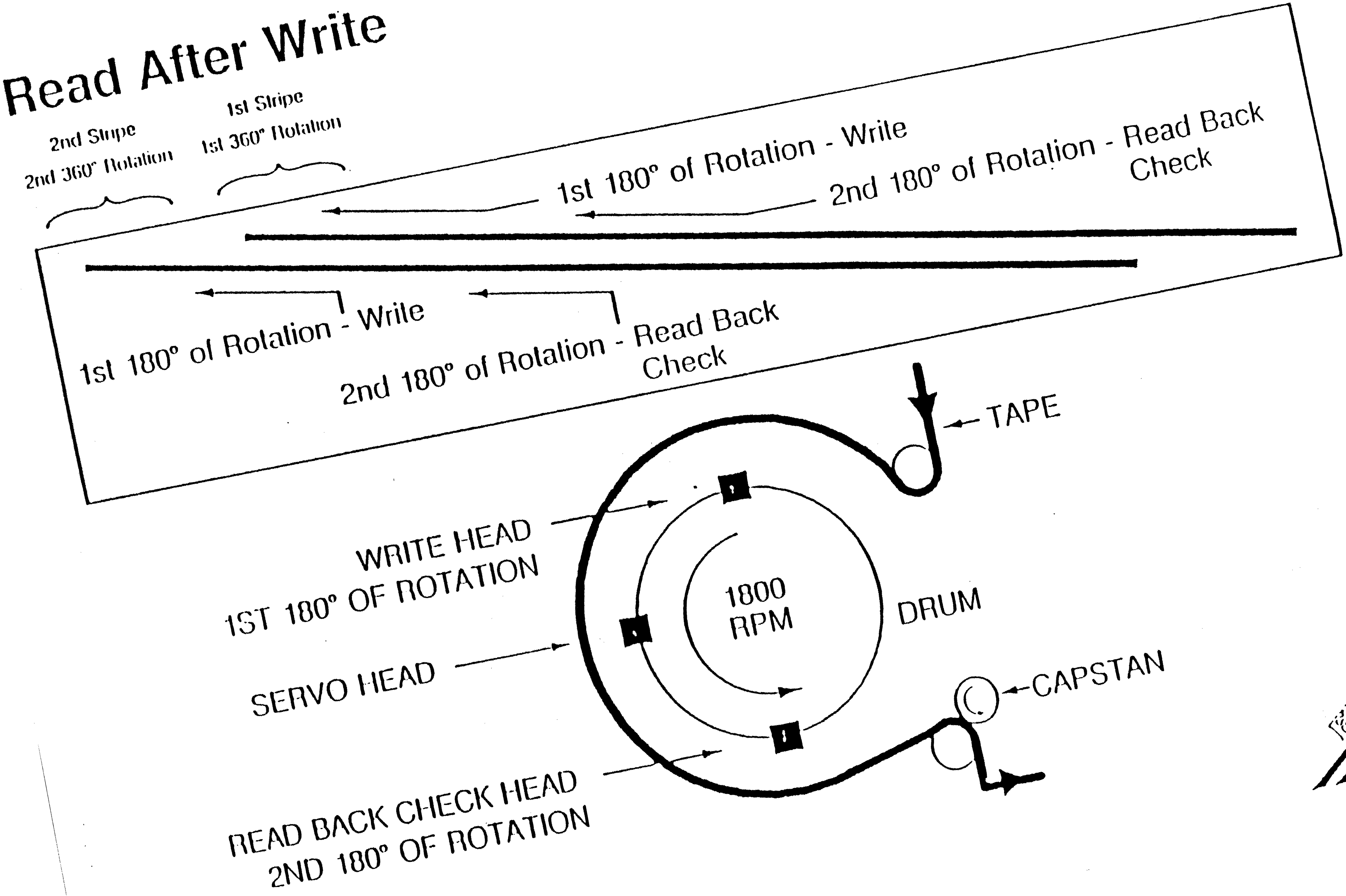
1 Disk per Cartridge

OPTICAL SCHEMATIC

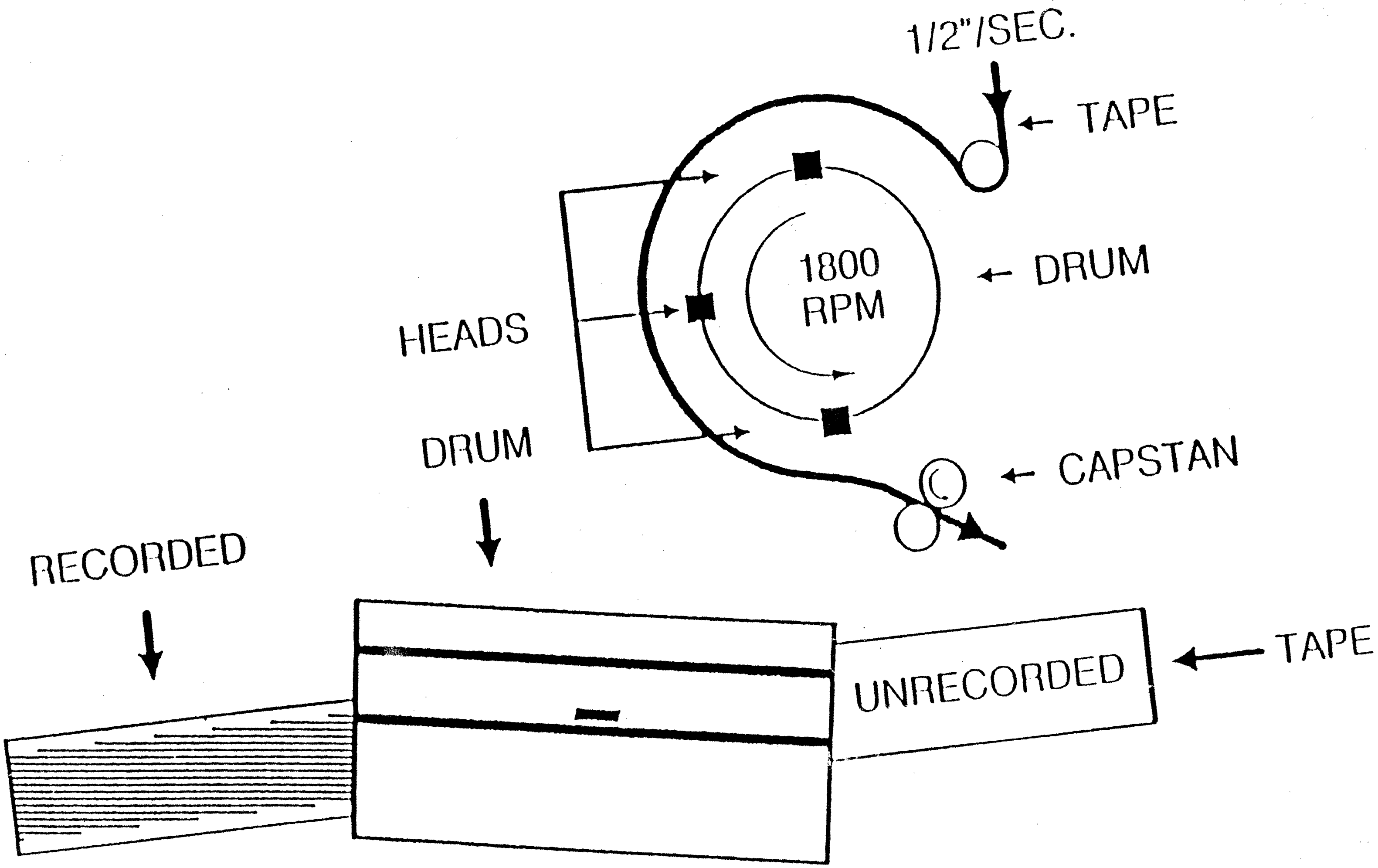
AN I.R. LED LIGHT SOURCE IS USED TO REFLECT THE IMAGE OF THE SERVO TRACKS THROUGH AN ASPHERICAL COLLECTION LENS ONTO A QUAD ELEMENT PHOTODETECTOR.



Read After Write

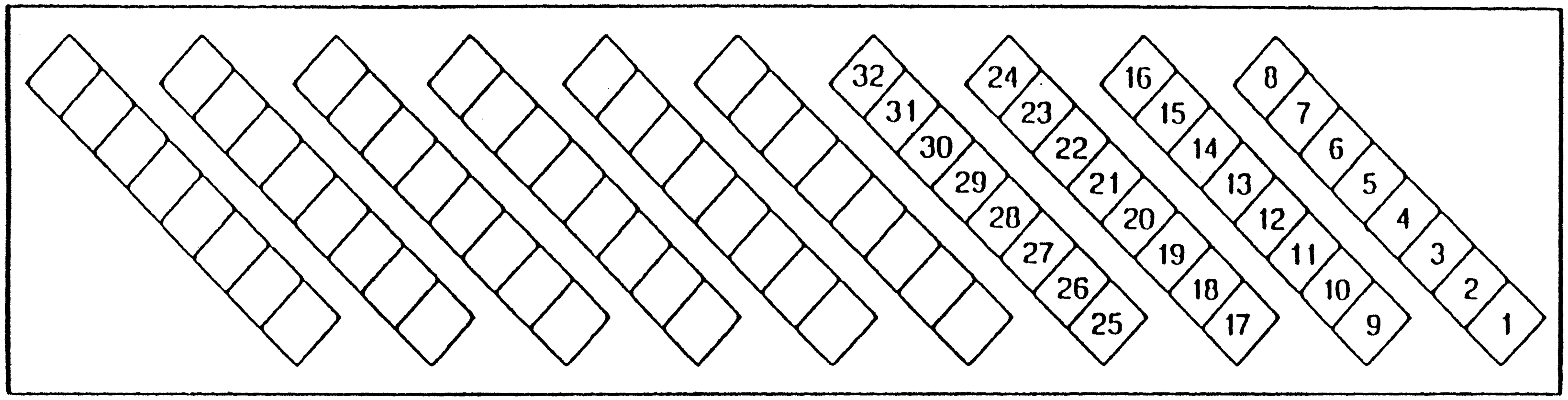


Helical Scan Recording

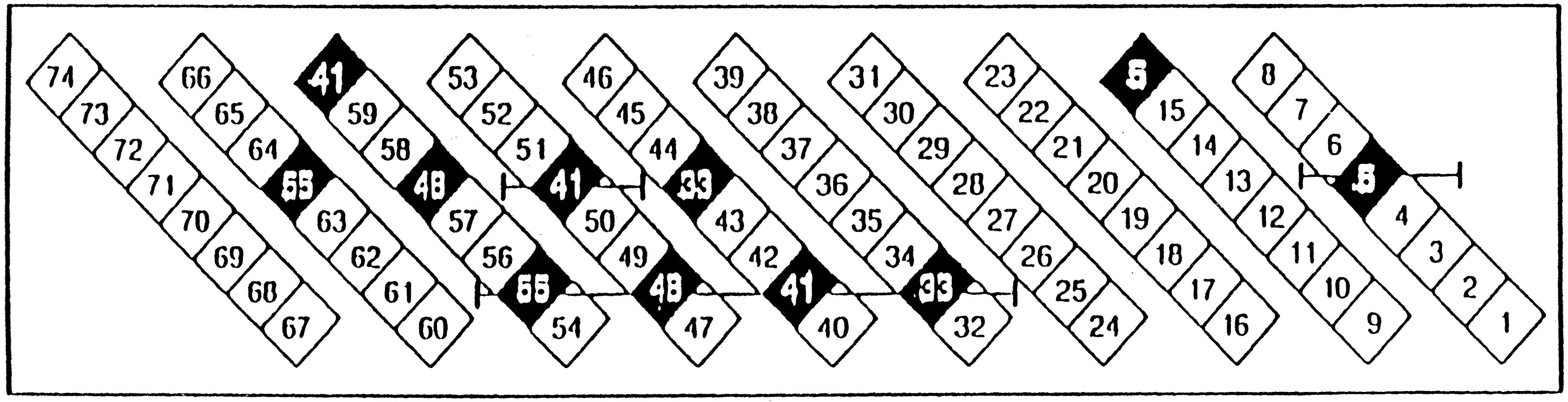


Read After Write

Normal Sequencing

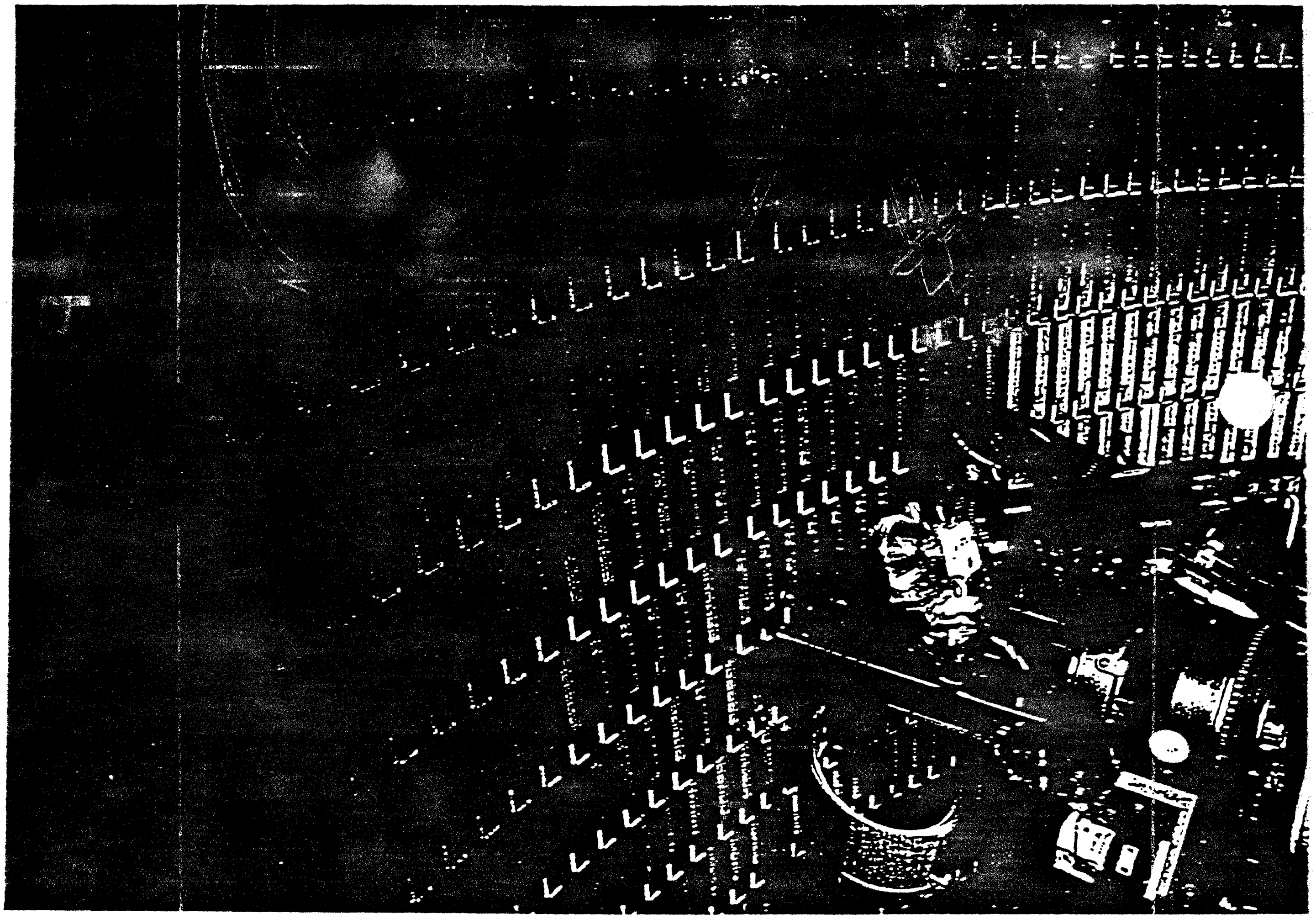


Rewrite Sequencing



StorageTek.

4400 Automated Cartridge System

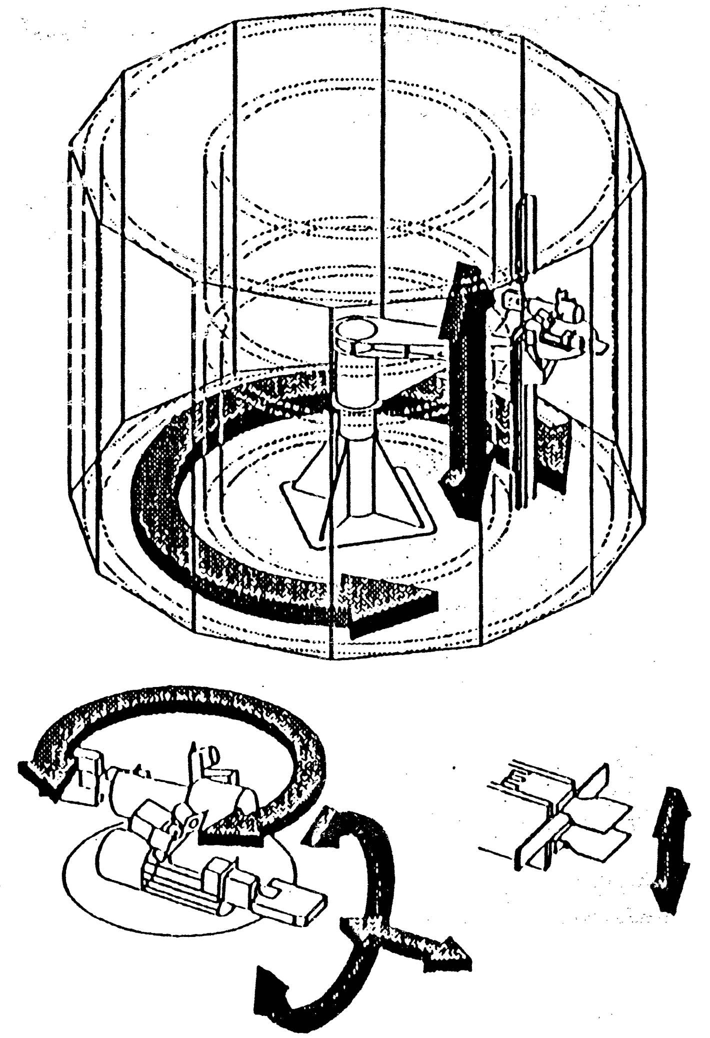


General Information

The 4400 Automated Cartridge System (ACS) is a fully automated information storage system. It automatically mounts and demounts 18-track cartridges on the StorageTek® 4480 — a cartridge subsystem that is completely compatible with the IBM® 3480 manual-only subsystem.

StorageTek 4400 Automated Cartridge System

SPECIAL PURPOSE ROBOT



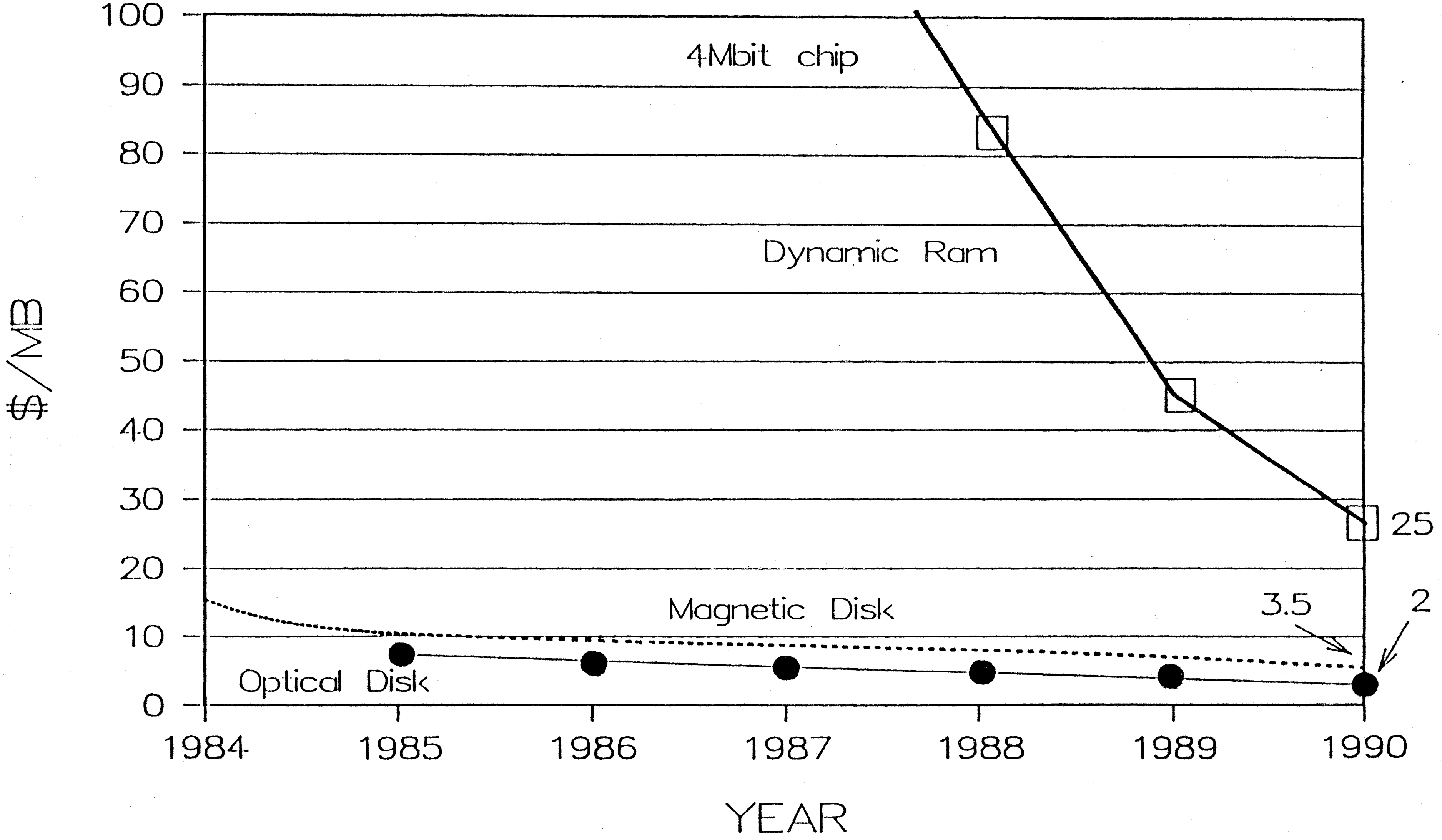
Six motions

- Theta (horizontal)
- Z (vertical)
- Phi (turn)
- Roll
- Reach
- Grab

Roll, Reach, Grab } Hand

Phi (turn), Roll, Reach, Grab } Turntable

Comparative Wholesale Prices for Various Storage Technologies



courtesy of Control Data Corp.
'87

MEASURING THE POTENTIAL OF STORAGE TECHNOLOGIES

- Physical Limits — (Translation: Ultimate)
- Engineering Limits — (Translation: Feasible)
- Marketplace Limits — (Translation: Rubber meets the Road)

Ultimate Limits?

- Magnetic Recording
  - Minimum Domain Size
  - Medium Signal to Noise Ratio

Spacing Dominant Parameter

- Optics
  - Limits due to Wavelength of Light

TECHNOLOGY LIMITS

- MEDIUM
- TRANSDUCER/BIT-CELL INTERACTION

MANUFACTURING PROCESSES KEY

PRODUCT LIFE AND DEMAND

USER GROWTH	40% CGR COMPOUND GROWTH RATE
TECHNOLOGY PROGRESS	26% CGR

Magnetic vs Optical Limits

- READBACK RESOLUTION

MAGNETIC

$$PW_{50} = [g^2 + 4(d+a)(d+a+\delta)]^{1/2}$$

FOR $g \to 0$; $a \to 0$; and $\delta \to 0$

WHERE g = gap; a = transition width parameter; δ = medium thickness

$PW_{50} \approx 2d$; d = spacing

$PW_{50} \approx \lambda$ (optical); λ = wavelength

equivalence: d = .5 micron; λ = 820nm (GaAs)

HOWEVER ASPECT RATIO (BPI/TPI) APPROX 2 IN OPTICS

IN MAGNETICS (30 YEAR AVERAGE) APPROX 13

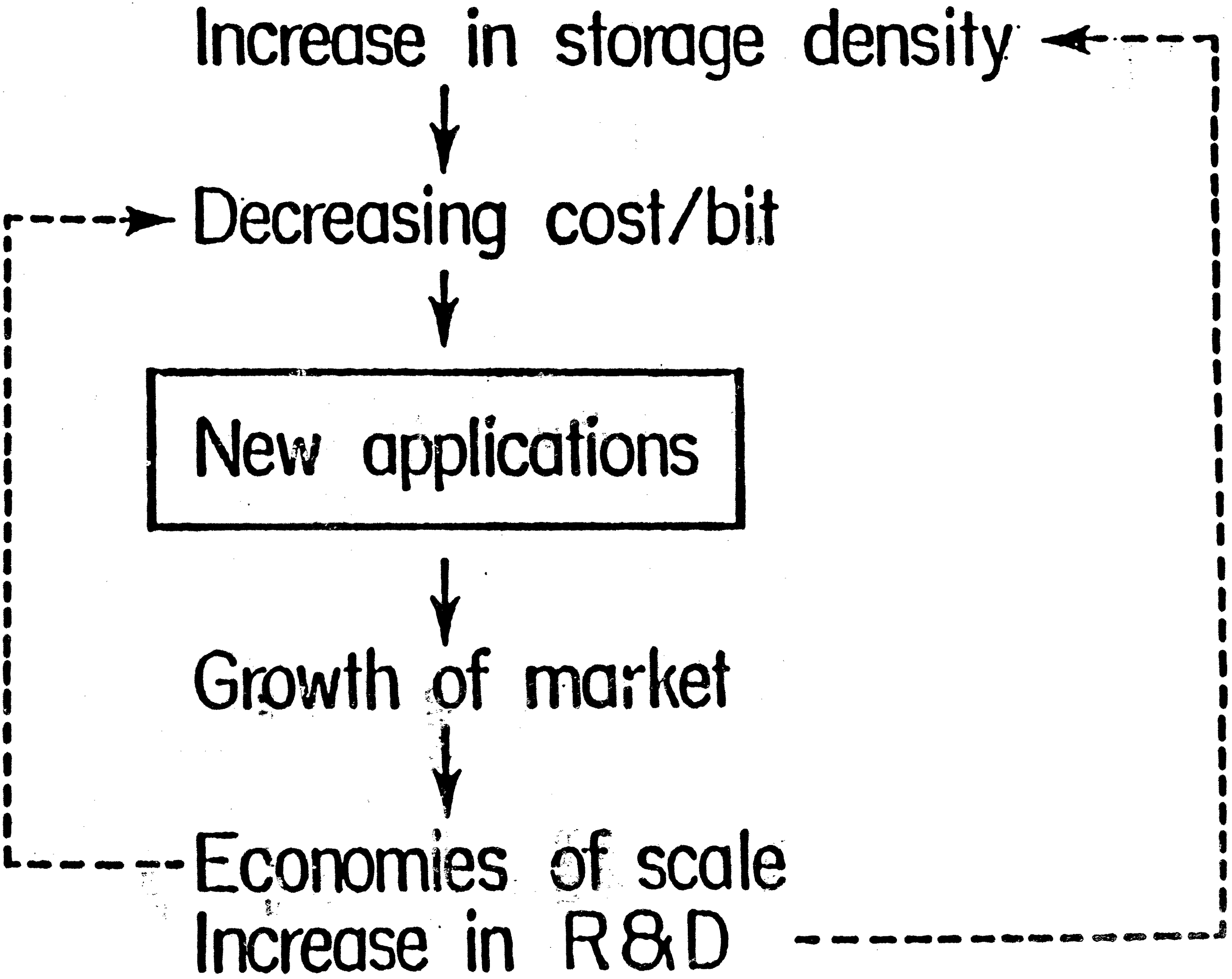
GENERIC ISSUES IN ULTRA-HIGH DENSITY DATA STORAGE ($\geq$ 10^8 bpi^2)

- File response time
  - data capacity per actuator
  - access time and data rate
- ECC overhead
  - media defect density
- Media resolution and noise
  - mark geometry
- System resolution and noise
  - position servomechanisms for read/write head
  - read/write method

COMPARISON OF MAGNETIC AND OPTICAL STORAGE TECHNOLOGY FACTORS

	Magnetic	Optical
Head/Disk Separation	0.1μ	1000μ
Substrate	Ultra-smooth Al	Al, Glass Polymer
Storage Medium	Thin Film < 1μ	Thin Film < 1μ
Encapsulation	No	Yes
Drive Internal Environment	Sealed HDA	Open to Ambient
Removability	No	Yes

Mass storage



Increase in storage density

Decreasing cost/bit

New applications

Growth of market

Economies of scale

Increase in R&D

LIST WORKSHOP IV - PRODUCT PROJECTIONS FOR 1990

PARAMETERS	HI END 5.25" DISK	HI END 3.5" DISK	SINGLE DISK 3.5"	SUB-3.5" DISK	MO 5.25" DISK	MO 3.5" DISK	CART TAPE 1/4"	CART TAPE 1/2"	8 mm TAPE	"DAT" TAPE	SEMI-COND.
Areal Density, Mb/in^2	110	110	200	50	580	580	9	1.4	57	114	50
KBPI	50	50	75	27	31.8	31.8	45.0	40.0	44	61	-
KTPI	2.2	2.2	2.6	1.85	18.2	18.2	0.2	.036	1.3	1.87	-
On-Line Capacity-MBF	1600	400	200	50	750	200	1300	1200+	3500	1300	200
Average Seek Time-ms	10	15	24	24	25	22.5	-	-	-	-	-
Average Latency-ms	5.6	8.3	-	9.5	8.3	8.3	-	-	-	-	-
Transfer Rate MB/s	4.5	2.4	-	1.25	1.9	1.25	1.35	4.5	0.5	0.2	1.5
*Capacity/ Volume-MB/in^3	10.3	10.3	9.5	4.2	55	65	90	60+	670	540	2.6
OEM Unit Drive Cost-$	3200	800	-	250	2500	600	750	20,000	1600	-	30,000
OEM Drive Cost/MB-$/MB	2.00	2.00	-	5.00	3.33	3.00	0.58	13.33	0.46	-	150.00
**Media Unit Cost-$	-	-	-	-	90	25	15	5	10	-	-
**Media Cost-$ per MB	-	-	-	-	.06	.125	.01	.003	.003	-	-
MTBF-Khrs	100	100	-	40	40	40	-	-	-	-	-
COMMENTS							Using a 2-channel hd	Assumes an 18-channel head and use of data compression			Transfer rate is per chip

PRODUCTS QUALIFY IF FIRST CUSTOMER SHIPMENTS BY END OF 4TH QUARTER 1990.

* Capacity/volume of media where media is removable; of drive, otherwise.

** End user pricing.

Lake Arrowhead
10/28/88