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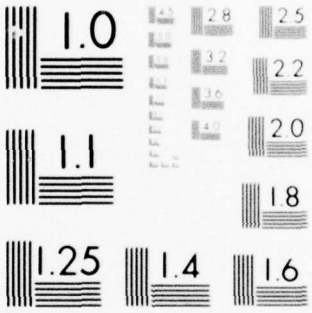

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RADC-TR-77-356
Final Technical Report
November 1977

ULTRA WIDEBAND DIGITAL RECORDING TECHNIQUES

RCA/Information Processing & Recording Systems

Approved for public release; distribution unlimited.

Laboratory Directors' Fund No. 01737601

ROME AIR DEVELOPMENT CENTER
Air Force Systems Command
Griffiss Air Force Base, New York 13441

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Design, modifications, test, evaluation and analysis were made on a pre-distortion encoder, record equalizer, HDMR head, playback preamplifier, delay modulation detector, and computer tape transport. Performance and performance limits were analyzed and applied to the modulation and coding, tape and head-tape interface, and magnetic heads technologies.

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EVALUATION

Continuing advances in the technologies supporting wideband communications and information handling are leading to extremely large volume digital data systems. Tactical exploitation of data for command and control applications requires immediate, real-time readout of recorded data. Techniques have been demonstrated that possess the required bandwidth capabilities, however, they do not possess the required immediate readout capability essential to the tactical commander

Presented are the results of a two phased study. Phase I concerned an investigation of techniques to extend wideband digital magnetic recording to accommodate input/output rates of 1.0 gigabit per second. Areas of concern included track density, linear area and volumetric packing densities and bit error rate in a two inch longitudinal format. Phase II coupled the high density digital technology with fast stop/start/shuttle technology for rapid access. A computer tape station modified for 2 inch video tape and vacuum buffers was employed as a test bed.

Jack D. Petruzelli

JACK D. PETRUZELLI
Project Engineer

SECTION 1

INTRODUCTION

This final report of the New Technology Study on Ultra Wideband Digital Recording Techniques is organized to follow as nearly as practical the directions provided in the Statement of Work, PR I-6-4087 dated 5 July 1975.

The first section is compiled as a sub unit that summarizes the complete program and can be extracted as a quick-look for wide distribution.

The second section encompasses Phase I and is divided into four major areas.

The third section encompasses Phase II and is divided into six areas, including recommendations for a Follow-On program.

The remaining sections contain support information for this report.

1.1 PROGRAM SUMMARY

1.1.1 Technical Problem

The amount of data that will be available as a result of high data rate communication systems will cause gross changes in data management techniques by the 1980 time frame. Tactical exploitation requirements for command and control applications demand immediate or real-time readout capabilities. The approach most consistent with a real-time or instantaneous readout is magnetic recording. Although techniques exist which can accommodate these data rates (laser holographic), they do not possess a real-time readout capability essential to tactical situations.

1.1.2 General Methodology

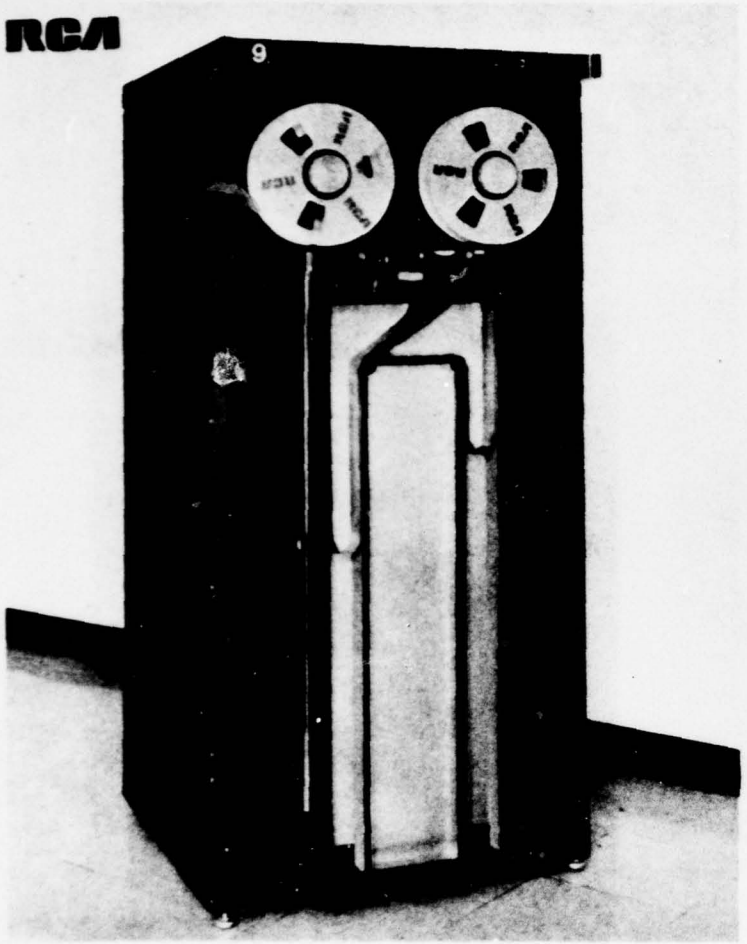
The investigative procedure employed on this program is in two segments: Phase I concentrated on the study and investigation of techniques necessary to extend wideband digital magnetic recording to accommodate input/output rates of 1 gigabit per second. Phase II concentrated on coupling this technology (high density digital) with fast stop/start/shuttle technology for rapid access for exploitation purposes. The end item of this program was a feasibility demonstration of the Phase II objective and this final report detailing the techniques investigated.

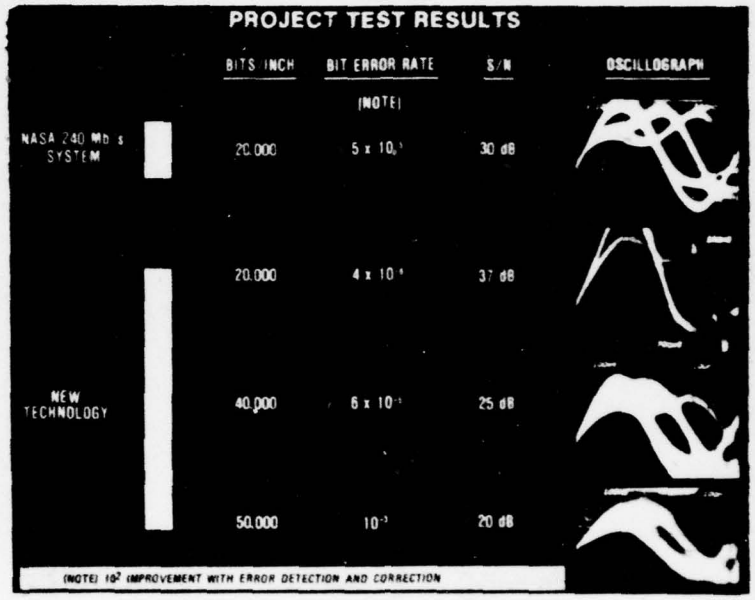
1.1.3 Technical Results

This study has resulted in an optimum system design approach for a fast access 1 Gb/s data recording/retrieval subsystem. A modified computer tape station, as shown in Figure 1A, resulted from the incorporation of a 2 inch vacuum capstan, 2 inch wide tape vacuum columns and bins, calibrated reel motors, NAB type reel hubs, pneumatic subsystems, and electrical interconnections. Detailed experiments were performed on the vacuum capstan torque and coefficient of friction using back coated tape. Reel motor parameters were calculated and measured as to their acceptability in the system. In addition, test data was obtained from a parallel study program, using newly developed recording technology, at up to 50,000 bits/inch linear bit packing density on standard video magnetic tape (Figure 1B). The improvement gained shows that the new technology hardware is achieving at 40,000 bits/inch what the original HDMR hardware achieved at 20,000 bits/inch. The bit error rate (BER) shown is uncorrected. The Error Model and Error Detection and Correction techniques developed have shown, by computer simulation, that a 100:1 improvement can easily be made in BER.

1.1.4 Implications for Future Research

The positive results of this small scale study indicates that a follow-on program should be highly successful. This follow-on program would provide test and evaluation of the fast access transport design developed on the present study program. Coupling this transport with the high packing density record techniques shown here should provide data storage and retrieval equipment which meets the Air Force goals.





A. New Technology Transport

B. New Technology Head & Electronics

Figure 1. New Technology Test Results

SECTION 2

PHASE I: ULTRA HIGH DENSITY DIGITAL RECORDING TECHNIQUES STUDY REPORT

2.1 TECHNOLOGY GOALS

Real time readout capabilities of high data rate communications from a storage medium is necessary to meet the data management requirements of the 1980s. The approach most applicable for tactical exploitation of access and control of this data is magnetic recording.

This study addressed these goals and investigated and demonstrated the techniques necessary to advance high density, digital magnetic, longitudinal recording technology to accommodate input/output rates of 1 gigabit per second. Areas requiring investigation are: (1) optimum data recording codes for optimum packing density, signal to noise ratio and resolution, (2) optimum head design to minimize crosstalk, skew, azimuth, noise, and record/reproduce losses, (3) optimum tape transport configuration, including the impacts of wide tape, high tape speeds, and size and location of vacuum chambers.

The following design objectives were explored:

Packing density: 50 Kilobits per inch Bit Error Rate: 1 in 10^{-6}

Minimum tape reel diameter: 14 inches

Minimum tape width: 2 inches

2.2 FUNDAMENTAL LIMITS OF MAGNETIC RECORDING TECHNOLOGY

RCA has identified the fundamental limits of magnetic recording technology including the number of bits/flux reversal, minimum bit error rate in-track packing density, cross-track packing density, flux reversals/inch and limits to the performance of magnetic head materials. The detailed designs of existing items were reviewed to ensure that the time obstacles to major improvements are defined. The principal recording technology components investigated are:

Head/tape interface
Record/reproduce response & losses
Magnetic head materials and fabrication
Modulation coding
Error detection and correction coding
Track Density Tradeoffs

2.2.1 Modulation & Coding

In the area of modulation and coding there are no severe limitations as to techniques and design approaches within the known information theoretic bounds. The performance limitations are primarily those of the recorder analog channel (write transducer, medium, read transducer). From the point of view of hardware mechanization, the current state of the art of high speed logic devices and LSI design has removed the last limitations to sophisticated and complex signal processing circuitry.

The limits of the present analog channel are presented in graphical form on the following 2 pages. The modulation/coding study was a two step process; first using the present analog channel model and finally, using the improved analog channel results from the head and head-tape interface studies, the analog channel can be fully characterized by its S/N and amplitude response (Figure 2), drop out rate and distribution (Figure 3) and phase response (read function = 90°, inter-symbol interference = 10%, group delay = 50ns).

2.2.2 Tape & Head - Tape Interface

In the area of tape and head-tape interface, the primary limitations in the present approach to higher density recording are the scale factors of the head-tape geometry and physics. The limiting tape and head-to-tape interface parameters are listed below:

<u>Scale Factor Induced, Limiting Items</u> (See following definitions of terms)

	-	Head-to-tape separation	(d)
	-	Tape dropouts	(D.O.) related to d/λ
X	-	Tape particle size	(p)
X	-	Particle retentivity	(pr)

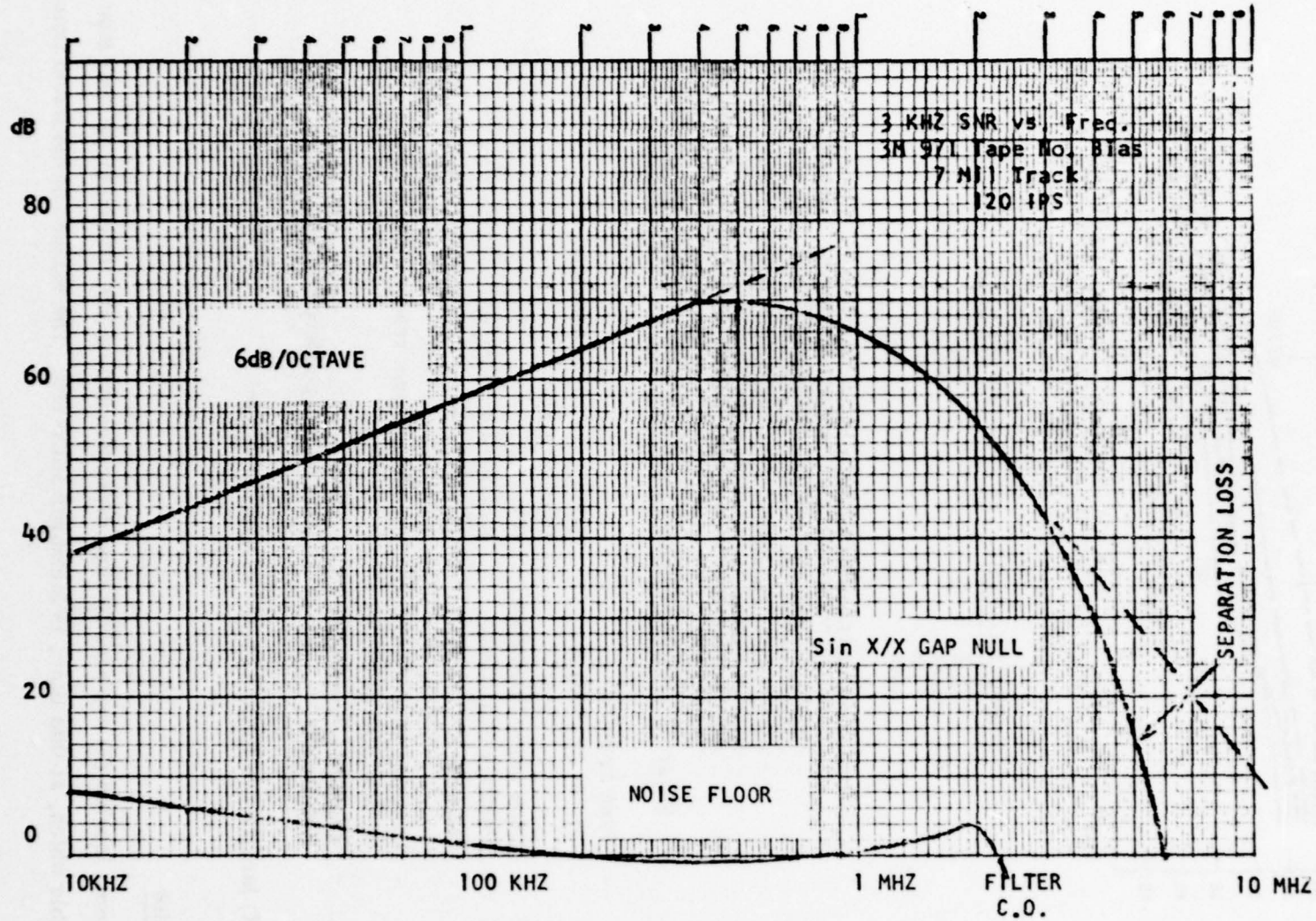
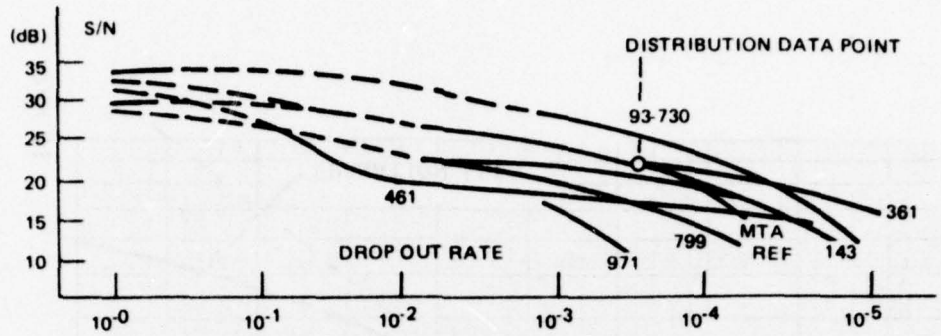


Figure 2. Analog Channel S/N and Head/Tape Response



DROPOUT SIZE (MILS)	DISTRIBUTION
0-19	0.60
19-31	0.30
31-44	0.09
44-00	0.01
	1.00 TOTAL

DROPOUT DATA ON CURRENTLY AVAILABLE TAPES WERE TAKEN TO PROVIDE THE "FADE" CHARACTERIZATION OF THE PRESENT AND PROJECTED RECORDER/REPRODUCER ANALOG CHANNEL.

THE CONCLUSION DRAWN FROM THIS TEST DATA IS THAT THE TAPE MOST LIKELY TO BE USED FOR THE PROJECTED APPLICATION WILL BE A VIDEO TAPE AND NOT A SO CALLED "PCM TAPE".

Figure 3. Analog Channel Drop Out Rate & Distribution

	-	Tape area/bit	
		length	(l) $l = \lambda/2 = 2g$ assumed
		width	(w) track size
X	-	Tape oxide thickness	(c)
X	-	Particle uniformity factors	distribution of particle sizes, Hc, Br, orientation.
	-	Quantity of particles within 2g of head gap	(q) determines read voltage
X	-	Tape Self demagnetization factor	(a) μ''/in dependent on Br/Hc ratio

(X) factors are limited by use of available tape

d Limits

The items labeled (X) are strictly tape dependent and we are limited to the best tape available which, at this time, is Memorex MRX-716. The balance of the listed items

are at least partially dependent on the "composite" head-to-tape separation (d), which has always been called "distance between head and tape", but which is in the true physical sense a four dimensional number. (d) varies across the track, (w) varies along the track, (l) varies considerably when considered as the distance between the head and the mean position of the tape particles (q) and all three vary with time. This composite effort can be listed as: $d = d_1 + d_2 + d_3 + d_4$ where:

(d_1) dc term	(average d)	$10\mu''$
(d_2) ac term	(tape roughness)	$6\mu''$ pp
(d_3) burst noise term	(tape dropouts/imperfections)	extremely variable - no independent measurements.
(d_4) dx/dt term	(dynamic response)	

d_1, d_2, and d_3 are spatial and physical static tape properties. d_4 is the result of d_1, d_2 and d_3 interfacing with a fixed head contour under sliding conditions, in the presence of a fluid (air) and is the dynamic response factor given all of the above inputs. d_1, d_2 and d_3 are given and fixed by the available tapes. d_4 is the only limiting item which can be addressed by this study. It is also an area which lends itself to computer analysis.

Definition of Terms & Limits

g = head gap length

Hc = tape coercivity in Oersteds (Oe)

Br = tape retentivity in gauss

p = mean tape particle size

acicularity = length/diameter of tape particle (p)

Tape squareness = Br/Bs: each particle has a Br/Bs of 1.0 (square loop); particle distribution, orientation, etc., reduce this ratio considerably and variably.

Bs = mean saturation flux density, which saturates all of tape, producing the maximum Br.

Orientation = degree of acicular particle alignment relative to desired axis of magnetization (1.0 is perfect, 0.5 is random).

(d) = head to tape separation; a very nebulous number because it is so dependent on tape surface roughness. In fact in most intimate contact systems d = tape roughness, if d is construed to be the maximum separation between head and oxide. If d is considered as distance from the particles, it varies from 0 to c in every tape.

c = oxide thickness; for particle tapes, limited to 60μ inch and larger by dispersion (surface tension) problems in the coating process.

w = track width

FR = Flux reversal; equals 20μ inches at 50,000 FR/IN

q = useable volume of oxide/FR = $FR^2 \times w$

V = read voltage which is proportional to q, Br---

D.O. = DROP OUT: when V is reduced to system S/N threshold

D.O.R. = DROP OUT RATE: ratio of D.O. to non-D.O. condition; nominally

$$BER = \frac{D.O.R.}{2}$$

BER = Bit Error Rate: ratio of bits in error to total bits in any considered # of bits

a = Tape self demagnetization loss; the length of the flux reversal transition zone. This is 0.5 x t.

t = oxide thickness

t' = effective oxide thickness $= \frac{\lambda}{2}$ typically

$\lambda = 2$ FR = minimum wavelength

μ = magnetic permeability or micron (10^{-6} meters)

μ'' = microinch (10^{-6} inches)

p Limits

The tape particle size is nominally 12 μ". This limits the shortest useable λ to the value p, at which λ the tape magnetization will be zero. Because p varies 2:1, this null is never zero, but the net effect is loss of ordered signal orientation. For presently available tapes, p limits λ to 24 μ" which limits FR to 12 μ". The 20 μ" FR (goal) will suffer an estimated 4dB loss due to FR = 1.7p. (See Figure 4.)

Combined d, c and g Losses

Assumed: head/tape separation (d) = 10 μ"

gap length (g) = 10 μ"

oxide thickness (c) = 100 μ"

The d, c and g read losses are:

Spacing loss (L_d) = 54 d/ λ (dB) [Westmijzi]

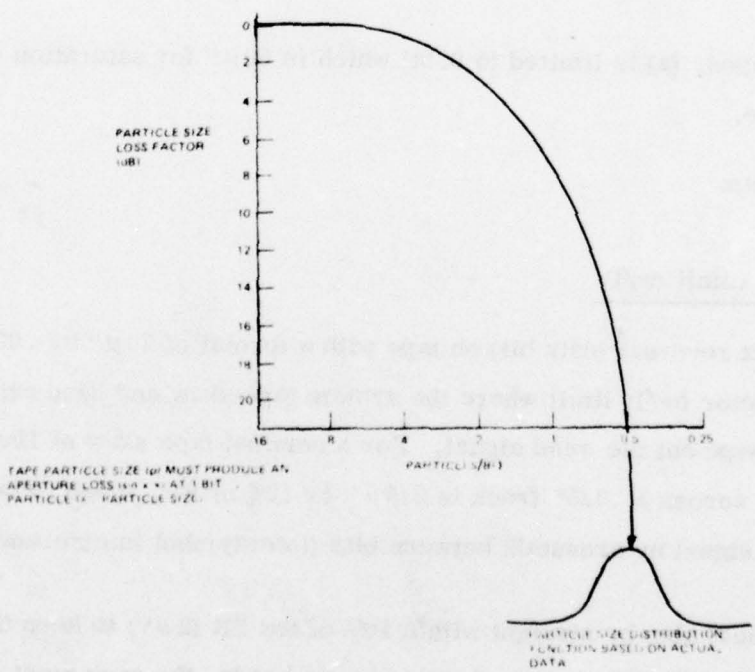


Figure 4. Loss Factor of Mean Particle per Data Bit

Thickness loss (L_c) = 16dB @ C = λ + 6dB/Octave = $20 \log_{10} \left[\frac{2\pi c/\lambda}{1-e^{-2\pi c/\lambda}} \right]$ [Westimijzi]

Aperture loss (L_g) = $20 \log_{10} \left[\frac{\sin \pi g/\lambda}{\pi g/\lambda} \right]$ [Wallace]

FR/IN	= 20K	25K	50K	
λ	= 100	80	40	
L_d	= 5.4	6.8	13.5	dB
L_c	= 16	18	24	dB
L_g	= 0	0	1	dB
Total	= 21	25	39	dB

Therefore a 14dB increase in S/N is needed to make up read losses incurred in going from 25K to 50K FR/IN. This effect is shown on the following chart (Figure 5) as a function of FR/IN.

(a) Loss

For available tapes, (a) is limited to 0.5t' which is 50μ" for saturation of full oxide on standard tape.

FR = 2a maximum

Bit Squareness Limit (w/l)

Recording a flux reversal (data bit) on tape with a format of 20μ" by .025" is approaching the scale factor (w/l) limit where the system tape skew and head azimuth errors will smear or wipe out the read signal. For a nominal tape skew of 100μ"/in the skew error across a .025" track is 2.5μ" or 12% of FR, which is beginning to effect the read signal by crosstalk between bits (intersymbol interference).

The head gap must also be straight within 10% of the FR (2μ") to keep the signal amplitude smear below 1dB. For separate read/write heads, the gaps must maintain azimuth parallel within 0.004°. Both of these factors are at the limits of mechanical tolerances.

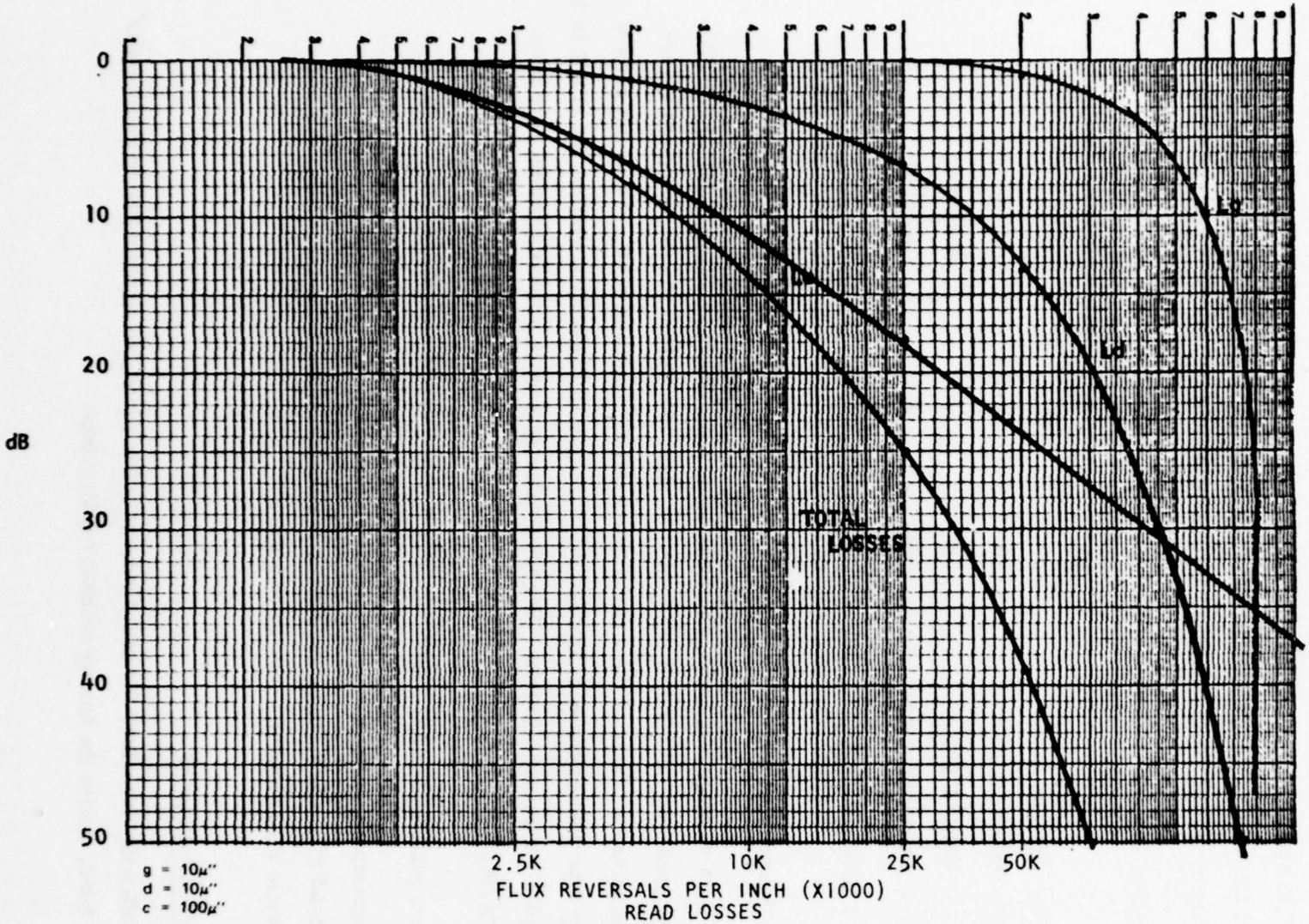


Figure 5. Read Losses

Two μ'' is about the limit that material can be polished, therefore any head gap will have at least $2\mu''$ of edge wander due to surface finish alone, plus $2\text{-}10\mu''$ of drift due to stress etc. For these reasons, $10\mu''$ gaps should be limited to use at W = 10 mils.

@ $20\mu''$ limit/TRK Track width (Mils)

	20	8	
limiting skew	800	2000	μ''/IN
tolerable skew	80	200	μ''/IN
limiting gap az	.04	.07	degrees
tolerable gap az	.004	.007	degrees

Table 1 lists the discussed scale factor limiting items.

2.2.3 Magnetic Heads

In the area of magnetic heads, the most severe limitation is the head read efficiency. We are presently not reading tape noise by about 10-12dB. The second most severe limitation is the length of the write magnetization transition zone. We do not know if we are tape demagnetization limited (a) or record field gradient limited, or single turn slew rate (amps/sec) limited. The total write system is presently useful only up to 33K FR/IN.

Present read limitations are:

preamp noise floor	=	0.056μ Vrms/turn
Head Eff. - S/N	=	25dB (excluding dropouts)
Write FR Gradient	=	2 (= t/a)

Read/Write Process

The following describes the read/write process which, in combination with the read/write head, limits the analog channel performance.

TABLE 1. SCALE FACTOR LIMITS

	Tape Demag. Loss(a)	KBPI (FR/IN)	Tracks Per Inch	$MBPI^2$ (I bit/FR)	d (μ")	Separation loss L_d	BER (RAW)	Tape Particle Size p (μ")	Bit l (μ")	Bit w (μ")	Bit Squareness Factor (w/l)	Part. Count per Bit (p/l)	p/l Loss Factor
IRIG (present)		33	28	0.9	10	9dB	10^{-6}	12	30	25×10^3	833	2.5	2dB
HDMR (present)		25	80	2.0	10	7dB	10^{-4}	12	40	8×10^3	200	3.3	1dB
3330 DISC (updated)		4	400	1.6	40	4dB	10^{-10}	1	250	2.5×10^3	10	250	0dB
Optical Disc			5555										
IRIG (development)		50	28	1.4	5	7dB	10^{-6}	12	20	25×10^3	1,250	1.7	4dB
Goal System		50	80	3.0	5	7dB	10^{-4}	12	20	8×10^3	400	1.7	4dB

Estimated particle aperture loss (dB)

1. Magnetization of Tape	a)	Varies according to field strength, direction and duration.
	b)	Highly non-linear at particle level, but linearizes with short λ.
	c)	Varies due to particle clumping, size Δ and proximity Δ.
	d)	Distorted by tape movement during field change (dx/dt).
2. Self Demagnetization of Tape	•	Caused by interaction of particle intrinsic fields after removal of record field.
	•	Also caused by increase in particle intrinsic demag field after removal of Hi μ Field Shunt (Head).
	•	Varies due to (c) and (d) above.
3. Read Process	•	Presence of Hi μ head reduces these fields and concentrates them in the head.
	•	Head field is a summation of the fields of all particles in the vicinity of the head (gap).
	•	Variation of the field in the head generates voltage in the head output wire ($d\phi/dt$).

2.3 IMPROVEMENTS REQUIRED TO ACHIEVE PROGRAM GOALS

2.3.1 Present System Losses

The losses incurred in the present system can be calculated if the ideal lossless performance level is known and the present system performance levels are measured.

The following calculations start from the ideal digital channel probability of error (BER) vs S/N. The minimum BER of 10^{-5} requires a channel S/N of 11.5dB with no dropouts. To achieve this S/N a minimum of 200 tape particles is required which limits the track width to 38μ" or 26,500 tracks/inch absolute maximum.

The ideal read signal for an ideal block of magnetized particles is calculated to be 8mv for the present 8 mil track and 80 turn head at 120 in/s at any BPI. This is valid

in an ideal lossless system because the 6dB/octave loss of tape magnetization (MMF), thickness loss (c), is offset by the 6dB/octave gain in $d\phi/dt$.

The write (record) losses are calculated to cause a 12dB reduction in the above assumed MMF which also causes the 12dB octave record loss variation in tapes when the recorded signal wavelength (λ) is less than the oxide thickness.

The present system signal and noise levels are given and the total losses indicated are 35dB. The read and write losses calculated are also 35dB when the head efficiency losses are estimated at 7 + 10dB = 17dB.

The present decoder performance is calculated to be 9.5dB poorer than the ideal detector based on actual bench test data.

2.3.1.1 System Threshold S/N

For an ideal detector, the system threshold S/N can be calculated[1] and is plotted below vs. BER (Figure 6, curve A). For Delay Modulation (DM) a 2dB increase is required to allow for the necessary double strobing of each bit, (curve B). Assuming that an EDAC scheme will provide 10^2 improvement in the channel BER, a raw BER of 10^{-4} requires 10.5dB S/N for the ideal DM detector and 10^{-5} requires 11.5dB S/N.

2.3.1.2 Track Width Limit

Tape particles produce quantum noise. A minimum number of particles (n) is required to achieve the threshold S/N power of 11.5dB when 11.5dB = 10 log n^{-2}; n = 200 particles.

Particle = $12\mu''$ long by $\pi(\mu'')^2$ area = $12\pi(\mu'')^3$ volume (10^{15} particles/in^3)

50% loading = $24\pi(\mu'')^3$/particle

X200 particles = 15,080 $(\mu'')^3$ volume for threshold S/N

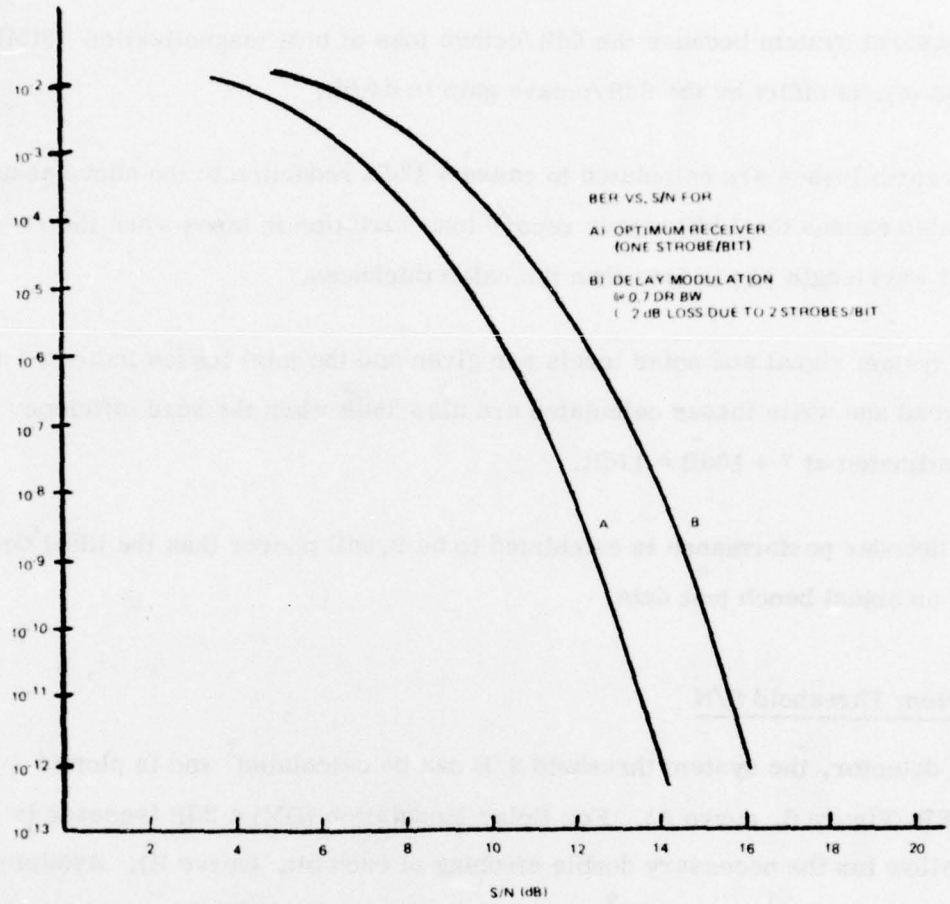
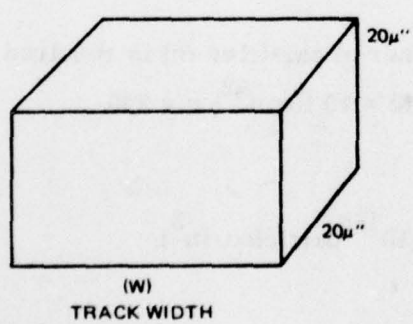


Figure 6. BER vs S/N

At a recording depth = to one FR:



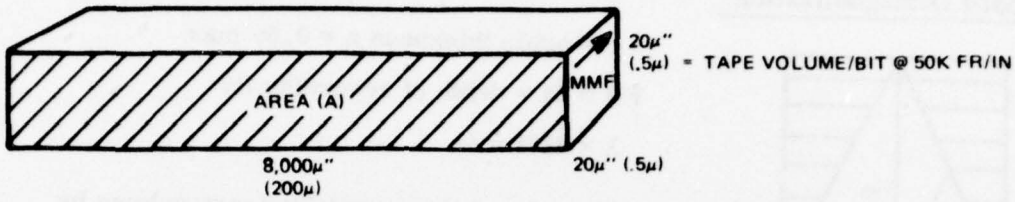
$15,080(\mu'')^3 = 20 \times 20 \times W$

$W = \frac{15,080}{400} = 38\mu''$ quantum limit

or 0.0265 TRACKS/μ'' = 26,500 TRACKS/INCH absolute limit with no guard bands

5.0×10^4 BPI $\times$ 2.6×10^4 TPI = 1.3×10^9 BPI^2 absolute limit if FR = 1 bit.

2.3.1.3 Present System Signal Limits (No Losses)



$$200 \times .5 \times .5 = 50(\mu)^3$$

Available tape Br = 1500 gauss = 0.15 Weber/Meter^2

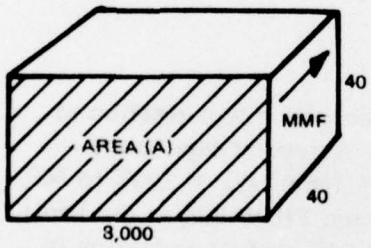
$$A = 100 \times 10^{-12}(m)^2 = 10^{-10}(m)^2$$

$$= \text{Flux} = Br \times A = 0.15 \times 10^{-10} \text{ Webers}$$

$$e = Nd\phi/dt = N \frac{0.15 \times 10^{-10} \text{ webers}}{0.167 \times 10^{-6} \text{ sec}} = 10^{-4} \text{ volts/turn}$$

$$dt = \frac{20\mu''}{1\ 20 \text{ in/s}} = .16\ \mu s$$

@ 25K FR/IN



$d\phi$ = X2 (X2 area)

dt = 1/2 (X2 bit)

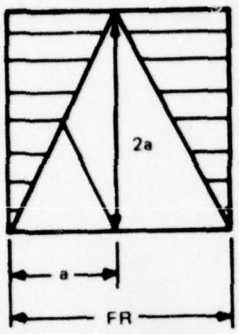
$d\phi/dt$ = 8 mv @ preamp input

Ideal tape output is only a function of track width for ideal HDMR recording.

V_{READ} LIMIT = 1 mv/Mil @ 80 Turns

2.3.1.4 Record Losses

a. Record Demagnetization*



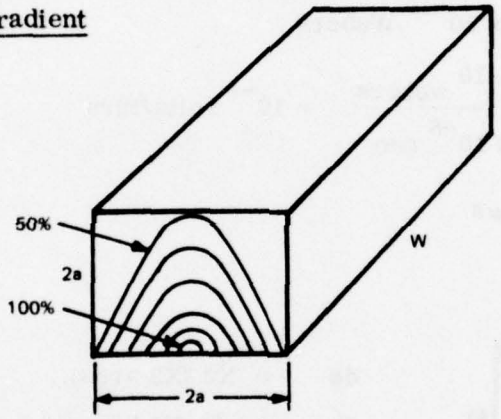
c = oxide thickness a = 0.5c max

FR = 2a = depth of recording (t)

λ = 2FR = 4a

(*) reduces the magnetized tape volume by 50% or 6dB (shaded area is demagnetized) 2a/a or a slope of 2 is the limiting remenant field gradient allowed by the tape self demagnetization effect.

b. Record Field Gradient



The record field gradient must necessarily limit the tape magnetization at the FR boundary to 50% (random) orientation. The degree of tape magnetization therefore, varies between FR boundaries from 50% to 100% to 50% and varies into the oxide from 100% at center between FR to 50% at the limit of record penetration (2a). This causes a nominal 50% or 6dB reduction in equivalent magnetized tape volume.

c. Total Record Losses

a plus b above equal 12dB loss over the assumed ideal magnetized tape volume. This also produces a 12dB/octave variation in record losses where $\lambda < c$, which has been confirmed by test measurements, and due to the same effect; 4:1 reduction of magnetized tape volume by $1/2\lambda$ and 1/2 t.

2.3.1.5 Present Signal/Noise Levels

2MHz BW
20,000 BPI (FR/IN)
100 in/s

Pre Amp Output Signal = 500MVpp @ 1MHz for optimum DM R/P (200MV rms)*

= -14dBm (Vrms = 0.707Vp)

Pre Amp Output Noise = -67dBm (3kHz BW)

(-39dBm @ 2MHz BW) $\left[20 \log \left(\frac{2\text{MHz}}{3\text{kHz}}\right)^{-2} = 28\text{dB} = 25{:}1\right]$

Pre Amp Gain = 65dB

Head Output Signal = 200MV - 65dB = 113μV

Head Output Noise = 113μV - 25dB = 4.5μV

Head Output S/N = -14 - (-39) = 25dB @ mid band (1 MHz)

Single turn head output @ 100% transformer eff. (80:1)

Signal = 1.4μV/turn

Noise = 0.056μV/turn

2.3.1.6 Present Read/Write Losses

No loss signal = 8 mv

Actual signal = 0.113 mv @ 100 in/s

X1.2 = 0.1356 mv @ 120 in/s

Losses $= 20 \log \frac{8}{0.136} = \underline{\underline{35\text{dB}}}$

Read Losses

Separation loss L_d = 6dB @ d = 10 μ"

Gap Loss L_g = 0dB @ g $\leq$ 20 μ"

*can vary ±6dB with heads; value given is typical.

Magnetic circuit, gap loss = 7dB

Core eff. x single turn eff. x transformer = 10dB

Record Losses

Tape demagnetization = 6dB

Record field gradient = 6dB

Total Losses 35dB

2.3.1.7 Present Decoder Losses

DM threshold S/N for 10^{-4} BER = 10.5dB

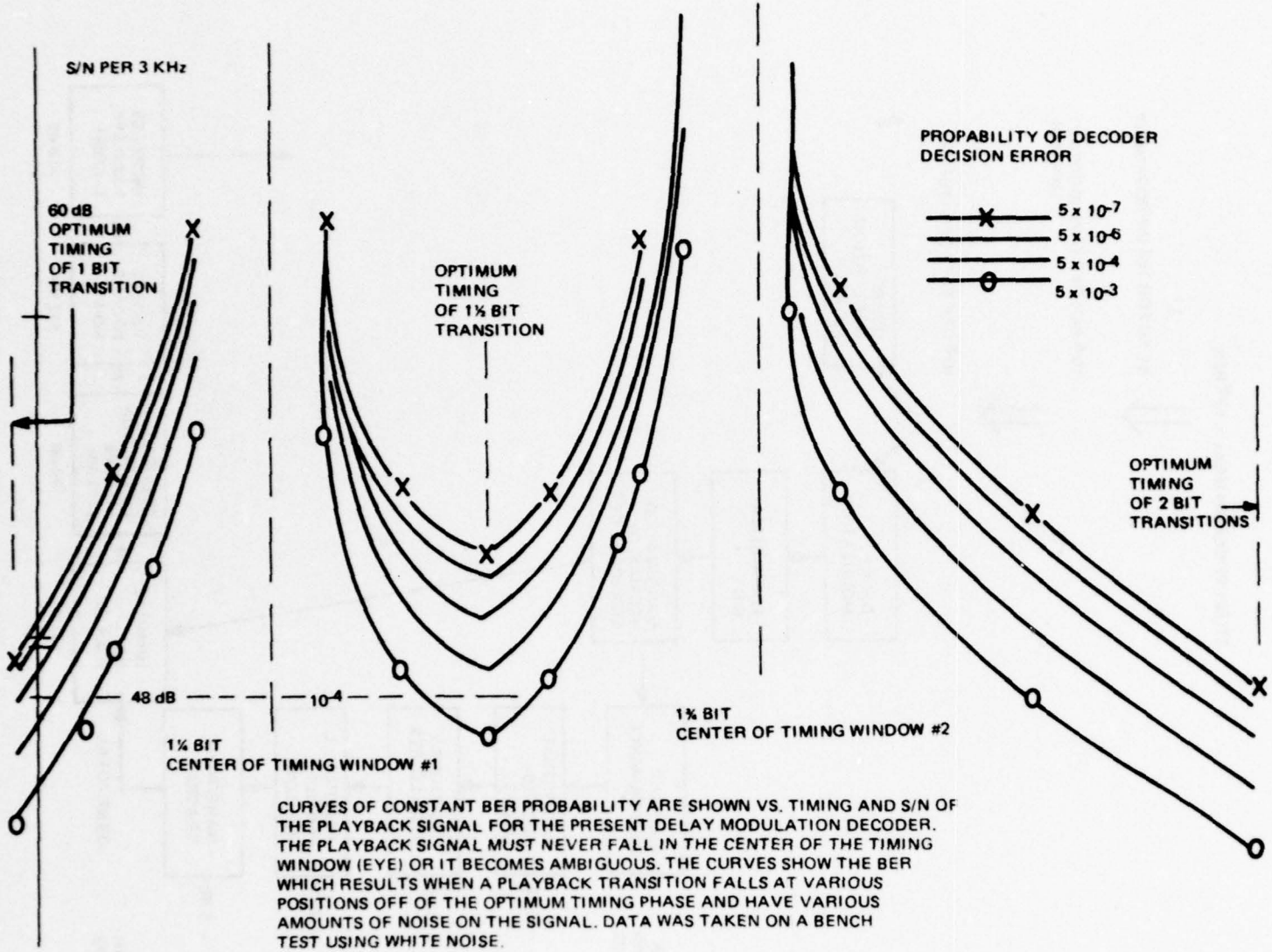
Present detector S/N for measured 10^{-4} BER = 48dB (3kHz)
(See Figure 7) with no timing errors = 20dB (2MHz)

Present decoder loss = 20 - 10.5 = 9.5dB with no timing errors

2.3.2 Additional Losses

The following flow chart (Figure 8) describes in summary form, the losses to be incurred in going from the present 20K FR/IN system to the goal 50K FR/IN system. These losses (33dB) are recoverable by achieving the improvement factors in the four areas shown. Full recovery will yield 10^{-4} BER at the goal values listed. EDAC presently achieves 10^2 improvement in BER with 8% overhead and can be assumed to achieve 10^3 improvement with the same or additional overhead and additional sophistication of algorithms. 10^{-7} BER is thus achievable with the present 10^{-4} raw BER. The raw BER is assumed to be totally due to dropouts when the detector BER is less than 10^{-5} at the system S/N.

The additional record losses at 12dB/octave are 15dB; read losses (from the curve previously used) are 13.5dB for separation and 1dB for gap aperture. 14.5dB less the present 5.5dB yield 9dB additional read loss.



CURVES OF CONSTANT BER PROBABILITY ARE SHOWN VS. TIMING AND S/N OF THE PLAYBACK SIGNAL FOR THE PRESENT DELAY MODULATION DECODER. THE PLAYBACK SIGNAL MUST NEVER FALL IN THE CENTER OF THE TIMING WINDOW (EYE) OR IT BECOMES AMBIGUOUS. THE CURVES SHOW THE BER WHICH RESULTS WHEN A PLAYBACK TRANSITION FALLS AT VARIOUS POSITIONS OFF OF THE OPTIMUM TIMING PHASE AND HAVE VARIOUS AMOUNTS OF NOISE ON THE SIGNAL. DATA WAS TAKEN ON A BENCH TEST USING WHITE NOISE.

Figure 7. BER vs. S/N and Timing

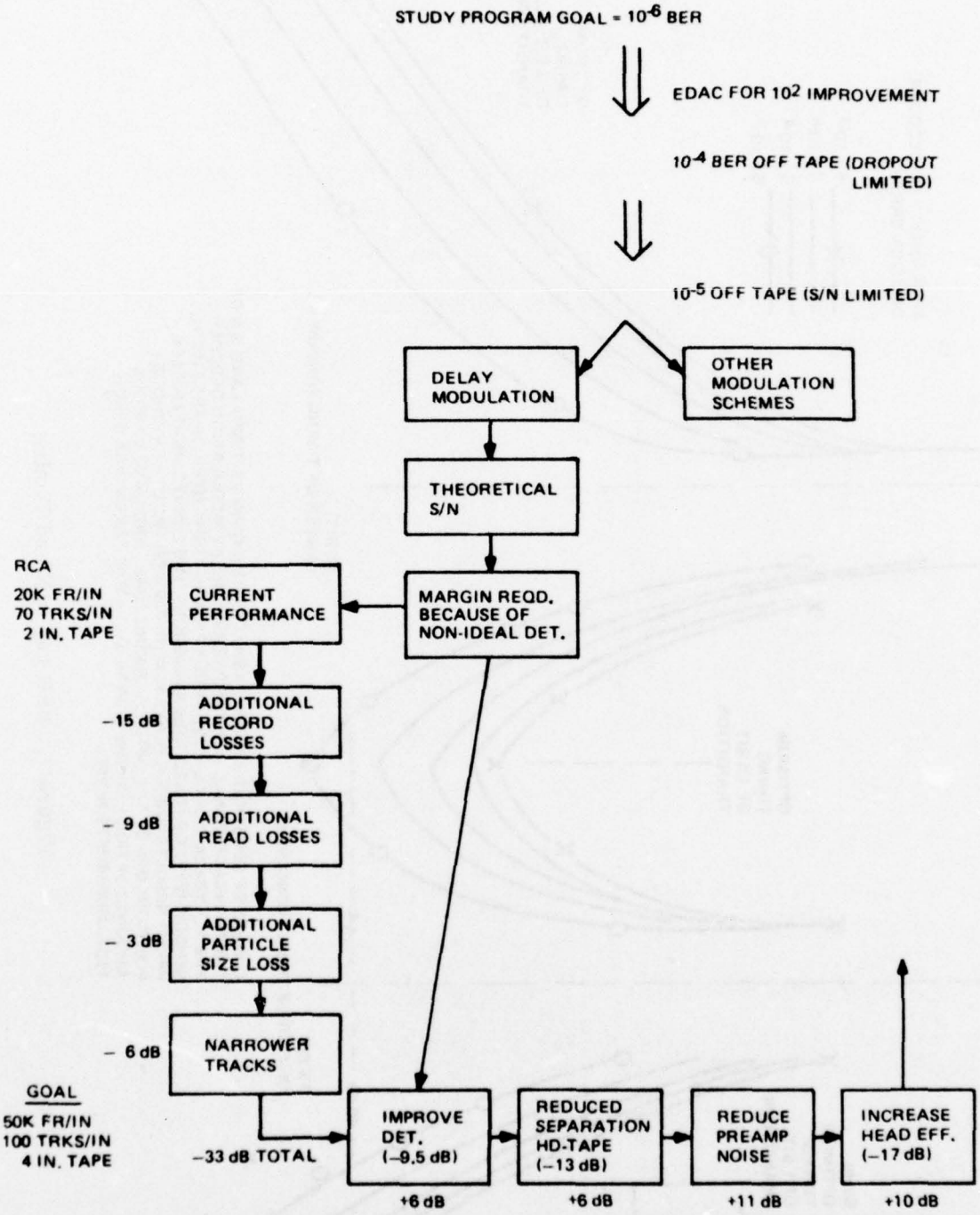


Figure 8. Losses Flow Chart to Achieve Goal

If we are limited to one bit/FR, 50K FR/IN equals 50K BPI, and 100 tracks/inch is a reasonable goal. If we maintain the present 6 mil guard band between tracks, the 70 tracks/inch to 100 tracks/inch reduces the data track from 8 mils to 4 mils for a 6dB loss. The 20μ" bit has a 40μ" λ and is approaching the tape particle size of 12μ". From the previously used aperture loss curve, the additional loss for tape particle size is 3dB.

Total additional losses are 33dB.

2.3.3 Improvement Estimates

Improvements in system performance can be gained in four areas. The detector has a 9.5dB loss of which 6dB should be recoverable. The head-tape separation loss is 13dB of which 6dB should be recoverable. The present read preamp noise is 12dB above the tape noise; 11dB should be recoverable. The magnetic head efficiency has an estimated total loss of 17dB (14% total efficiency) of which 10dB should be recoverable.

The improvements total 33dB.

2.4 SYSTEM OPTIMIZATION

2.4.1 Analog Channel Characterization

The first and most important step in system optimization is the most complete and detailed characterization of what has been called the analog channel. Figure 9 indicates the core position of the analog channel in a system model.

Major aspects to be characterized are:

- channel response in the frequency and time domain
- noise spectral distribution:
  - uncorrelated
  - correlated (from adjacent channels)

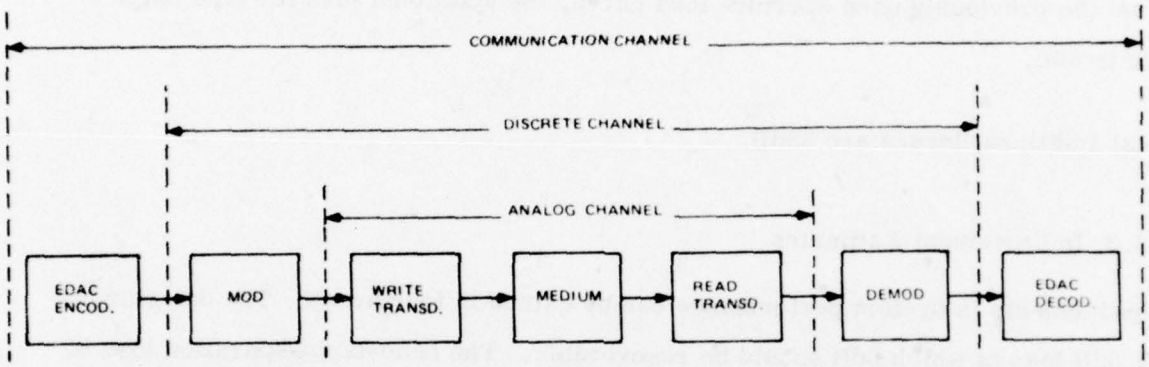


Figure 9. Digital Magnetic Recording System Model

- dropout statistics: distribution of burst length and guard space
- parameters variability (statistics)

The performance limitations of an analog channel are primarily those of the write transducer, medium, and read transducer and are shown in Table 2.

TABLE 2. ANALOG CHANNEL LIMITATIONS

• S/N	Head/Tape/Electronics
• Amplitude Response	
- Head/Tape Response	Head/Tape
- Drop Outs (Fading)	Tape/Dynamics
• Phase Response	
- Intersymbol Interference	Tape/Write Field/Skew
- 90° Phase Shift ($d\phi/dt$)	Read Function
- Group Delay	Electronics/Wiring

Once the analog channel is precisely characterized, the designer of the communication channel - on the initial assumption that he has no control on the analog channel - can start reviewing his options, assessing the merits of each, and predicting performance for given sets of choices.

Each element of the analog channel was investigated as to the possibility of improving its contribution to the overall channel characteristics.

The result is an improved analog channel to be used for the final design to be breadboarded.

2.4.2 Digital Channel Improvement Options

There are three major digital areas where performance improvements can be obtained external to the analog channel:

1. detection (Table 3)
2. error control (Table 4)
3. modulation (Table 5)

These three areas can be put immediately into proper qualitative perspective by observing that while any improvement in any of the three areas would involve some added hardware complexity — which is acceptable, both technologically and financially — any improvement obtained from a modulation or error control scheme potentially involves a loss of SNR or transmission rate. The point to be made is that as the margin left for potential performance improvement gets smaller, the designer is well advised to ensure that the detection scheme is as close to the optimum as possible before proceeding to other areas of improvement.

1. Detection. The case of reception with no intersymbol interference will be discussed first. The read-transducer acts as a differentiator with a three-level output. Each output pulse carries information not only about the occurrence of a flux-reversal but also about the state the transmitter was in before the reversal occurred. Likewise, when delay modulation is used each transmitted waveform carries information also about the next symbol to be

transmitted (look-ahead). These two examples show that we are dealing with a channel with memory that can be modeled as a convolutional code or a finite state Markov process.[2] The receiver should be mechanized so as to exploit as much of the information available as possible; not by making a decision on one symbol at the time, but by making the best estimate over the memory span of the channel (bit-by-bit sequential detector).

In real systems affected by intersymbol interference, bandwidth equalization, either in the frequency or time domain, is usually added to the receiver to minimize the amount of interference at the sampling instants. Although effective in many cases, this is not an optimum scheme, since it suppresses information about the symbol to which the interference belongs. This is particularly so, if high transmission rates per cycle of bandwidth are desired. The relatively recent signaling schemes called partial response or correlative actually exploit intersymbol interference by introducing it intentionally in the waveform to control the spectrum.

Recent developments in optimum non-linear receiver are based on the concept of matched filter extended to a sequence of symbols (maximum likelihood sequence estimators, MLSE). The basic idea is as follows: the receiver takes a sequence of received symbols of length comparable to the length of the channel impulse response (say N symbols), matches it with each of the possible (2^N for binary symbols) sequences of N symbols, computes for each the conditional probability of occurrence and chooses the most likely sequence as the transmitted one. MLSE mechanizations, much simpler than the basic concept may imply, have been developed. The Viterbi algorithm is one of them.

TABLE 3. DIGITAL CHANNEL IMPROVEMENT OPTIONS, DETECTION

1.	Add memory to allow analysis of groups of data bits (look back-look ahead).
	(Utilize unique pattern sequence to help make decision (built in redundancy).
2.	Exploit intersymbol interference as control or prediction.
3.	Maximum likelihood sequence estimation (MLSE) type algorithms.
	Optimize the Detector

2. Error Control. Qualitatively, and from a practical point of view, the channel for a high density digital recording system is easily characterized: it is a bursty channel featuring an extremely low probability of random errors.

Errors are caused by signal dropouts, occurring at random as to duration and frequency, but with average values that decrease as the signal level increases. Statistics are available to model a fading channel.

When a dropout occurs, it affects a roughly circular spot on the tape, and hence, a few tracks across the tape but for a wideband system, hundreds or thousands of bits along a track.

Next we observe that if the beginning of the dropout could be detected and pointers set to the tracks involved, we would deal with erasures rather than error. Less redundancy would be required for coding since a code can correct twice as many erasures as errors. In fact, a single parity check applied to a string of binary digit, no matter how long, can correct any single erasure. By interlacing the codewords as many times as the length of the burst in bits, all bursts of that length or less can be corrected.

More specifically, a 160-track tape can be instrumented for error control (against dropout) as follows:

a. divide all 160 bits across the tape into 20 8-bit supersymbols, of which 19 carry data and one is the parity check supersymbol;

b. encoding: the parity check results from the modulo-2 sum of all 19 data supersymbols;

c. decoding: fill all erasures with zeros; compute the syndrome by adding modulo-2 all 20 received supersymbols; correct each erasure by adding to it the binary symbol contained in the corresponding position of the syndrome.

This simple scheme with about 5% redundancy can correct a single dropout involving up to 8 adjacent tracks. In addition, it can detect at least one random error, which would be corrected if we had a means to identify the track in which it has occurred. Earlier we have discussed potential improvements in the waveform detection by taking advantage of the information carried by each symbol about the preceding and/or the following symbol. This information can be used to detect the possibility of an error, which once correlated with the transverse parity check will lead to the correction of the error if it has indeed occurred.

This surprisingly simple and yet powerful coding scheme is one of the many options that coding theory offers. It also shows that efficient schemes need not be complex or sophisticated or require elaborate channel modeling. Efficiency usually results from an integrated design approach which considers modulation and coding at the same time, not necessarily — although desirable — for the purpose of combining them into a single process.

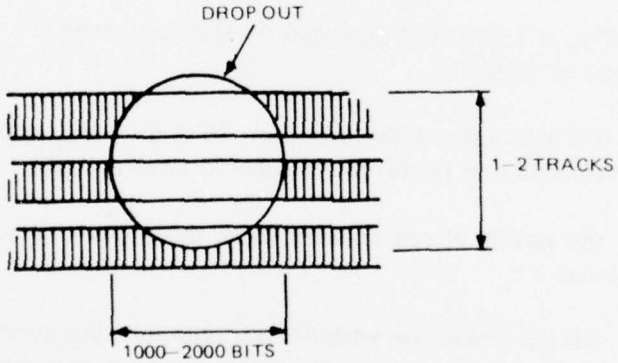
TABLE 4. DIGITAL CHANNEL IMPROVEMENT OPTIONS, ERROR CONTROL

1. Add drop-out detector—correcting "erasures" instead of errors doubles EDAC power.

2. Use redundancy and unique code sequence to increase error detection power.

3. Interlaced EDAC code words to break up errors.

4. Trade off across track vs. along track EDAC schemes.



Optimize Error Control

3. Modulation. Modulation in this application is the process of encoding the binary data sequence into another sequence of binary (or N-ary) waveforms that facilitate the extraction of timing at the receiver, and shape the frequency spectrum of the signal to match the frequency response of the channel.

An upper limit to the response of a given recording system is set by the highest density of flux reversals (transitions) allowed for an acceptable level of signal distortion. The lower limit is set at zero - frequency where for most practical systems no component is allowed for any possible data sequences. An optimum modulation scheme then is the one that allows as high a data rate as possible within that frequency band.

A variety of modulation techniques have been developed with varying degree of success and practical applicability. They may be broadly grouped into binary and non-binary approaches. The non-binary approaches consider multi-level or multi-phase waveforms, and attempt to trade the inevitable loss in SNR at the decoder/detector with the inherent greater efficiency of higher order alphabet (as against binary). Progress in this area of research has not advanced as much as in the binary waveform approach. Indeed, promising binary techniques are being generalized to non-binary codes.

The rather simple and efficient binary coding scheme (delay modulation) successfully used by RCA, matches reasonably well the frequency response of the channel, except for the dc response of certain repetitive data patterns that, if persistent, may create signal distortion. This problem seems common to most schemes developed thus far and its solution appears the major target of current research.

The conceptual basis of current research in binary coding is to map successive segments of a data sequence into sequences of binary symbols with certain constraints,[3] such as:

a. No fewer than d consecutive zeros are allowed in the coded sequence; this sets the highest transition rate;

b. no more than k consecutive zeros are allowed in the coded sequence (minimum transition rate for time extraction);

c. the accumulated charge at any digit position in the sequence is bounded by ±C units (to constrain dc response).

Inevitably these coding schemes require the addition of redundancy (for effective schemes 100% or more). However, the upper limit of the coded waveform bandwidth is still controlled by the highest transition rate and may remain the same as for the noncoded sequence if we chose d=2 and add 100% redundancy. The gain of course is in an easier synchronization and a zero dc component.

Run-length limited or bandwidth compaction are different names for this basic coding technique.

A certain amount of loss in efficiency is inherent in these schemes due to the redundancy added in the coding process. For this reason researchers are investigating the possibility of using this redundancy also for error correction or, at least, detection.

For high density systems featuring long error burst along the track, error correction schemes acting along the track rather than across appear rather inefficient. The incorporation of some form of error control into waveform encoding would then be of doubtful usefulness.

Another potential area of research is multi-channel or two-dimensional coding, where now patterns of symbols across the tracks would be controlled as well as symbol patterns along the tracks.

The application of partial response techniques used successfully in communications systems appears particularly suitable for wideband recording since instead of adding redundancy to reduce distortion, the techniques exploit the distortion itself to convey information, and is known as Enhanced Delay Modulation (EDM).

The proposed task IV investigation is expected to be primarily of an analytical nature to extend and advance the level of development for those particular approaches most efficient for wideband system applications. Experimental work can then follow to demonstrate/prove the task IV conclusions/recommendations.

TABLE 5. DIGITAL CHANNEL IMPROVEMENT OPTIONS, MODULATION

General	•	Make the best analog channel fit.
	•	Make the best use of the detector.
Specific	•	Minimize number of octaves.
	•	Minimize signal rate.
	•	Eliminate dc from signal.
	•	Add memory and do block coding.
	•	Block coding overhead plus EDAC overhead for error control.
	•	Trade off compaction vs. statistical errors.
		Use multi-channel modulation (2 dimensional)
		Optimize Modulation Technique

2.4.3 Tape Magnetics

Tape is a given and limiting factor. It is given because tape development is out of scope for this effort. It must be analyzed, however, so that its limitations are as perfectly understood as possible and so that we may know how to work around them. The following discussions give insight as to how these limits could be changed.

The tape self demagnetization is of primary concern, and the effects of tape particle size and oxide coating thickness are of major concern in the tape magnetic performance. The tape surface topography is of major concern in establishing and maintaining a low separation loss and a high field resolution. Separation has the same effect on resolution as increasing the head gap size. All of these problems are severely reduced when plated metal tapes are considered. This approach requires new head-tape interface geometry and control.

The following (Table 6 and Figures 10 thru 12) show that we are reaching the limit of particle sizes used in the available magnetic tapes. The direction to go for reduced limitation is smaller particles for shorter wavelength (λ), higher coercivity and thinner coatings to reduce the self demagnetization loss (improve resolution), metal film and denser loadings for increased read magnetization and lower noise medium.

<u>TAPE DEMAGNETIZATION.</u> Of all the head and/or tape resolution parameters the area of greatest limitation is the demagnetization properties of the tape. Two types of demagnetization exist, self demag. and record demag. Figure 13 is a simplified model of the two flux reversals (bit cells) at a BPI of 50K, $\lambda/2 = 20\mu''$. Note that there are actually three loss effects occurring during and after a bit cell is recorded, all of which finally results in a reduction of total flux ϕ available during playback.

1. Record Demagnetization Lines.
2. Self Demagnetization Lines (increases after particles leave head).
3. Flux lines lost in the unused oxide.

TABLE 6. MAGNETIC PARTICLE AND TAPE PROPERTIES OF AVAILABLE TAPE

α Ferric Oxide Fe_2O_3	Cobalt Doped αFe_2O_3	CrO_2
Acicular	Cubic	Extra-Acicular
Size 1 = 5-25μ in (16typ)		1 = 20 μ in typ
$\frac{1}{d}$ = 5-20 (6typ)		$\frac{1}{d}$ = 8typ
Hc/Br = 300/1000	500/1600	500/1600
Br/Bs = .75 oriented/0.5	0.83/0.6	0.9/0.5
.50 unoriented	0.77	0.80

Effects of Smaller Particles

- Lower noise (more particles and more uniform size/unit volume).
- Higher self demagnetization.
- Smaller λ recording capability.

Metal Film Tape Characteristics

- Much thinner than particles.
- More than 2 times coercivity (1200 O_e).
- Higher magnetic continuity - avoids flux closures around particles and surface clusters.
- Smoother surface - closer contact plus possible magneto-optic playback. Latter especially significant since playback process is limiting in metal tapes.

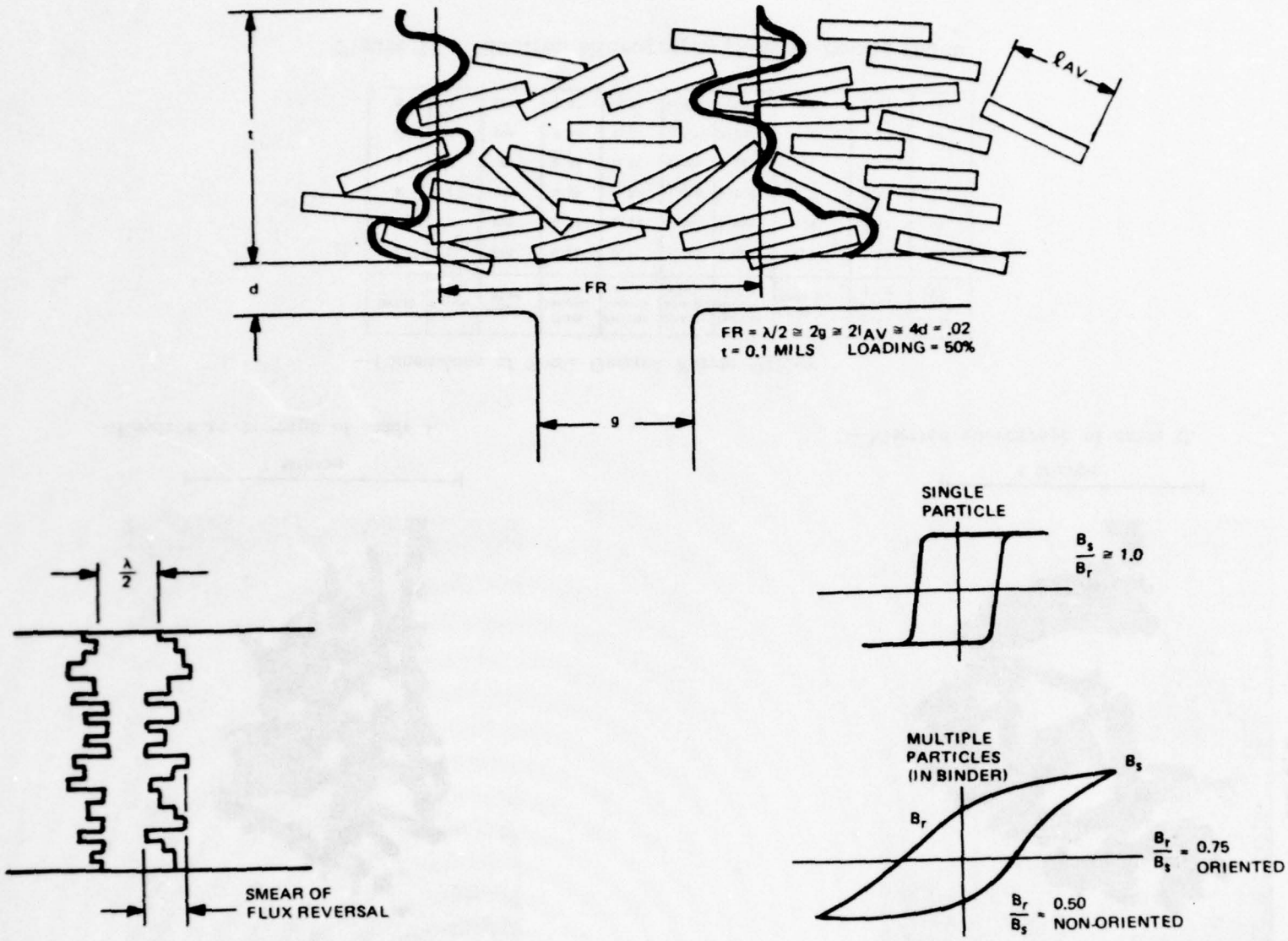


Figure 10. Effect of Particle Tapes on Maximum R/P Resolution

1 Micron

—Electron micrograph of oxide A.

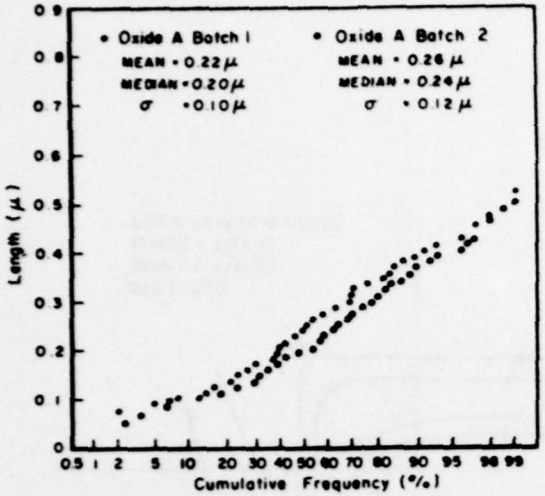
1 Micron

—Electron micrograph of oxide C.

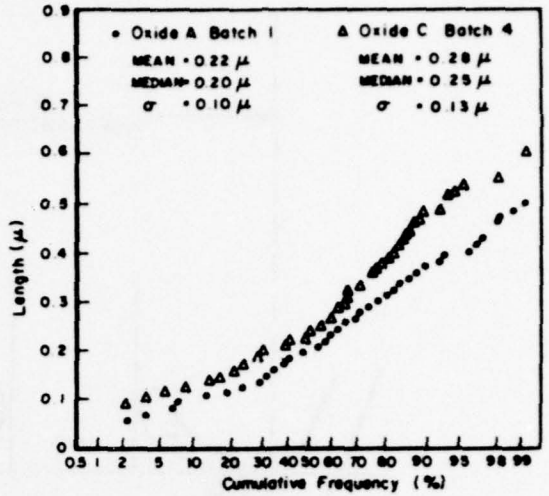
—Dimensions of Some Gamma Ferric Oxides

Oxide	Batch	Sample Size	Mean Length $\ell(\mu)$	Median Length $\ell(\mu)$	Mean Width $w(\mu)$	Median Width $w(\mu)$	Mean ℓ / Mean w	σ of Length $\ell(\mu)$	σ_r of Length (%)
A	1	170	0.22	0.20	0.045	0.040	4.9	0.10	46
A	1	128	0.21	0.19	0.044	0.040	4.9	0.11	49
A	2	100	0.26	0.24	0.050	0.048	5.2	0.12	46
B	3	89	0.44	0.41	0.096	0.089	4.6	0.21	47
C	4	146	0.28	0.25	0.070	0.067	4.0	0.13	48
D	5	141	0.27	0.25	0.057	0.055	4.7	0.12	46

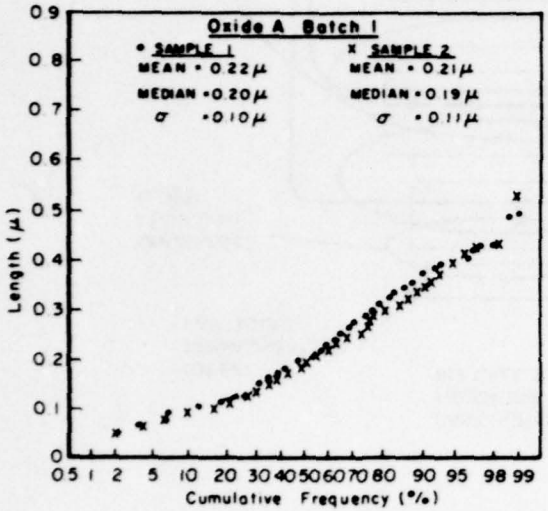
Figure 11. Electron Micrographs Gamma Ferric Oxide



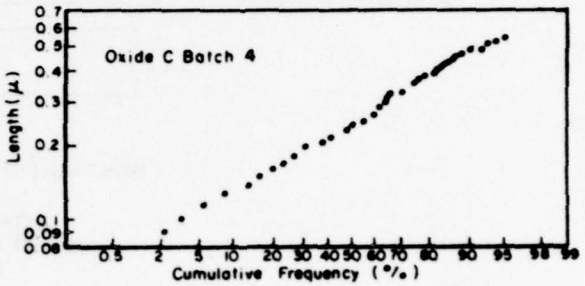
—Arithmetic probability graphs of two batches of oxide A.



—Arithmetic probability graphs of oxides A and C.



—Arithmetic probability graphs of two samples of oxide A.



—Logarithmic probability graph of oxide C.

Figure 12. Particle Size Gamma Ferric Oxide

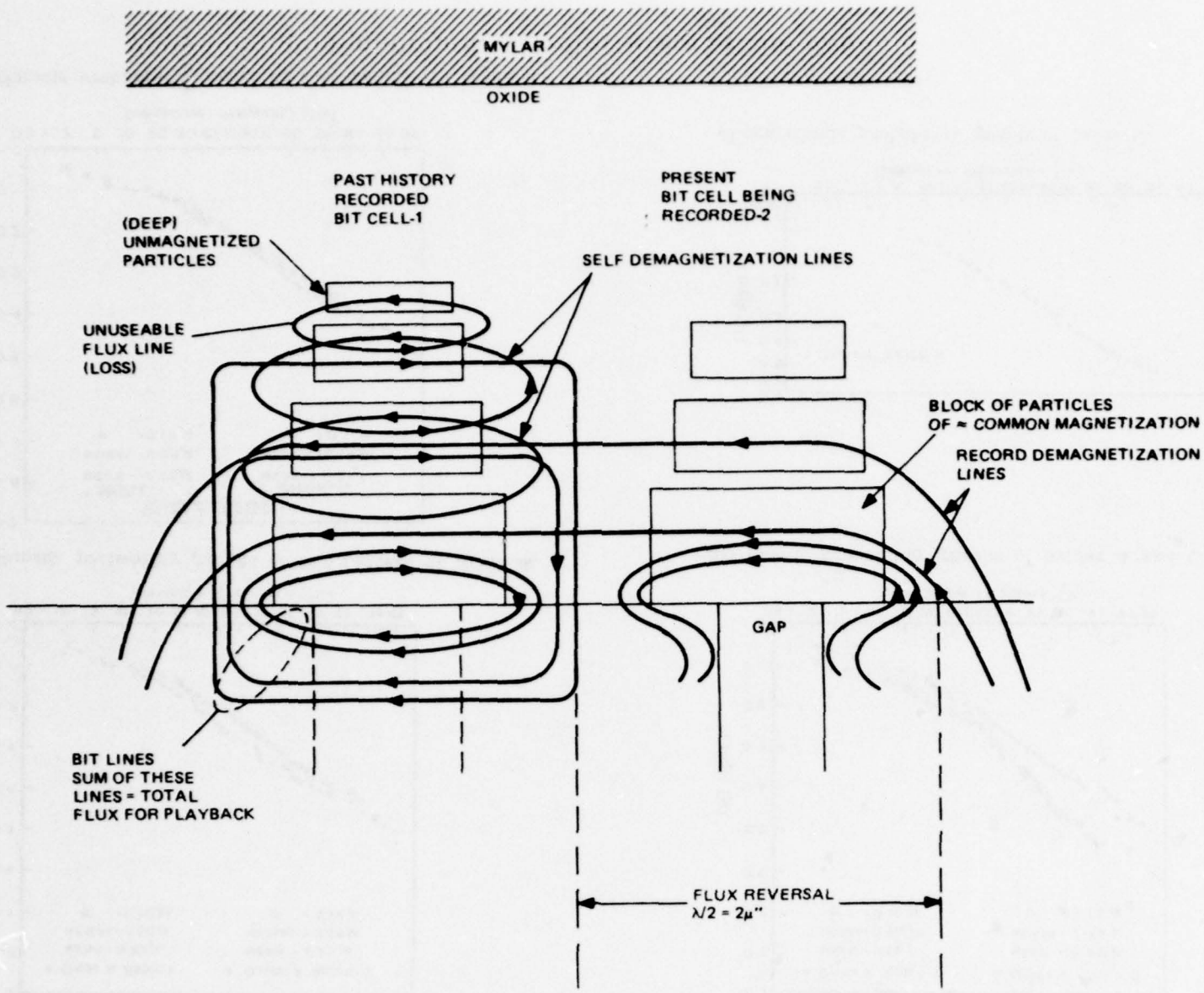


Figure 13. Model of Tape Demagnetization

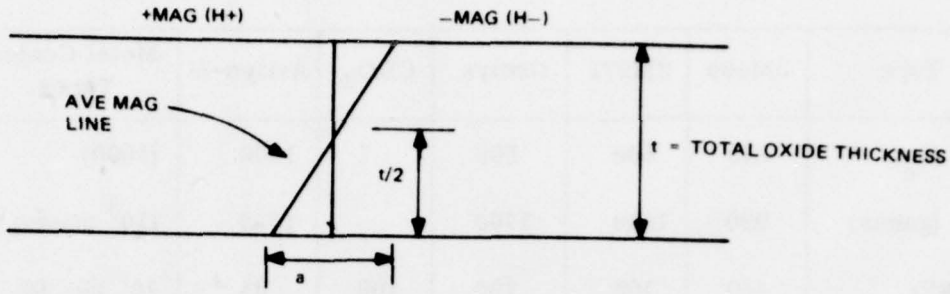


Figure 14. Typical Flux Reversal

The primary properties of the tape which contribute to these demagnetization losses are Br, Hc, and oxide thickness.

The property of Record Demagnetization (a) is defined as $a = \frac{Br\,t}{2\pi\,Hc}$.

The above expression is the Record Demag. created by a step function of magnetizing flux as would be created after changing the direction of a saturating field H+ to H- in an instantaneous period of time as in Figure 14.

This single isolated transition is not at all similar to the short pulse duration recording intended for this program. It can, however, demonstrate the relative difference of available recording tapes. See Table 7.

This agrees with test data that shows that pulse density is inversely proportional to oxide thickness.

From inspection of Table 7, a = t/2 for most oxide tapes.

This is a very useful result in so much that the property "t" is always a known physical parameter. To obtain high density pulse recording, t is effectively reduced to t' by limiting the record current and reducing the gap size such that t' = 20μ", as shown below Table 7.

TABLE 7. MAGNETIC TAPE CHARACTERISTICS

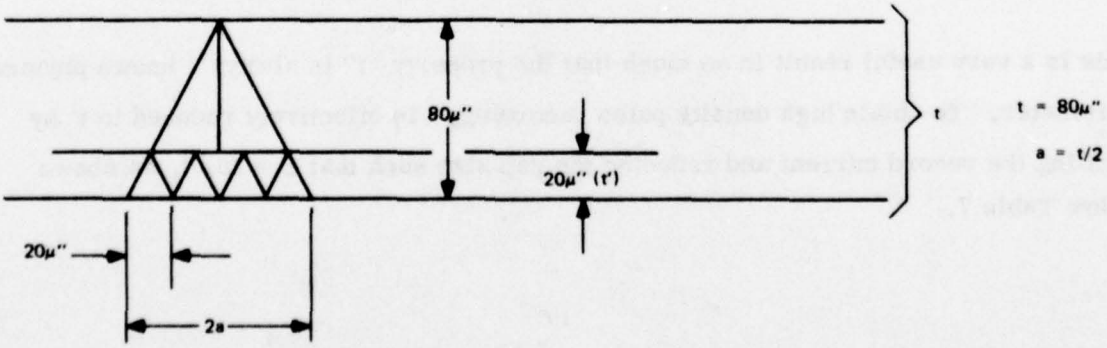
Tape	3M400	3M971	Crolyn	CRO_2	Avilyn-M	Metal Coated Tapes
Hc (0_e)	310	500	500	1	1400	(1000)
Br (gauss)	920	1500	1700		1300	(10^4 gauss)
t (μ'')	480	100	190	100	84	40 20 10 5
a (μ'')	227	48	103	54	12	64 32 16 8
3M XRM-IV						
Hc		1000	1000	1000		
Br		3000	3000	3000		
t		200	100	50		
a (μ'')		96	48	24		

Typical tape magnetic values and mechanical characteristics are shown in Figure 15.

These ratio of terms t and a represent the slope of the magnetization line in Figure 15 as does: $a = \left(\frac{Br}{\pi Hc}\right)\frac{t}{2}$

$$\text{slope}\left(\frac{t}{a}\right) = \frac{2\pi Hc}{Br} = K \text{ for any given tape}$$

For any given tape t must be reduced to reduce a.



At an effective recording depth of 20μ" four transitions can exist instead of one.

This, of course, reduces the total flux available for playback and resultant loss in signal to noise. Any attempt to overdrive at these high transition densities causes "peak-shift" or "pulse crowding" and other problems associated with intersymbol interference.

The conclusion that one must draw is fairly self evident. The oxide should be reduced in thickness and/or the ratio $\frac{Hc}{Br}$ (slope of the demagnetization line) should be increased.

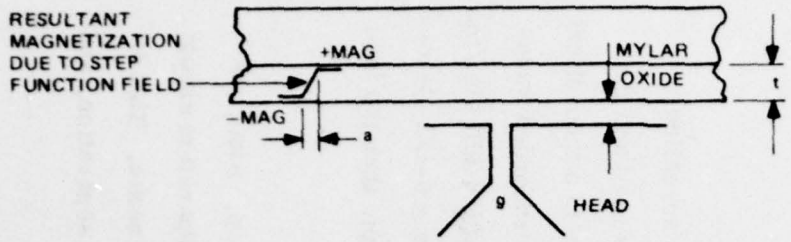
Typical tape values and mechanical characteristics are shown in Figure 15.

2.4.4 Head-Tape Interface

Many of the limitations on bit packing density are associated with the so-called "*contact conditions*" existing at the interface between the record/play head and the magnetic medium. Aside from the aperture loss (SIN (X)/(X)), there is a theoretical separation loss between flat surfaces of $-54.6\ d/\lambda$ dB where λ is the recorded wavelength and d the separation. Because current state-of-the-art provides 33K bits/in. packing density ($\lambda = 60\ \mu$ in.), a "separation" of 6μ in. already causes a 5-1/2 dB loss in output. If the packing density is increased to the goal of 50,000 bpi, then the loss due to the same separation would increase to about 8dB.

Clearly, the separation of concern is that existing precisely at the gap. Also, the nature of physical surfaces precludes the assignment of a value to separation except in the context of equivalent separation, and even that in a statistical sense. This is because surface roughness is of the same order of magnitude as the separation, and both surface position and roughness vary with time.

Tracking errors also lead to signal loss. Two basic kinds of errors arise: Lateral shift and angular skew. Both errors may be due partly to characteristics of the tape transport and tape medium and partly to manufacturing tolerances of the head. The



$$\text{DEMAG FACTOR (a)} = \frac{B_r t}{2\pi H_c}$$

$$PW_{50} = 2\sqrt{(d + \frac{t}{2} + a)^2 + \frac{(g)^2}{2}}$$

	TYPICAL VALUE	RANGE	OPT	PROPOSED DIRECTION	PROBLEMS
(COERICITY (Hc) OERSTEDS (Oe)	500	300-1000	MAX	1000	HEAD B_s
RELATIVITY (B_r) GAUSS	1500	$900\text{-}10^4$	MAX	NO CHANGE	DEMAG FACTOR
*DEMAG FACTOR (a)	50	12-200	MIN	ALT TAPE	B_r/H_c
*PW_{50} (μ") FOR 1 FLUX TRANS)	200(1)	20-1000	MIN	20"	B_r/H_c
DROPOUT RATE (D.O. RATE) @ 20 dB ABOVE NOISE (2)	10^{-5}	$10^{-4}\text{-}10^{-6}$	10^{-6}	SELECTING AND/OR COND. TAPE	

IMPORTANT MECHANICAL CHARACTERISTICS

1. LIFE OF TAPE
2. WEAR RATE IMPOSED ON HEAD
3. SURFACE IRREGULARITIES (AFFECTS DROP-OUT RATE)
4. UNIFORMITY OF PARTICLE DISPERSION, H_c & B_r
5. MECHANICAL MOTIONS CHARACTERISTICS

*THESE VALUES ARE DERIVED AND NOT IN TAPE SPECIFICATION LITERATURE

(1) FOR SATURATION RECORDING (RECORDING FULL OXIDE DEPTH)

(2) MINIMUM S/H FOR CHANNEL PERFORMANCE

Figure 15. Typical Tape Values and Mechanical Characteristics

following items to be discussed are factors in performance. Each is worthy of further study and improvement, although not every item will yield more than a modest gain in performance.

2.4.4.1 Tape Properties

Figure 16 shows the various properties and features of a tape recording medium. Roughness and waviness, as well as scratches and fibrosity are descriptive terms that measure departure from geometrical flatness. The knowledge of the statistical nature of these variables allows a formulation of effective localized separation between the tape and a perfect surface. When the two are in actual contact, such effective separation then establishes a minimum irreducible loss.

Electron microscopy provides an effective method to study the nature of surfaces. It makes it possible to see the results of calendering, choice of binder, particle size, etc. Also, a better understanding of wear phenomena can be gained if it occurs.

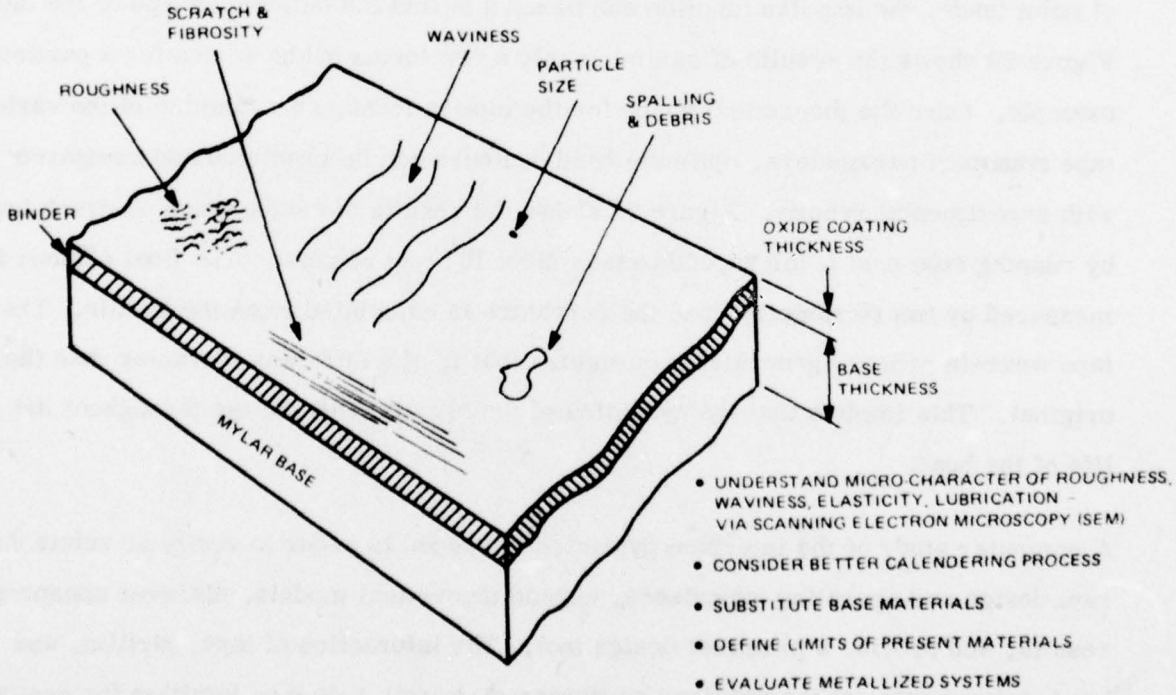


Figure 16. Tape Properties

The fact that surface character changes with use can be seen in Figure 17. This shows that the dropout rate can be reduced one to two orders of magnitude by preconditioning the surface. Preconditioning by running the tape many times is costly, however, and there may be a single-pass process that would accomplish the same result.

TAPE STRUCTURAL PROPERTIES. For the geometric proportions currently used, the tape should be mathematically characterized as an elastic plate, rather than as a perfectly flexible string (Figure 18). It does not automatically conform to all irregularities of the interface, but bends elastically with a curvature that may lead to increased local separation over rapidly changing profiles. Moreover, the tape interaction with the induced air film also produces differential curvatures along the head.

2.4.4.2 Air Film Forces

Figure 19 shows the impulse function computed for a quadruplex head tape guide configuration. By expressing a pressure distribution across a section of tape in terms of point leads, the impulse function can be used to find the deflected shape of the tape. Figure 20 shows the results of summing only a few terms of the series for a particular example. Once the theoretical shape for the tape is found, as a function of the various tape transport parameters, optimum head contours can be predicted and compared with experimental results. Figure 21 shows the results of contouring a 14-track head by running tape past it for 25,000 passes (25×10^6 feet of tape). The final contour is measured by interferometry, and the curvature is calculated from the profile. The tape wear-in process generates a curvature that is of a different character than the original. This implies that the dynamics of the air film will change throughout the life of the head.

A computer study of the interface dynamics is needed in order to verify or refute current design and operating experience, expand theoretical models, discover unexpected results, and provide a practical design tool. The interaction of tape, airfilm, and head is too subtle, at the spacings encountered, to rely solely on intuition for design.

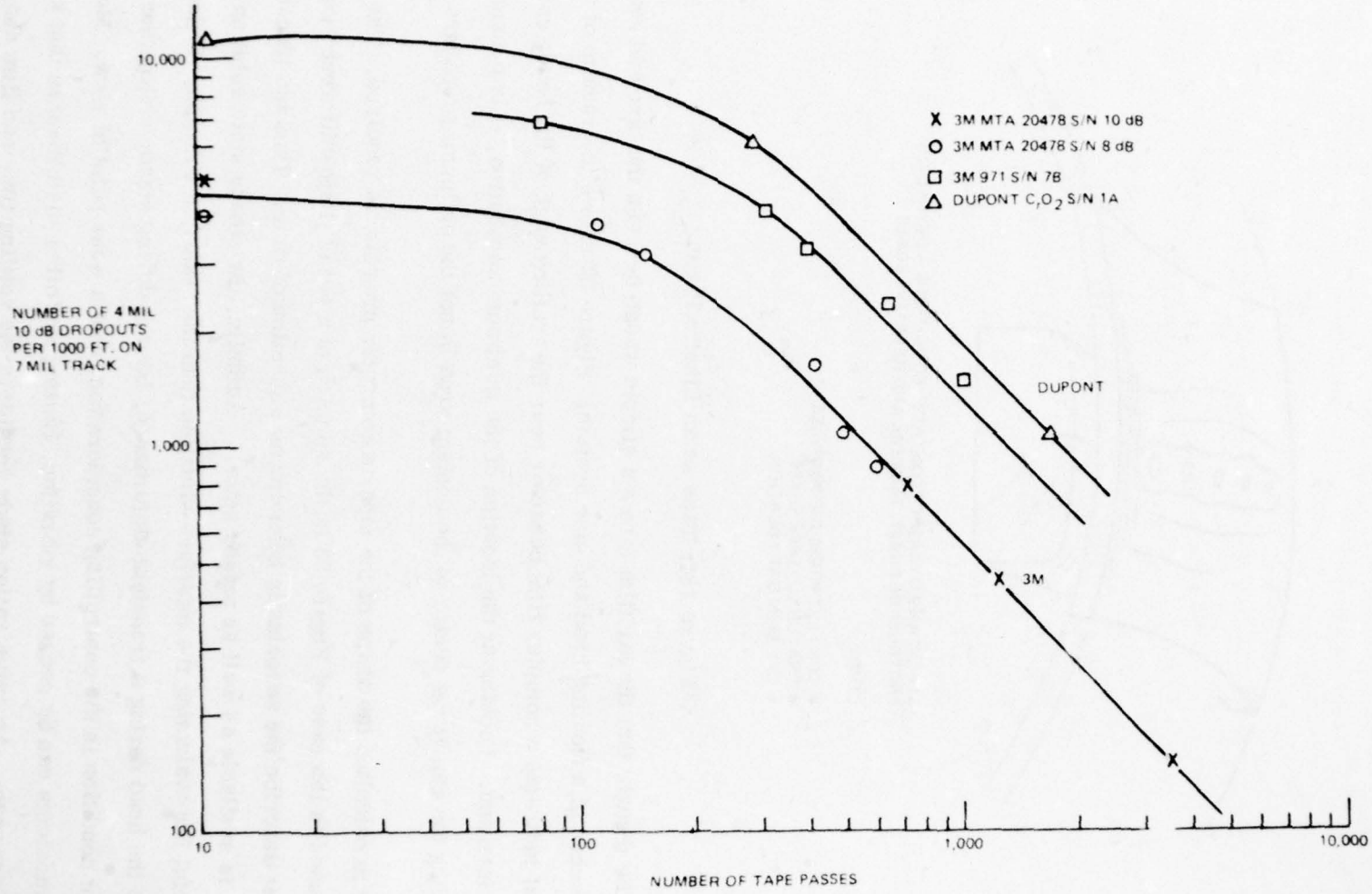
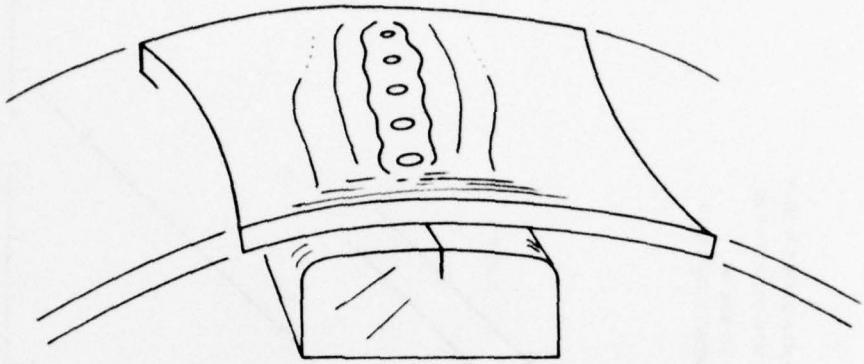


Figure 17. Magnetic Tape Drop Out Performance Improvement vs. Use (with Surface Conditioning and/or Magnetic Heads)



STATIC AND DYNAMIC "CONTACT" CONDITIONS – DEPEND ON PROTRUSION, SHAPE, TENSION, AND RELATIVE SCALE

STUDY

- CONTACT PRESSURE PROFILES
- "NATURAL" TAPE SHAPE
- OPTIMUM GAP LOCATION

Figure 18. Tape as an Elastic Plate

It might be thought that the air film forms a simple wedge between the tape and head, as in the case of a floating head and disc system. Figure 22 shows the results of a study that indicates a complex film behavior near the trailing edge of the head, contrary to intuition. Looking at the location of the minimum separation, it is evident that placing the gap at the center of the contact area is not the optimum procedure.

In order to calculate the shape of the tape, a computer program is required. The method used in the case of Figure 23 is the solution of a set of finite-difference equations that describe the aeroelastic behavior as a function of time. Thus the transient solution is available as well as steady state. Actually, the steady state solution is less useful for evaluating the interface situation than the transient solution. If the tape contacts the head during a transient disturbance, but not during steady state, then the transient condition is the controlling consideration from a wear point of view. Moreover, transients can be caused by vibration, flutter, and other disturbances that are normally present. An optimization study considers the settling time and film shape

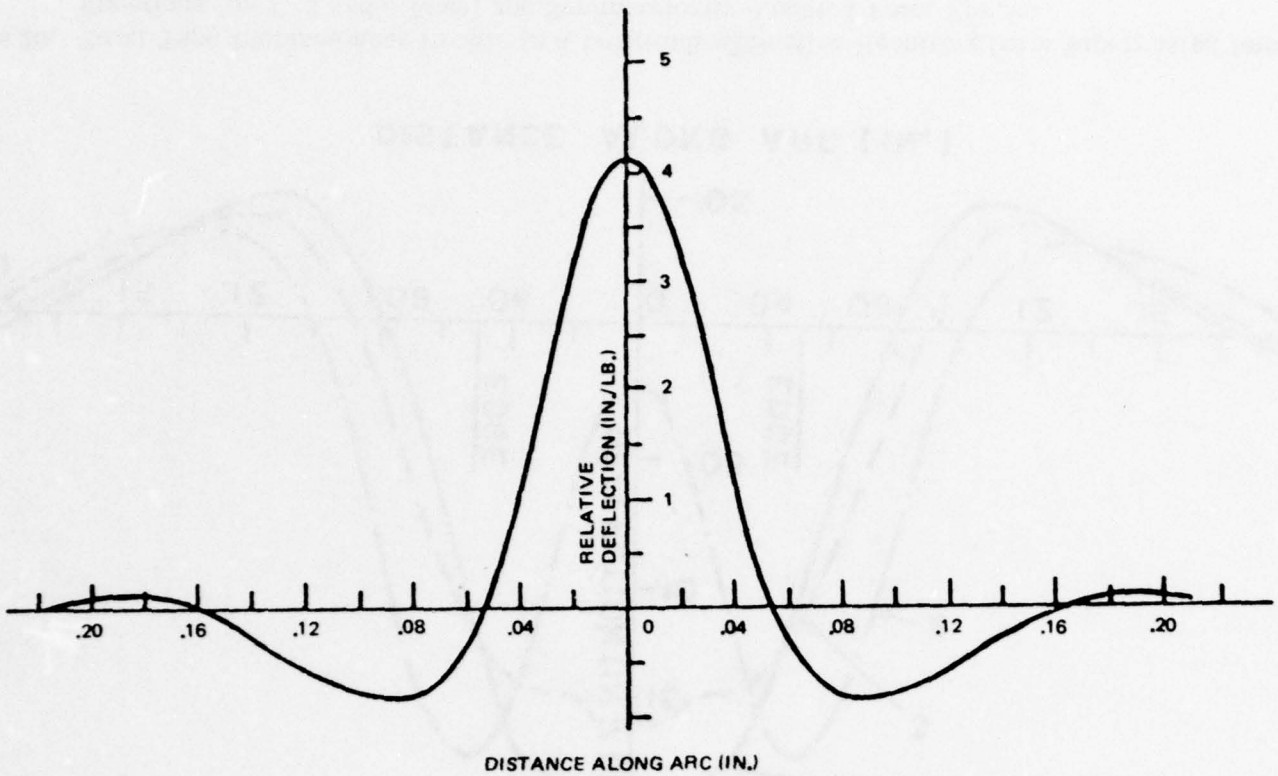


Figure 19. The Central, Longitudinal Section of the Impulse Function Computed for a Quadruplex Tape/Guide Configuration. An Impulse Function is the Deflection of the Tape in Response to a Point Force.

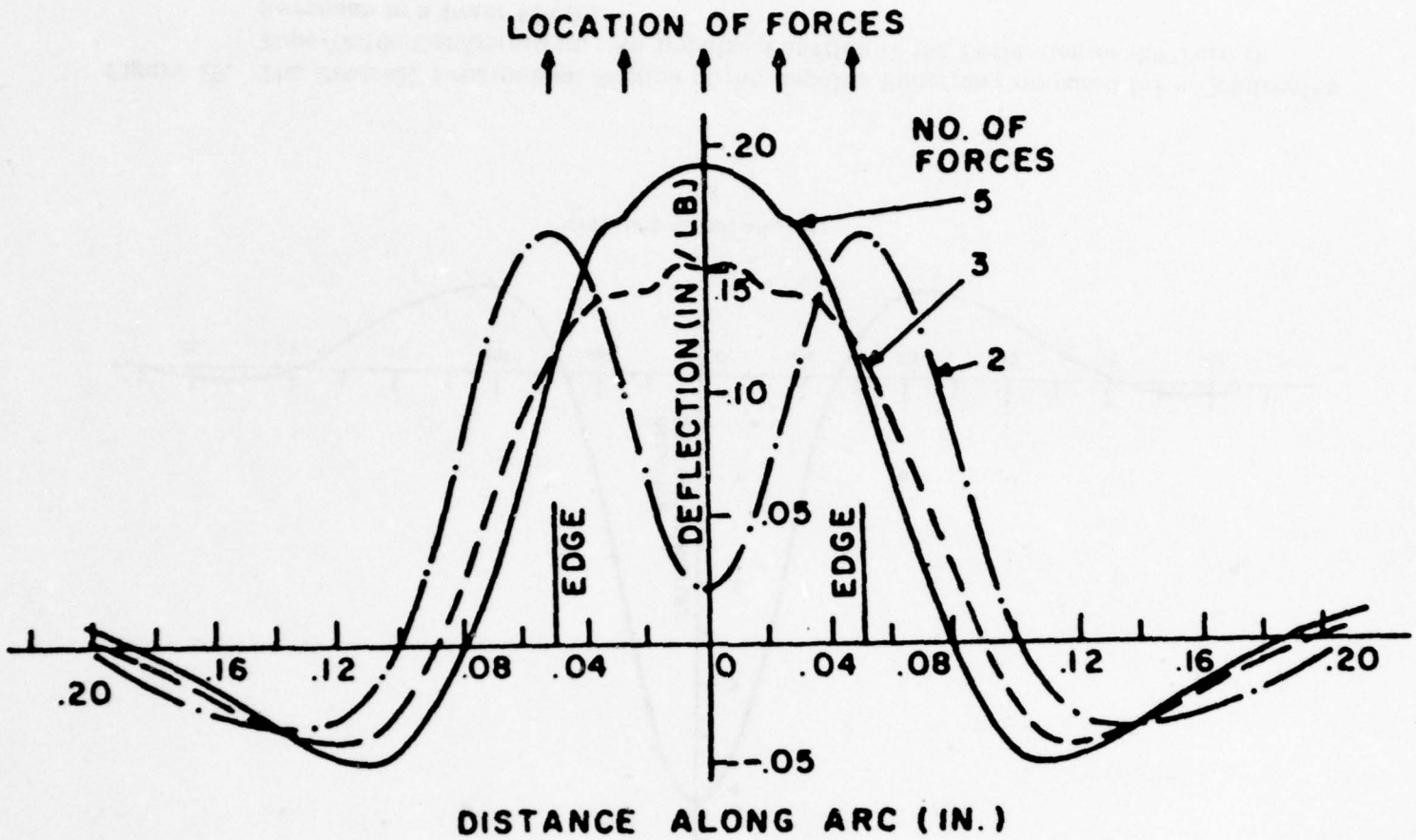


Figure 20. Total Tape Displacement Profile in a Longitudinal Section Resulting from Superposing Impulse Functions for 2, 3 and 5 Equal and Symmetrically-Located Point Forces

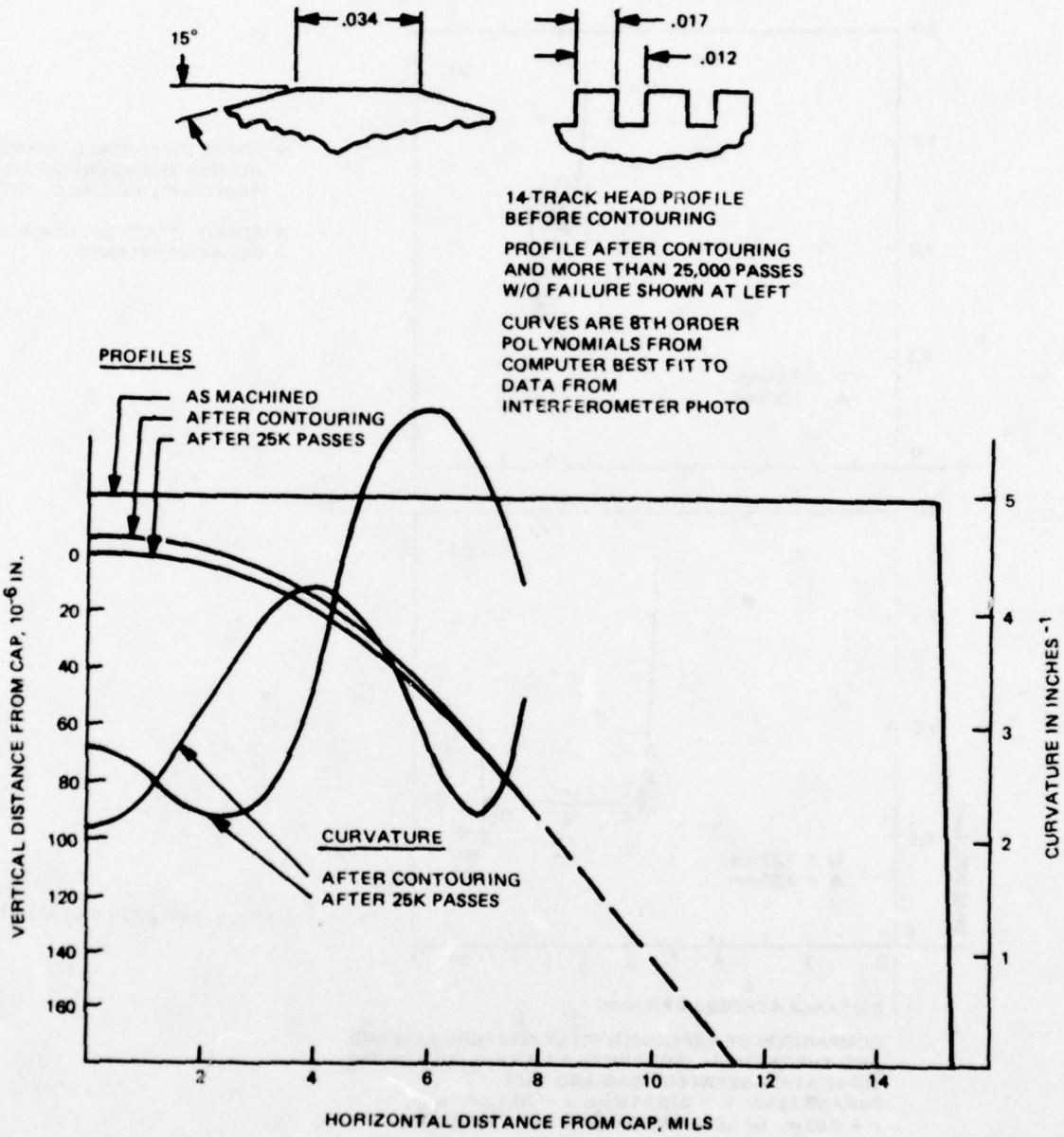
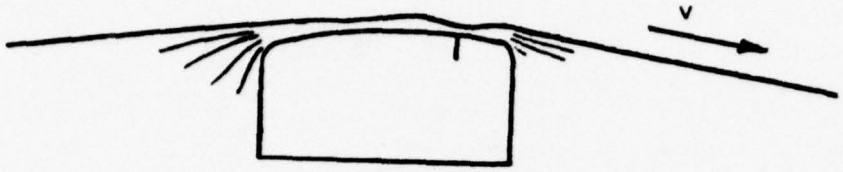
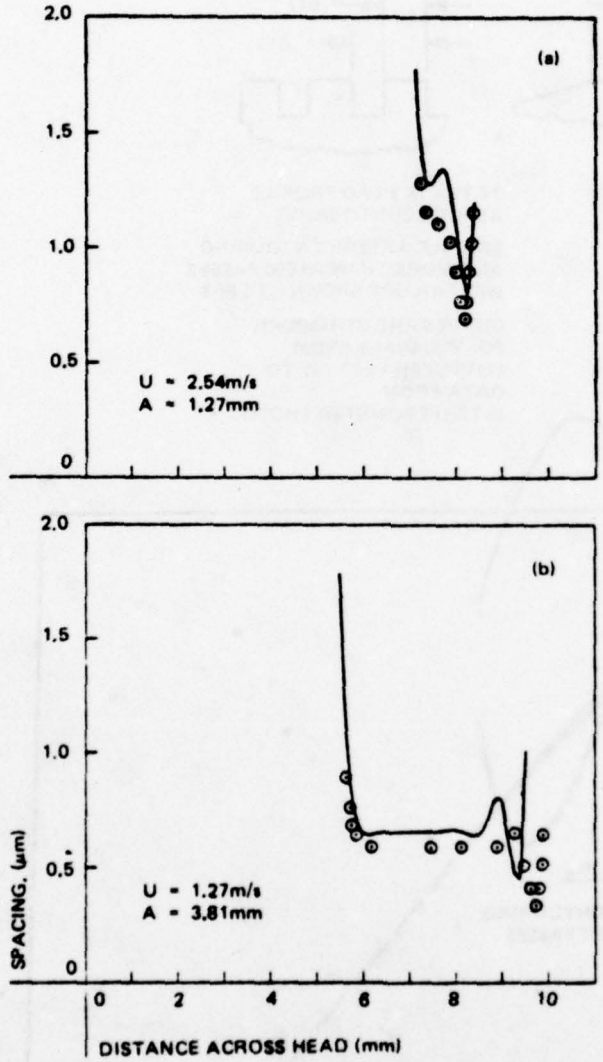


Figure 21. Contour Data for TIROS-N Life Test Head



- SOLUTION OF COUPLED EQUATIONS FOR AERODYNAMIC FILM AND ELASTIC TAPE

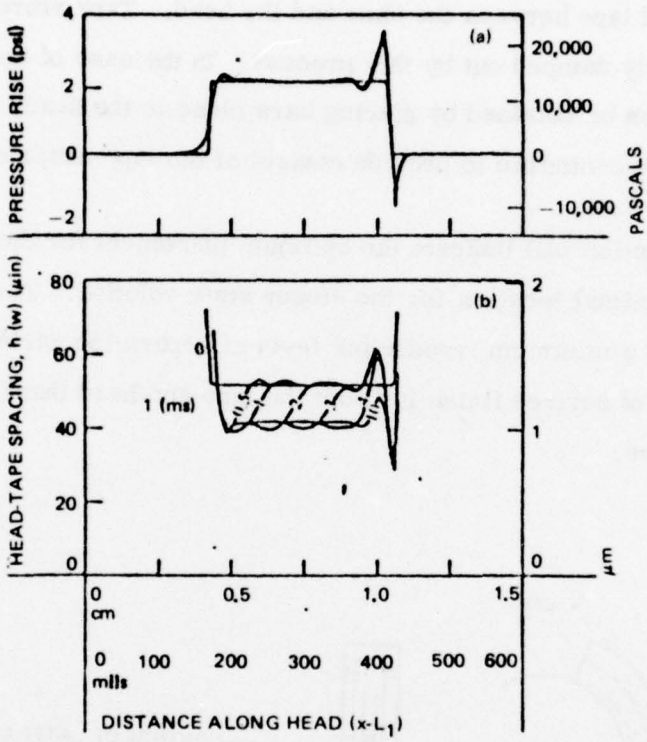


- FINITE DIFFERENCE FORMULATION ALLOWS TRANSIENT SOLUTION WITH ARBITRARY INITIAL CONDITIONS
- STEADY STATE SOLUTION WITH DECAY CONSTANTS

SOURCE: IBM J RES & DEV 11/74

COMPARISON OF EXPERIMENTALLY MEASURED (POINTS) AND THEORETICAL (CONTINUOUS LINE) VALUES OF THE SEPARATION BETWEEN HEAD AND TAPE. PARAMETERS: T = 276.70 N/m: t = 38.1 μm: and r = 0.02 m. (a) SEPARATION FOR THE CASE OF A UNIFORM SPACING ZONE.

Figure 22. Air Film Separation



- GENERATION OF HIGHER ORDER HEAD CONTOURS
- SURFACE FINISH TRADEOFFS
- PLACEMENT OF CAPSTANS, ROLLERS, GUIDES, VIBRATION NODES
- HEAT GROOVING
- OPTIMUM GAP LOCATION (MAY DIFFER FROM STATIC SOLUTION)
- MINIMUM EXPECTED VIBRATION LEVELS AND SEPARATION CHANGES – LATERAL, TRANSVERSE, AND LONGITUDINAL

Figure 23. Dynamic Optimization Study

(Figure 23) for various conditions, and the possible use of node stops to control frequency and amplitude of tape vibration. Actually, a similar technique has been used in the VTR tape recorder as seen in Figure 24, where the headwheel shoe creates a very short span of tape between the shoe and the head. Tape vibrations external to the shoe are effectively damped out by this process. In the case of the longitudinal head, similar results can be obtained by placing bars close to the head. The bars (node stops) may or may not be contoured to provide control of the tape shape over the pole tips.

The computer solution will indicate the optimum placement for the gap line which may differ from the optimal location for the steady state solution. The transient solution may also indicate a minimum irreducible level of separation variation which in turn implies a quality of surface finish for both the tape and head that is unproductive to attempt to improve.

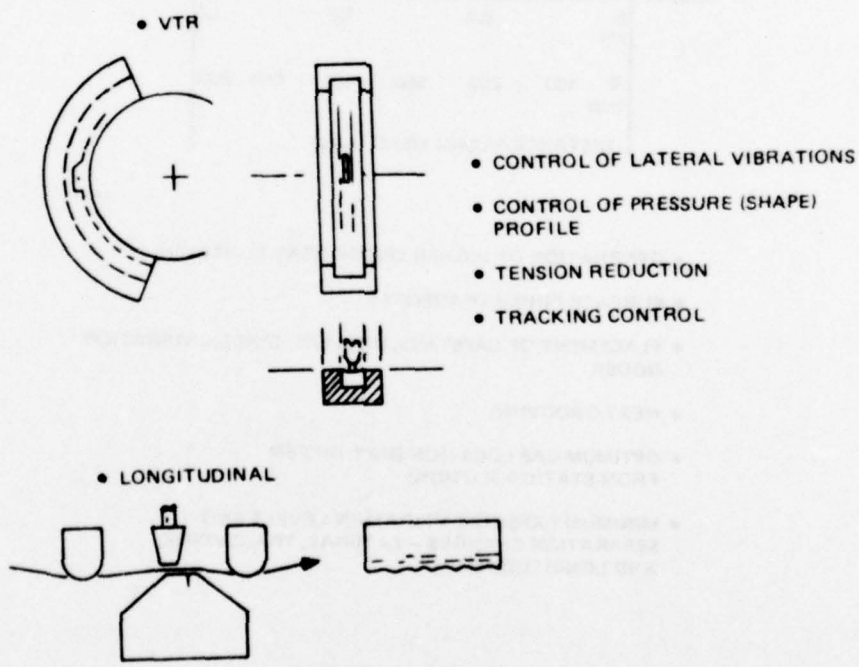


Figure 24. Nodal Stop

2.4.4.3 Tracking

The mistracking of tape also causes signal loss and these effects must be considered in balance with the aperture and separation losses. Figure 25 shows various sources of tracking error; the primary ones being the effects of edge stiffness (curl), tape skew, width variation, wrinkle and scallop.

Improvements can be expected in traditional methods of guiding plus new methods that reflect the tightening of dimensional tolerances. In Figure 26, the traditional method of moving a guide roller or air bearing is shown. This method of twisting the guide roller limits control of the location of the tape edge to relatively large tolerances (±5 mils) and relatively slow response. An alternate method to guide roller is a fixed air bar that can be servoed by differential air pressure in response to signals from an edge sensor that can be either pneumatic or electronic (i.e. a light detector).

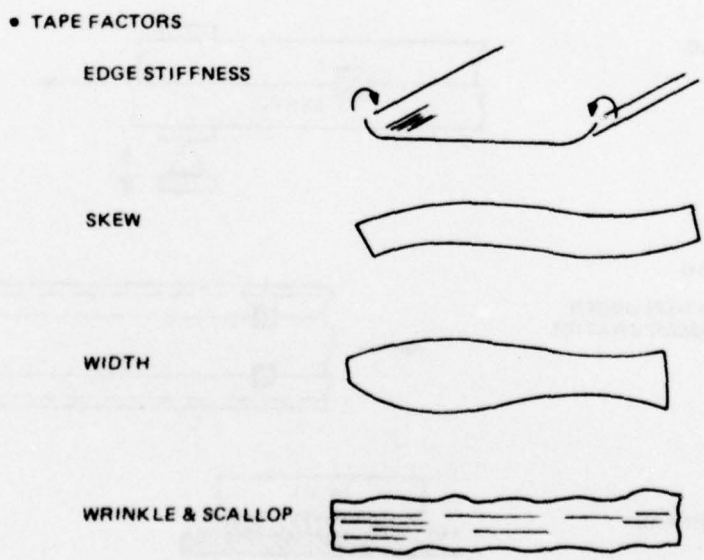


Figure 25. Tracking

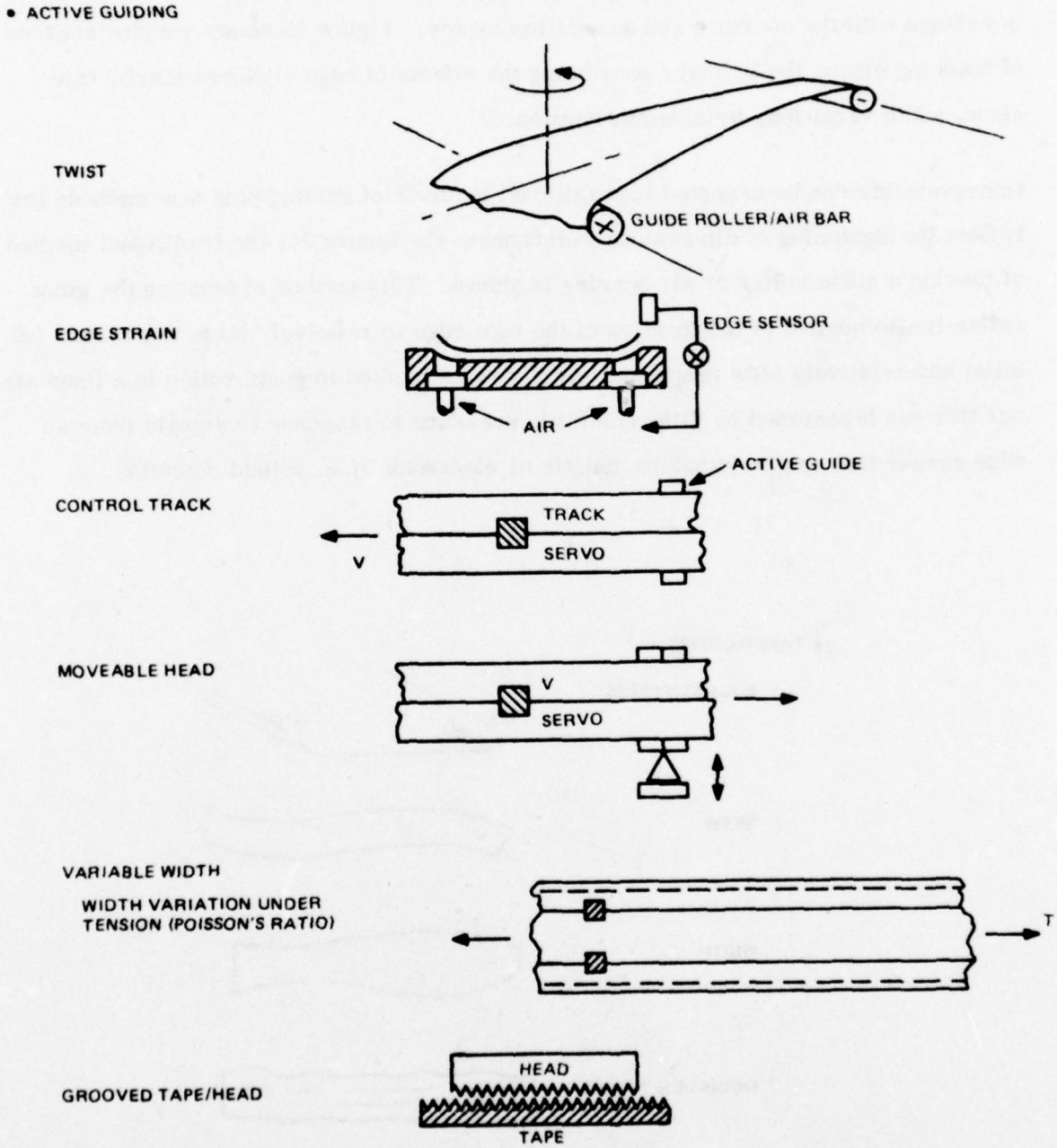


Figure 26. Tracking

Inasmuch as the control is really desired for the recorded tracks rather than the physical edge, a magnetic sensor that reads the location of the recorded track is a preferred method. Such a sensor could be used either on a recorded data track or an auxiliary control track for the purposes of edge guiding, being coupled either with a movable roller or air bar or with a movable head. If most of the edge variation has been removed by first-order means, a head coupled to a voice coil can be used to remove the residual variation (±1 mil). The movable head has the additional advantage of the ability to respond at high frequencies.

A method of tape guiding that depends on grooved tape has recently been proposed by Viteck Corporation. If the head or tape guide is similarly grooved, than the tape is constrained similar to the stylus in a phonograph groove. With multiple grooves, the net tracking force is relatively large even though the tracking force for a single groove is very small.

The investigation and optimization of the sum total of the above factors should lead to a precision tracking system that constraints the lateral variation recorded track to the order of ±1/2 mil.

2.4.4.4 Scale Factors

As the recording gap has been scaled down from the order of 500 micro-inches (typical of original audio recording systems), the track width and tape thickness have not been scaled in proportion. There has been some reduction in tape thickness but it has been determined primarily by base film technology, market demand, and other factors primarily related to the manufacturing and transport process. The problem with tape that is relatively thick is the fact that it is relatively stiff and does not readily follow the contour of the head as has been mentioned above. Track width reduction has followed the ability to manufacture heads with many tracks per inch. The limiting situation here is the ability to wind very small coils and at the same time maintain head efficiency. The limitation of a relatively wide track compared to the gap length is that

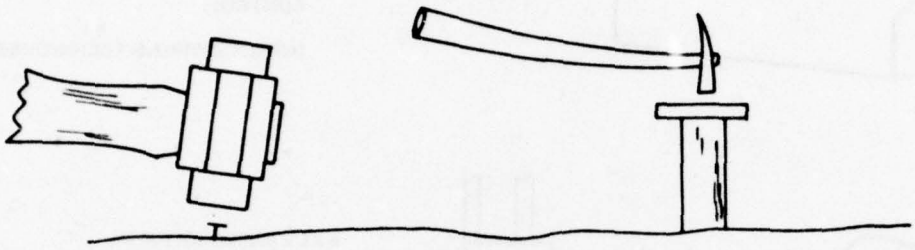
skew problems become exaggerated as shown in Figure 27 because tape skewing tends to be measured in terms of angle. A wide track requires a much smaller skew angle for the same signal loss. At the same time, pressures and forces also scale down as the dimensions; for instance, a small radius of curvature at the gap leads to large pressures if the tape tension is not reduced at the same time. Inertial pressures also increase with small radii of curvature for the same tape speed. Thus, we find that if the radius of curvature is decreased at the same time that the velocity is increased, inertial pressures may cause the tape to float away from the gap unless tape tension is increased. The balancing of these forces, therefore, must be done very carefully, with difficult tradeoffs implied. As part of the problem of balancing the scale factors, the track density should be examined for the tradeoffs of bit packing density per inch (longitudinal) vs. the bit packing density across track. It is the bit packing density per square inch that is of the ultimate concern and it may well turn out that the relief from high bit packing densities along the track may be worth the effort involved in increasing the track density can be envisioned as the outgrowth of integrated magnetics.

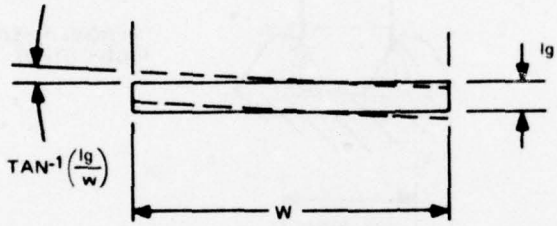
2.4.5 Record and Playback Head-Electronics Matching

This section will consider the head as both a record and reproduce head. Additional optimizing can exist for the record head or playback head if built separately. Separate heads are not out of the realm of possibility but for this application considered impractical.

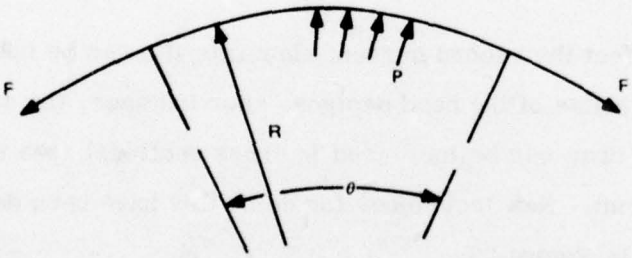
2.4.5.1 Record Matching

The most important consideration of this section of the magnetic recording system model is the record current slew rate (amps/sec) of the flux generated in the gap by the current in the single turn (I_S). I_S itself may not ideally represent the drive current I_p due to transformer and capacitive losses. If K=1 the transformer is a perfectly coupled unit and then $I_p = \frac{N1}{N2}(I_S)$. Such is not the case; degradation does exist and I_S suffers in slew rate. Since the wire is very small, and buried between the tracks of the head, the actual I_S has not been measured. External field sampling detectors

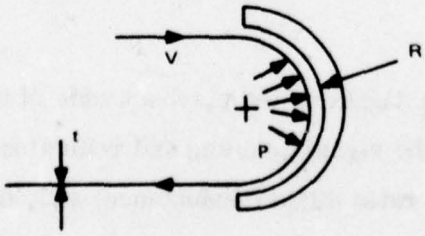




• SKEW IS ANGLE DEPENDENT



• PRESSURE IS PROPORTIONAL TO FORCE/RADIUS (SAME WRAP ANGLE)



• INERTIAL PRESSURE PROPORTIONAL TO $(V^2/R)t$

Figure 27. Scale Factors

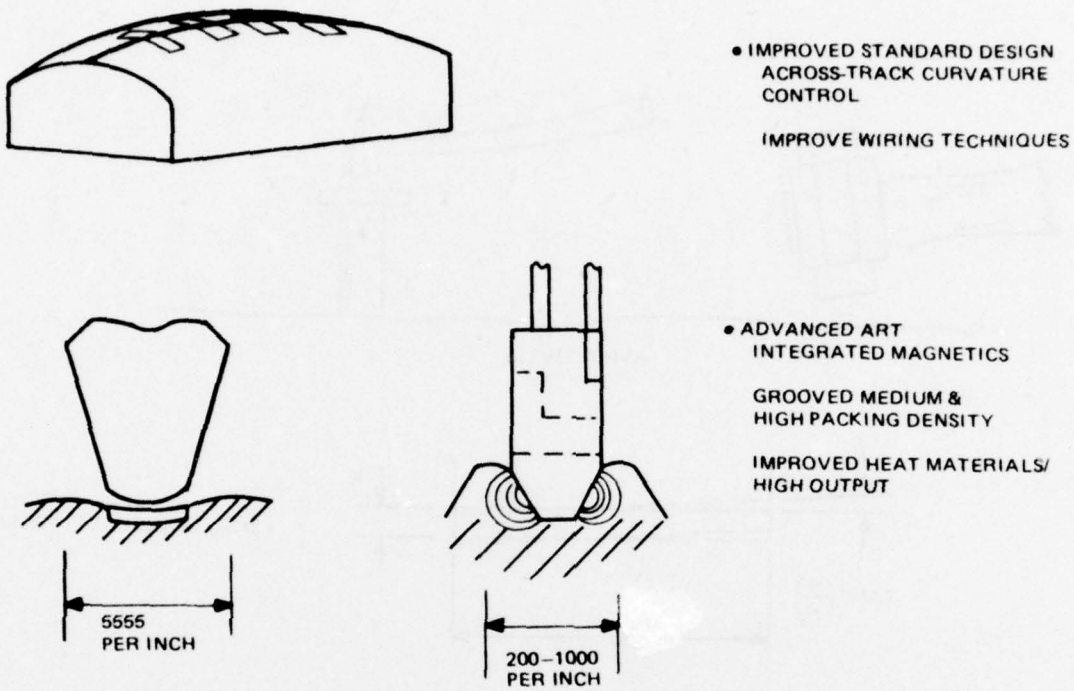


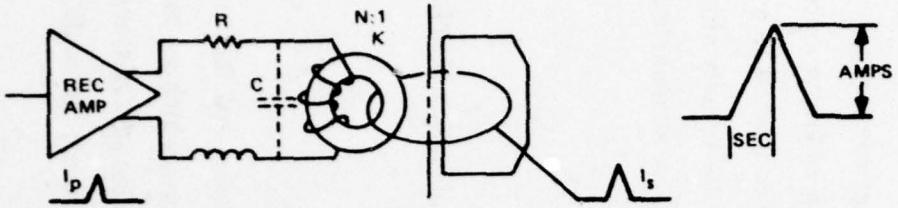
Figure 28. Track Density

probably offer the best chance of success in measuring the slew rate of I_S and the effective field slew rate emanating from the gap.

The parameters which affect the record current slew rate (I_S) can be optimized to the limit of the physical restraints of the head designs. For instance, the secondary winding (usually a single turn) can be increased in cross sectional area to reduce its resistance (R) in the circuit. New techniques for doing this have been developed. A summarization is shown in Figure 29.

2.4.5.2 Playback Matching

The most important area to investigate on the playback side of the head electronics matching are improvements in the signal coupling and reduction of shunt signal paths. This would allow a higher turns ratio (higher inductance) and, therefore, a larger signal level to get over the preamp noise floor.



MATCHING NETWORK

PARAMETERS	TYP VALUES	RANGE	OPT VAL.	DIRECTION	PROBLEMS
SLEW RATE PRI (I_p) AMPS/SEC	4×10^5 N=40	(0-10) 10^5	60 X 10 S/N	REDUCE R, L	ELBOW ROOM
SLEW RATE SEC (I_s) AMPS/SEC	?	?	60×10^5	REDUCE R, L	SLEW RATE MAY BE LOW
R-L BREAK (RL) F WHEN (R.=wL, KHZ)	20	1-50	1	REDUCE R, L	PRIMARY REFLECTED Z FROM SEC
RESONANT FREQ PRI (f_o) (MHz)	5	0.1-10	10	10	LEAD LENGTHS
CAP (C) (PF)	10	2-20	0	3	LEAD LENGTHS
COEFFICIENT OF COUPLING (K)	.95	.90–.999	1.0	SELECT FERRITES	DIFFICULT TO PROVIDE ENOUGH PRIMARY TURNS
INITIAL PERM	6000	1000–10K	10K	SELECT FERRITES	
MAX PERM	10,000	1000–12K	12K	SELECT FERRITES	
MAX FLUX DENSITY B_{max} (GAUSS)	4500	3K–7K	7K	SELECT FERRITES	
LOSS FACTOR TAN	10 (1 MHz)	5–50	5	SELECT FERRITES	

Figure 29. Record Matching

As stated in 2.4.5.1, the primary head limitation in Record is the slew rate. In playback, the same physical parameters are limitations but affect the head in a different way. The "R" and "L" of the single turn have a dramatic effect on the low frequency roll-off of the head. In the near ideal state $R \approx \frac{\omega L}{10}$ where "R" is the total resistance in the single turn and ωL is the resistance of the segment of turn passing thru the matching transformer. The method to achieve the condition where $R \approx \frac{\omega L}{10}$ is well known. By increasing the number of turns on the input of the transformer, the inductance looking into the input of the matching transformer is greatly increased. Unfortunately this lowers the overall voltage gain of the head which requires more turns thru the small hole under the vertex of the head which normally is limited to one turn. A multi-turn structure increases the construction difficulties quite rapidly although on several systems this technique has been employed successfully. A summarization is shown in Figure 30.

2.4.6 Record/Play Head Efficiency

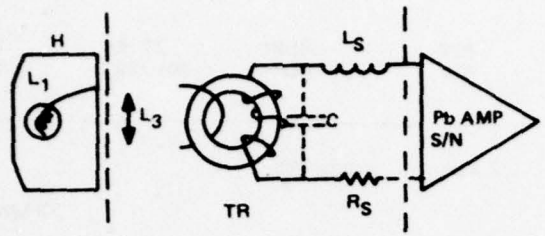
The efficiency of the head in record is of small concern and in playback of primary concern. A summarization is shown in Figure 31.

2.4.6.1 Record Efficiency

This is not a problem as long as sufficient record drive is available and the record current slew rate is not limiting the peak current needed. A limit which we have not yet hit is head core flux saturation (B_S). If tapes with coercivities of 700 Oersteds or higher are used, or if the present record head efficiency is reduced, B_S could become a materials problem.

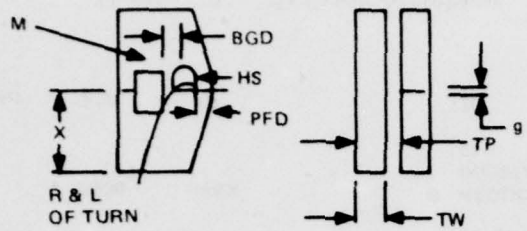
2.4.6.2 Playback Efficiency

The playback efficiency is limited in two major areas; the gap shunt loss and the core losses. Both areas can be attacked by investigating head construction design changes and the core losses can be attacked by investigating better magnetic materials.



PARAMETERS	RANGE	OPT VAL.	DIRECTION	PROBLEMS
1. HEAD ELEMENT INDUCTANCE (L_1)	nh	$>L_3, <L_2$	INCREASE	BASIC DESIGN LIMIT
2. TRANSFORMER PRI IND (L_2)	nh	$>L_3, >L_1$	INCREASE	BASIC DESIGN LIMIT
3. CONNECTING LEAD INC (L_3)	nh	0	REDUCE	BASIC DESIGN LIMIT
4. TOTAL LEAD RESISTANCE (R)	μOHM	0	INCREASE WIRE SIZE	BASIC DESIGN LIMIT
5. SECONDARY INDUC. (L)	5-20uh	DEPENDS ON TOTAL C	REDUCE C	RESONANCE LIMITED
6. SEC. RESISTANCE (R)	1-10Ω	0	INCREASE WIRE SIZE	
7. DISTRIBUTED CAP. (c)	1-20pf	0	IMPROVE WINDING TECH	
8. TURN RATIO (TR)	10-100	HIGH	IMPROVE COEFFICIENT OF COUPLING	RESONANCE
9. S/N (Vs)	20-30	MAX	REDUCE NOISE INCREASE HEAD EFF.	PREAMP NOISE
10. RESONANT FREQ (f_o) (MHz)	6-10	10	10	LEAD LENGTHS

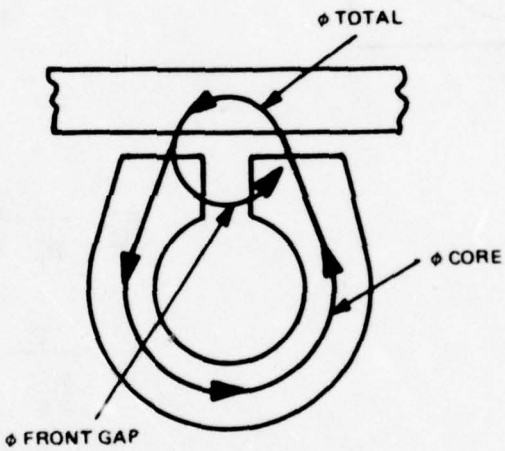
Figure 30. Playback Matching



PARAMETERS	TYP. VAL.	RANGE	OPT VAL.	PROPOSED DIRECTION	PROBLEMS
GAP (g) μ"	10	3-20	OPTIMIZE FOR MAX READ V	IMPROVE FIELD SHAPING	POOR FIELD SHAPE
TRACK WIDTH (TW) INCHES	.008	.004–.015	.010	TRY .010	OK
TRACK PITCH (TP) INCHES	.014	.01–.02	.014	TRY .014	LIMITED ROOM FOR WIRE
POLE FACE DEPTH (PFD) INCHES	.0008	.0003–.002	REC–.001 Pb–.0003	NEXT TECH FOR LOW PFD	BREAKAGE
BACK GAP DEPTH (BGD) INCHES	.020	.01–.02	.02	SAME	NONE
HOLE SIZE (HS) INCHES	.005 DIA	.003–.010	VAR	CHANGE SHAPE	CUT WITHOUT WORK HARDENING
RES & IND (R&L)	.005Ω & 5 nh	–	LOW R – HI L	INCREASE L	LIMITED ROOM
(X) INCHES	.075	.05–.10	.075	REDUCE X	WEAKENS HEAD
CONTOUR (C)	COMPLEX				
NUMBER OF TURNS (N)	1	–	PB-2, REC 1	TRY 2	SURVIVAL DURING BONDING
MAT'L (M)					
μ_o (1KHz)	7K	5K–10K	HIGH	AIV	NEARING "STATE OF THE ART"
B_{sat} (GAUSS)	10K	3–12	HIGH	AIV	

Figure 31. Record/Play Head

a. GAP SHUNT LOSS. A classical limitation of a standard magnetic playback head is the read flux lost in the read gap. No fundamental change has ever been made to the basic design structure. All playback heads have a set of pole tips separated by a gap space. The gap size varies directly according to the resolution requirements of the system which causes a reduction of the read S/N. Recent material and new machining technique developments have negated the effect somewhat by allowing the pole face depth to be greatly reduced. The efficiency of the read head magnetic circuit is controlled by the ratio of the reluctance of the core and the reluctance of the gap. For an ideal situation all the flux from the tape should pass thru the coil which will generate the output real voltage E.

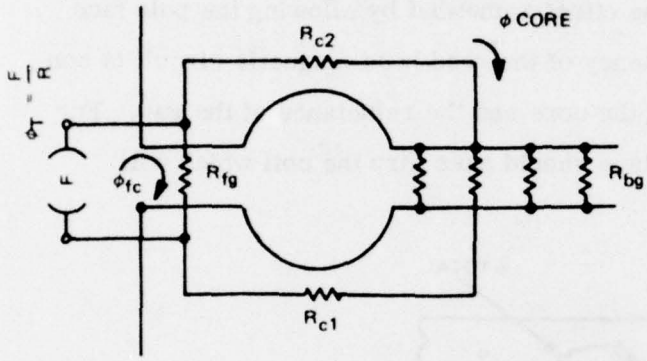


Some flux, however, is shorted out by the front gap and is therefore lost and of no use whatsoever. It is apparent that the efficiency of the aperature (GAP) type head is a function of the pole face depth (PFD) to gap size ratio (see table). Historically this value has been:

	AUDIO	VIDEO	HDMR	PROPOSED
GAP	100u"	60u"	12u"	8u"
PFD	.005"	.0025"	.0008"	.0003"
RATIO	50/1	40/1	66/1	38/1

The general expression for head efficiency can be derived by writing the equation for the flux (ϕ) division as it passes into the tape head and divides up inversely proportional to the reluctances.

The equivalent circuit for the gap reluctance of a magnetic head is:



ϕ_T = total flux

ϕ_C = flux in core

ϕ_{FG} = flux in frontgap

$\phi = F/R$

$$EFF = \frac{\phi_C \times 100}{\phi_C + \phi_6}$$

$$\phi_C = \frac{F}{R_C + R_{bg}}$$

$$\phi_6 = \frac{F}{R_g}$$

$$E = \frac{1}{\frac{1\,R_C + R_{bg}}{R_g}} \approx \frac{1}{\frac{1 + R_C}{R_g}} \quad \text{where } R_{bg} = 0$$

For Alfecon, at frequencies above 50 KHz, the classical method of computing R_C from known parameters is useless because the solid core material has most of its flux concentrated in the skin of the material. The approach used to calculate head efficiency is to establish a Ratio between Rc and Rg.

This was done on a video head by measuring the output read level at a pole face depth of 2.0 mil and then at 1.0 mil. The playback voltage ratio = $0.7 \sim \frac{2.0}{1.0}$ pole face depth.

$$\frac{Eff_1\ (2.0)}{Eff_2\ (1.0)} = .7$$ Measured sample @ 9MHz (160° μ "λ)

$$\frac{Rg_1}{Rg_2} = 1/2$$

$$\frac{Eff_1}{Eff_2} \text{ Reluctances} = \frac{\dfrac{1}{1 + \dfrac{R_C}{R_{g1}}}}{\dfrac{1}{1 + \dfrac{R_C}{R_{g2}}}}, \quad R_{g1} = 2\,R_{g_2}$$

$$\frac{E_{ff_1}}{E_{ff_2}} = \frac{R_{g2} + R_C}{2R_{g2} + R_C} = .7 \qquad \frac{R_C}{R_g} = 1.33$$

$$E_{ff} = \frac{1}{1 + 1.33} = .43 = 43\%$$

The value 43% is the efficiency of a commercial video head. The head structure is very similar to what is used for HDMR type heads. Such measurements and calculations are planned for our structure to establish a bench mark at least for head playback efficiency.

Since the head performance (Eff) is inversely related to the poleface depth, major efforts can be applied to application of new head construction techniques which result in pole face depth less than .0005". It becomes obvious that such a structure cannot be a free standing cantilever structure which historically is prone to collapse. Also, machining to such sizes, although not impossible, causes reject rates of head clusters to become very high. Other innovations offer design advantages where the pole face

depth is an integral and homogenous part of the head track having say .0002" magnetic depth but offers .002-005" structural depths. Such designs do exist. Incorporation of those design will require creative engineering and will be a challenge.

b. GAP MATERIALS. Quartz and Alumina gaps are nominally fine for wear and gapping. If, however, a gap material could be used which had a magnetic permeability of less than unity, it would impede the flux flow across the gap and yield a more efficient magnetic transducer. Only one material is presently known to offer an advantage in this area; namely, bismuth alloys.

c. HEAD CORE MATERIALS

1. Alfecon IV (A IV)

RCA is presently pursuing a better magnetic head core material for its video head application. A material designated A IV is being made at the RCA David Sarnoff Research Laboratories. The material is being developed to provide long head life and greater magnetic efficiency (lower write current (I_R) and higher read voltage (FM V_{PB})). Test and descriptive data on A IV material must be withheld pending patent application. Test data on a head made with A IV is available and presented below.

Parameter	AII	AIV	Δ
I_R	59 MApp	35 MApp	-4.5 dB
FM V_{PB}	0.15	0.45	+9 dB
VID S/N	48.9	49.8	+0.9 dB

The most significant test result is that the off-tape read voltage (FM V_{PB}) tripled. This 9 dB improvement (at 10 MHz) is less significant in the video recorder; 0.9 dB being the video S/N improvement.

The reason for only 0.9 dB is that the video recorder is reading tape noise. The present HDMR system is 10 dB, or more, short of reading tape noise. The +9 dB gain in head output will yield a 9 dB gain in S/N if this gain also applies at the lower frequencies of 1-6 MHz. This must be evaluated by HDMR head tests using A IV.

2. Granular Magnetics

Another area of magnetic materials research that RCA was investigating in 1970-1972 is granular magnetics[4,5] where two or more materials are co-sputtered in variable mixtures to form new amophorus materials which are very fine grained and have high permeability and resistivity. This technique is presently limited to thin films of less than a few thousanths of an inch. This thickness is adequate for the skin thickness associated with metal head magetics in the 1-10 MHz range and lends itself readily to co-sputtering of new magnetic materials onto the present head configuration in the areas where the magnetic flux flows; the gap, pole tips and single turn hole. This effort was dropped in 1972 before any conclusions were made. We should pick up where it left off and try a couple of experiments based on these prior ideas.

The first two attempts should use a quartz target overlayed with strips of 80/20 permalloy and 50/30 peralloy. Heads made with these two blends could then be tested and an evaluation made. Scanning Electron Microscope (SEM) photos should also be taken to analyze the alloy and crystal growth patterns.

3. Mechanical Alloying

Mechanical alloying[6], is cold-welding a mixture of metal powders, which produces a medium to large grain alloy. No specific alloy is under consideration at this time.

4. Splat Cooled Alloys

Another technique for making a very hard, amorphous, fine-grained alloy is splat cooling. In this process a molten metal mixture is dropped into water (to make round wire)

or onto a spinning drum (to make flat wire). Allied Chemical of New Jersey is presently developing a "Metglas" material which has the following properties:

Coercivity (Hc) 0.01 oersteds

Resistivity (ρ) 200 X 10^{-6} ohm-cm

Saturation (Bs) $\approx$ 16 K gauss (X2 A II)

Magnetostriction (λs) zero to ?

The extreme hardness and other above factors give this material a potential for magnetic heads. Two limitations it does have may be too serious to overcome; it only comes in 1 mil X 1/2 inch cross sections and it goes crystaline above 200°C. Both factors limit the construction technique which could be used.

5. Alloy Casting

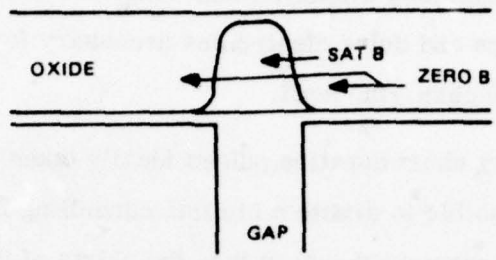
Alfecon I, Sendust, Alfesil, etc. are products of alloy casting which is melting and coating a mixture of metals in a vacuum in an inert gas atmosphere. This technique has been the most productive in the past and in fact A II is a hot pressed sintered version of this technique. A IV is also an outgrowth of this technique.

2.4.7 Read and Write Field Interface Factors

2.4.7.1 Write Interface (Field)

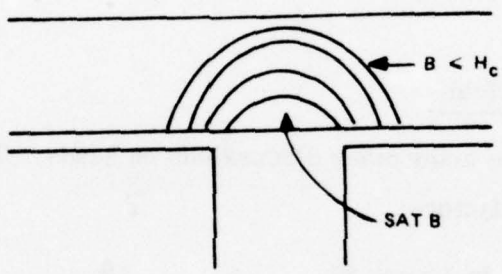
The record resolution for pulse recording is dependent on: record demagnetization of the tape, the slew rate (rise time) of the flux field at the gap, and the distribution (shape-gradient) of flux field intensity (B) around the gap region. Ultimately all three of these parameters need to be optimized. The record demagnetization and slew rate problems are treated elsewhere. The remaining point of concern is the pulse field shape.

The ideal field shape would be:



In real life the flux at the gap covers an area much larger

More like:



The field assumes such a configuration due to several factors:

a. The finite corner of the pole tip saturates causing the remaining line of flux to begin jumping the gap at a point other than the finite corner (points up and down stream from the gap).

b. Lines of flux repel each other and spread out consistent with the path of least reluctance.

Several techniques such as the 'X'-field by Cameras have been invented to improve the write field. The X-field head employs an external in-phase field (cross field) which improves the shape of the trailing edge of the record zone, i.e., the transition from high magnetizing field to a low level field (below H_c of the tape) is accomplished in a much shorter physical distance from the gap. Cameras accomplished this by adding a second gap up-stream from the primary recording gap. The flux in the second gap and record gap are so related that a vector cancellation of flux occurs downstream from the gap which can reduce the transitional record region.

This technique could be physically employed on a single 50 KB/in. channel but because of all the extra wires, gaps and drive electronics necessary for such a device it seems very impractical for an 80 chan./in. head.

Since the recording of very short duration pulses ideally takes place in less than 1/10 of a bit cell, it seems possible to create a similar cancelling field by post field shaping or post erasure. Such a technique would reduce the skirts of the recorded pulse and increase the flux gradient. Some experimental work has already been done in this area at RCA and IBM.

A summarization is shown in Figure 32.

2.4.7.2 Read Interface (Field)

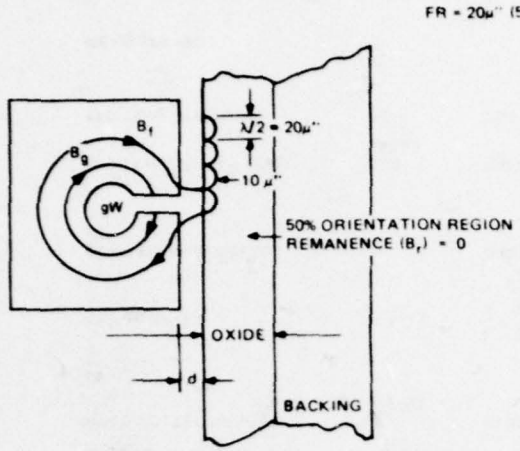
This area is covered by the many other discussions on heads. The key interface here is the head-tape interface factors.

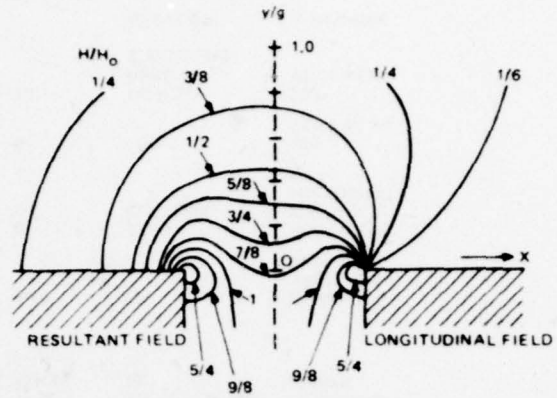
A summarization is shown in Figure 33.

2.4.8 Tape Transport Configuration

The functions investigated below were to determine what modifications could be made to an existing 1/2 inch wide computer transport and still approach the original design goals. The present video recorders utilizing 2 inch wide magnetic tape were reviewed as to their capability to handle 2 inch tape at 180 inch per second (ips) play speed and 360 ips shuttle speed. The limiting factor for these transports is the high inertia of a tension arm buffer system and capstan pinch roller combination.

The standard computer transports, Honeywell M0096, B&H 3700B, and Wango Mod 1037 are 1/2 inch tape and are too small to modify for handling 2 inch tape. These units are relatively slow in start/stop conditions (5 sec for 120 ips).

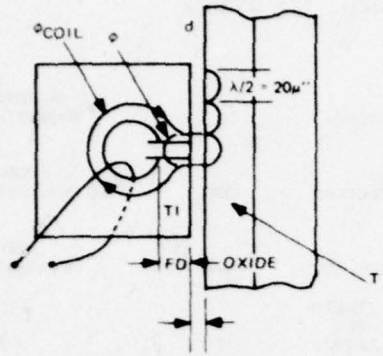


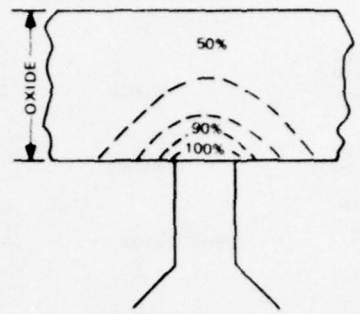


LINES OF EQUAL RELATIVE FIELD STRENGTH AROUND RECORDING GAP (DUINKER [1957]).
H_o = FIELD DEEP INSIDE GAP

PARAMETERS	TYP. VAL.	RANGE	OPT. VAL.	PROPOSED DIRECTION	PROBLEMS
REC GAP (gw) IN MICROINCHES (μ")	10	3-20	OPT FOR MAX ROAD SIGNAL	IMPROVE FIELD SHAPING	POOR FIELD SHAPE
SEPARATION (d) (μ")	5	0-15	0	STUDY CONTOUR EFFECTS	ROUGH TAPE SURFACE MODULATES "d"
OXIDE THICKNESS (t) (μ")	110	60-450 (OXIDE) 2-20 (METAL)	FR/2	OBTAIN THINEST AVAILABLE	FEW MANUFACTURERS OF VERY THIN FILMS
REC FIELD B_f (GAUSS)	1000	500-1000	ADJUST	OPTIMIZE SHAPE	FIELD WIDENS DUE TO HEAD B_{sat}
REC GAP FIELD B_g (GAUSS)	2000	1000-2000	0	CONTROL	PROBLEM ON PB
TAPE DEMAG. FACTOR (a) (μ")	50	12-200	<FR/2	CONTROL	IMPROVES WITH REDUCED OXIDE

Figure 32. Record Interface Factors





PARAMETER	TYP VAL	RANGE	OPT VAL	PROPOSED DIRECTION	PROBLEMS
RELUCTANCE OF FRONT GAP (RFG)					
RELUCTANCE OF BACK GAP (RBG)					
RELUCTANCE TAPE TO HEAD (RTH)					
FLUX IN HD COIL (ϕ COIL)					
FLUX IN POLE TIP (ϕ TIP)	<1 GAUSS				
READ VOLTS/TURN (V) μV_{p-p} $\frac{d\phi}{dt}$ COIL	15 $\lambda/2=50$	10-30	15 @ $\lambda/2=20$	IMPROVE HEAD EFF	READ HEAD LOSSES
READ GAP (g_r)	$< \lambda/3$	$\frac{\lambda}{3} - \frac{\lambda}{5}$	$\lambda/10$	OK	DEMAND VERY LOW RFD
HEAD SEPARATION (d) μ''	5	0-15	0	STUDY CONTOUR	ROUGH TAPE SURFACE MODULATES "d"
POLE FACE DEPTH (PFD) μ''	500 (50 g_r)	300-2000	0	<200	200 VERY WEAK
PFD TO g_r RATIO (ϕ^1)	50/1	25/1 – 100/1	10/1	IMPROVE HEAD STRUCTURE	200 VERY WEAK
READ EFF (%)	?			GET IT UP!	γ, RFG/RBG

Figure 33. Playback Interface Factors

2.4.8.1 Tape Speed

The design goal was to have a transport to move tape in a play mode at 240 ips and obtain this constant velocity in 0.003 sec.

2.4.8.2 Tape Width

The feasibility model transport was designed to handle 2.00 inch magnetic tape. This was done because of the availability and ready access of reels and tape. The width could be larger than 2.00 in but no studies were made as to their dynamic characteristics.

2.4.8.3 Start/Stop Performance

The tape dynamics of the assembled system were calculated to determine the forces required to accelerate the reel/tape system to 240 ips in less than 0.003 sec.

RCA feels strongly that fast start/stop would provide a great operational advantage in the future system. Fast start/stop and rapid search have already been a key focal point in a recent product distribution program. An RCA technology study objective is to advance low density digital computer tape transport technology in high density digital applications, for both fast search (over 400 in/s) and fast start/stop (less than 0.01 seconds) to provide "fast access" to data frames stored on tape reels. This concept has major operational benefits for sort and random access of serial/chronological input data or achived data. RCA feels that this technology should be further developed.

2.4.8.4 Vacuum Columns

The increase of tape velocity and acceleration involve more than changing the characteristics of the capston and reel motors. The basic law of force = mass x acceleration at the high tape speeds would give excessive tape tension during start/stop operations.

The basic element that distributes the accelerator forces and prevents these from being transmitted to the tape are tension arms. However, the force to operate the tension arms comes from the tape and with even the most advanced tension area design the force to operate exceeds the tape elastic limit.

The method used to meet the above condition is to use tape vacuum columns to replace the tension arms. In the vacuum column buffer, the tape is stored in two separate chambers.

The advantage of the vacuum buffer is in the absence of any extraneous mass other than the tape to accelerate during the start/stop operation.

a. LENGTH. The basic equation is derived from the difference in the tape length over the capstan and from the tape reel in the time required to get the tape to maximum velocity.

$$\Delta L = 1/2\, V_f t_c + V_f (t_s - t_c) - 1/2\, V_f t_R$$

$$= V_f (t_R - t_c) - 1/2\, V_f t_R + 1/2\, V_f t_c$$

$$= V_f (t_R - t_c) - 1/2\, V_f (t_R - t_c)$$

$$= 1/2\, V_f (t_R - t_c)$$

ΔL = Tape length storage required until equalization

V_f = Final Velocity of tape

t_c = time of capstan acceleration to constant velocity

t_r = time of reel acceleration to constant velocity

Figure 34 and 35 graphically present the reel and bin equalization lengths and velocity [illegible]

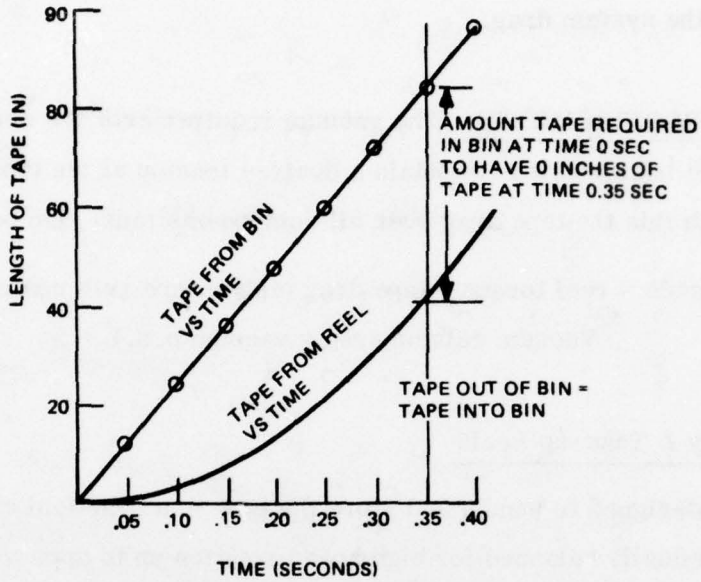


Figure 34. Tape Lengths of Reel and Bin Equalization

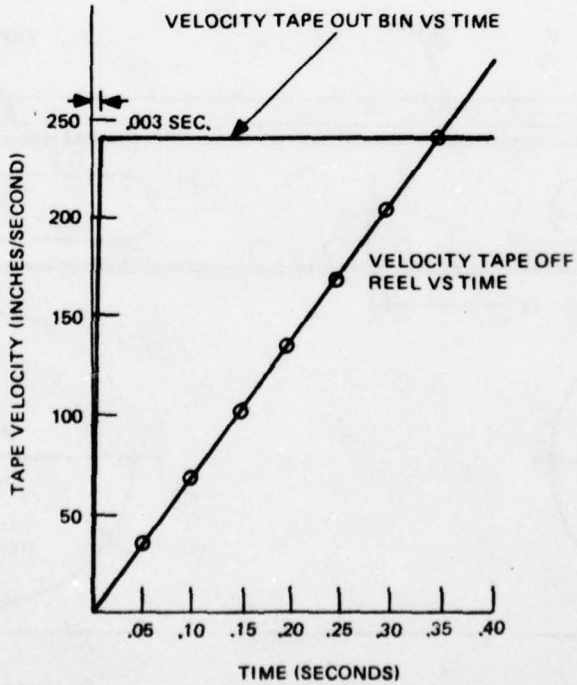


Figure 35. Reel and Bin Tape Velocities Interaction

Two configurations of reel and tape bin designs are shown in Figures 36 and 37. Configuration B (Figure 37) conserves space but requires two additional air bearings that willl increase the system drag.

b. VACUUM REQUIREMENTS. The vacuum requirements are dependent upon the amount of "hold back tension" to obtain a desired tension at the tape heads. In conjunction with this the tape drag over all components must also be considered.

Tape tension heads = reel torque - tape drag (entire tape path upstream of heads) - Vacuum column area x vacuum p.s.i.

2.4.8.5 Supply & Take-up Reels

The reels are designed to handle and store the tape in a practical and efficient manner. They are dynamically balanced for high speed rotation up to approximately 1,000 RPM. The weight should be kept to a minimum but normally will be only a small percentage

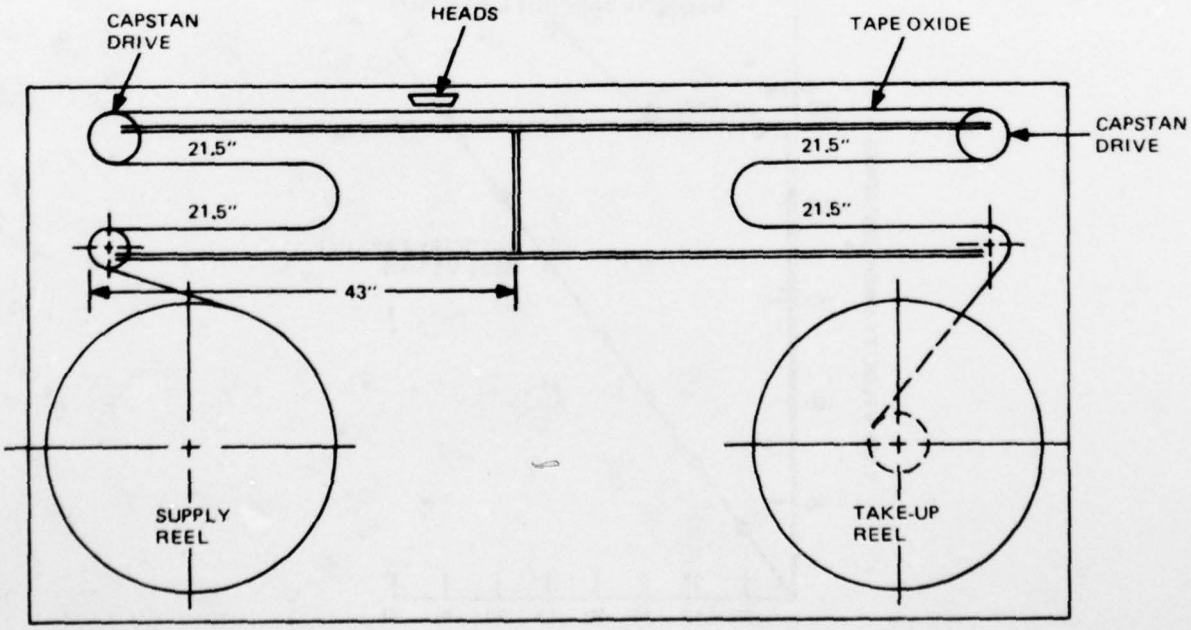


Figure 36. Reel-Bin Configuration A

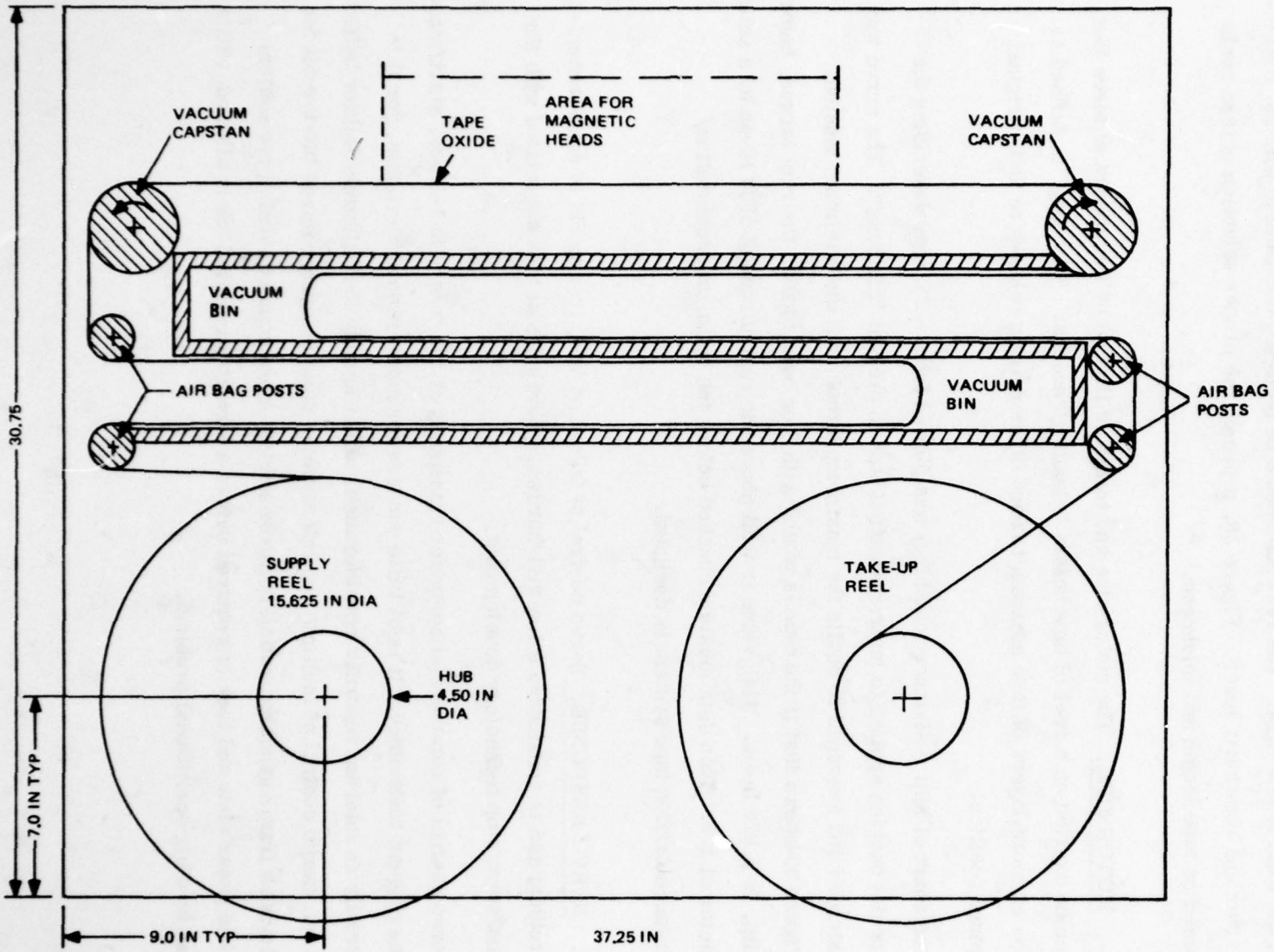


Figure 37. Reel-Bin Configuration B

of the total tape weight. The reel hub should be designed compatable with the reel inverter and rotational speed. Figure 38, presents the proper selection of tape reels based on tape length and thickness.

a. MOTOR SIZE. The motor size and torque is limited by the amount of force that can be exerted on a reel of tape before "cinching" occurs. "Cinching" is defined as one or more layers of tape adjacent to each other moving relative to their original wound position.

The chart of Slip resistance (cinching) was plotted from a 3M tape describing the special backing applied to instrumentation tape to prevent "cinching". The curve was extended and averaged to obtain the maximum torque with the minimum tension. Figure 39 shows that if the tape is wound with 8 oz back tension the reel torque, before slip, is 2,976 in-oz. This value is well above the reel-torque of 1800 in-oz by a safety factor of 1.6. This data must be checked before the optimum acceleration/ de-acceleration tape system is designed.

b. SERVO RESPONSE. Servo control of fast start/stop transports is not a technology problem and is considered a low risk hardware development task associated with the fast start/stop technology development.

Servo control of commercial computer transports at 120 in/s with 1-5 sec. start/stops use present technology. It is of little concern for a one-recorder-system, for it is strictly an internal recorder consideration, affecting only the deflutter/dejitter buffer size. Servo control of multiple recorders which must be synchronized bit-for-bit for playback frame synchronization requires a much more sophisticated servo system when phase slew and lock is required before a straight velocity lock is allowed. This can be a big operational problem.

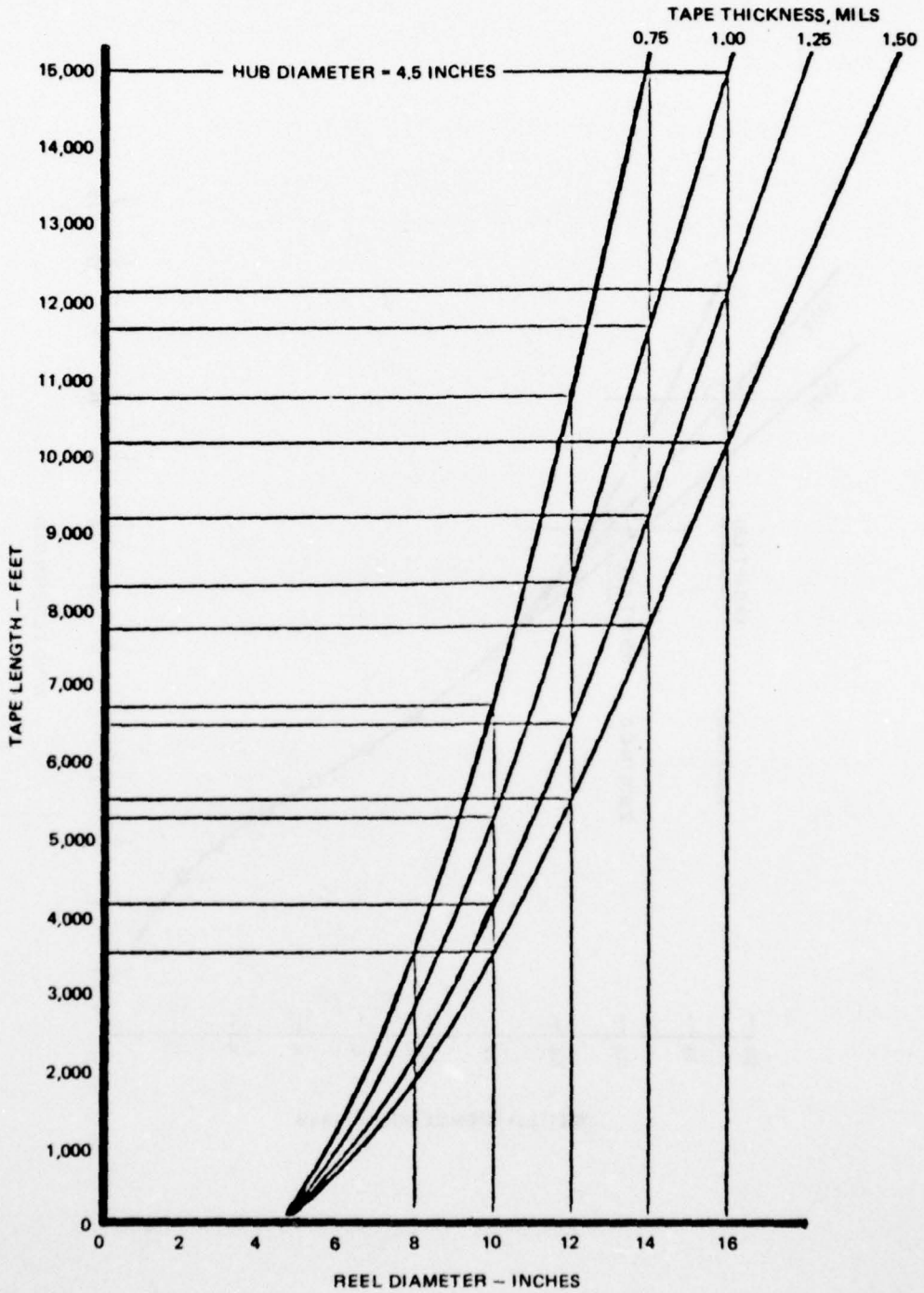


Figure 38. Tape Reel Selection

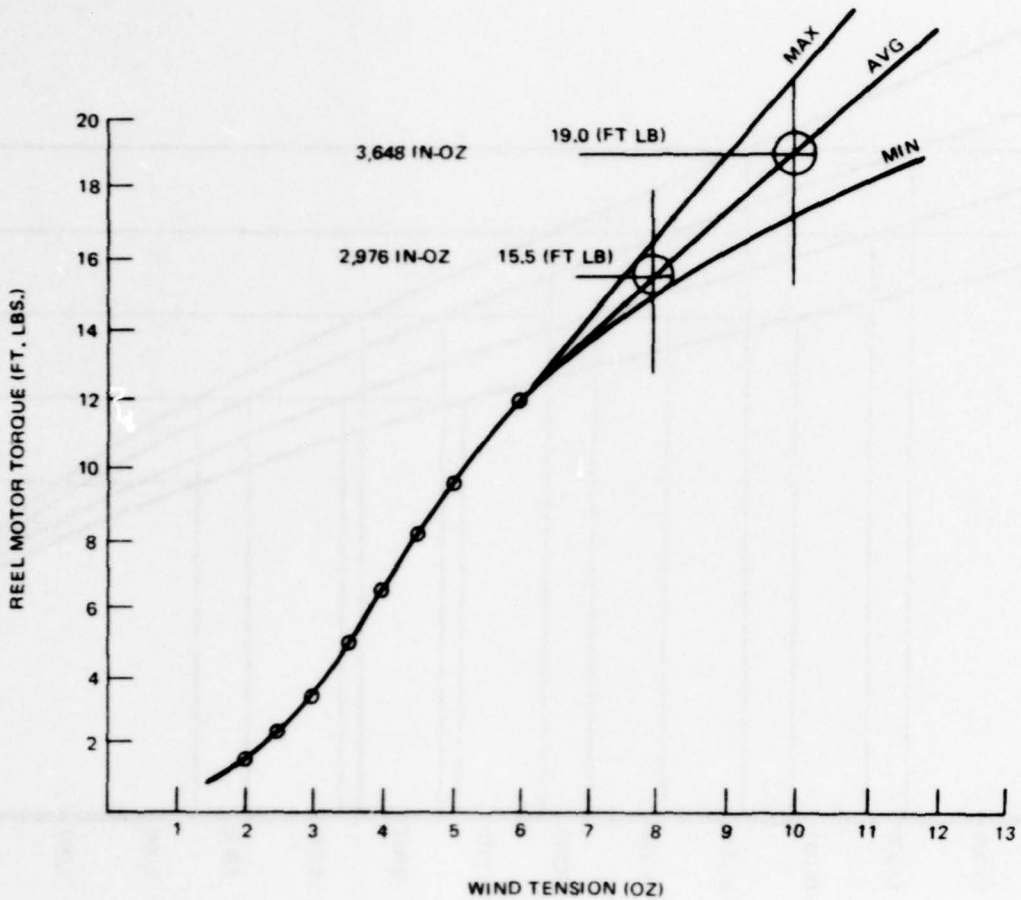


Figure 39. Slip Resistance of Back Coated Tape

2.4.8.6 Rewind Performance

High speed rewind is required to utilize the tape most efficiently. It reduces the reloading time cycle and allows more rapid searching for discreet data segments within a reel. The rewind speed goal is 600 ips and requires 7 minutes to rewind 14,000 feet of tape on a 16 inch reel.

SECTION 3

PHASE II FAST ACCESS DIGITAL RECORDER STUDY OF ALTERNATIVE TECHNIQUES

Present video recorders utilizing 2-inch magnetic tape were reviewed as to their capability to handle 2 inch tape at a play/record speed of 180 ips and a rewind (shuttle speed) of 360 ips. Transverse video transports have a play/record speed of 15 ips and a shuttle speed of approximately 500 ips. These basic machines have a start time of 0.4 sec @ 15 ips. Start time is the time required for the tape to reach constant velocity.

3.1 ADAPTATION OF AVAILABLE HIGH DENSITY TAPE TRANSPORT TECHNIQUES.

The present video recorders available to modify are designed to handle 2 inch tape and 16 inch diameter reels. The drawback to these transports is that they use pinch roller/capstan and tension arms to move tape and control tape tension. This fact alone does not make it economically feasible to modify for high tape speeds due to the high inertia of the tension air buffer system.

3.1.1 Start/Stop Characteristics

The high start requirement of 0.003 second @ 240 ips is not possible with a pinch roller/capstan combination. The use of vacuum capstan in combination with the vacuum column tape buffer system would allow the acceleration required.

The stop requirement would not be as fast as the start and would be capable of stopping the tape from a play mode (240 ips) within 3 feet of tape. The rewind mode of 600-900 ips would have to be investigated due to the tape cinching problem that was previously discussed.

3.1.2 Shuttle Rewind Characteristics

The Video or High Density Transports are capable of 600-700 ips rewind speeds with 2 inch tape. The present maximum stop time at 400 ips is 2 seconds on a fast rewind broadcast video recorder. The effort to decrease the stop time @ 400 ips resulted in tape cinching on the reels.

3.1.3 Tape Guidance

Tape guidance on the standard recorder is accomplished by a fixed dimension guide post. The tape can float between the two edges of the guide surfaces. This variation is in the order of from 0.001 to 0.005 inch.

3.2 ADAPTATION OF AVAILABLE COMPUTER TAPE TRANSPORT TECHNIQUES

Computer transports are more in line to accommodate the high tape handling speeds but they are only capable of handling the narrow 1/2 inch tape. The RCA 845X Tape Station was modified to accommodate 2 inch tape by designing and manufacturing air bearings and vacuum tape loop columns. A special vacuum capstan was installed to drive the critical segment of tape past the magnetic heads. Other transports are relatively small to adapt to the large motors required for high tape speeds and the weight of the 2 inch tape. The transports reviewed were the Honeywell Mod 96, Wango Mod 1037, Ampex FR Transports, and Bell & Howell 3700B. These units all handle 1 inch tape and with a start time of approximately 5 seconds @ 120 ips.

3.2.1 Start/Stop Characteristics

The start/stop characteristics of the computer transports are faster than the digital type recorder mainly because the tape is only 1/2 inch wide and its low mass is easy to accelerate.

3.2.2 Shuttle Rewind Characteristics

High speed tape shuttle of 500 to 700 ips allows location data to be read thru the increased air film floating the tape over the head. Stop time in the order of 2 seconds will not damage the tape nor cause tape pack cinching.

3.2.3 Tape Guidance

The tape for the computer transport is biased to one edge of the tape. This bias is accomplished by several methods, canted guide posts, tapered roller posts or canted surface guide. The canted surface guide is best because the tape edge is guided along a large surface (6-8 inches) and edge variations are averaged out on the contact surface. On all the other guide systems the tape has a relative small guide surface.

3.2.4 Tape Stress

This again is lower in the computer transports due to the lower forces. The stress in the tape is highest during start/stop modes and with the vacuum bin buffer and air bearing turn around posts. These air guides reduce the tape drag to a minimum and therefore better control of the tension can be provided by the reel servos.

The electrical time constant of the reel servo motor was measured and transient response calculated. Although the electrical time constant is greater than expected, adequate reel servo performance, based upon this motor, will be obtained. The 845X transport reel servo amplifiers are being evaluated to know the circuit details from design, maintenance, and performance limitation standpoints.

3.2.5 Constant Tension/Low Flutter Technique

A system has been devised to remove the flutter which occurs in any tape transport. This system is to use a double vacuum bin on each reel side. The

1st vacuum bin is the standard unit designed to handle the differential tape length due to the accelerations of reel and capstan. The 2nd vacuum bin is considerably smaller and is located just before the capstan drive and after the head for the other reel as shown in Figure 40.

3.3 VARIABLE TAPE SPEED TRANSPORT TECHNIQUE

Slowing the recorder down 2:1 and 4:1 for playback into a lower thruput rate system presents no technical problems. At these reduced speeds the tape will be traveling at normal rates. There will be some electronics hardware impact, however. Multiple playback rates will require some circuitry switching and may require larger dejitter/deflutter buffers. This concern is definitely not a technology study task and can be satisfactorily addressed in follow-on programs.

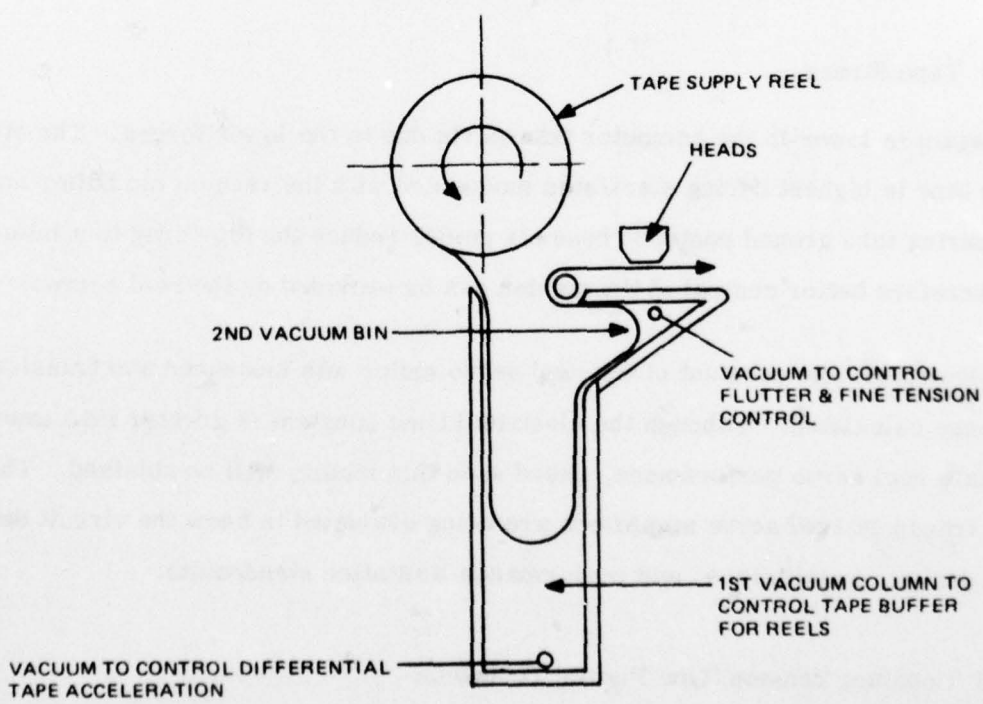


Figure 40. Functions of the Vacuum Columns

3.4 HARDWARE EXPERIMENTS PERFORMED

The modified computer tape station resulted from the incorporation of a 2 inch vacuum capstan, 2 inch wide tape vacuum columns and bins, calibrated reel motors, NAB type reel hubs, pneumatic sub-systems, and electrical interconnections. Detailed experiments were performed on the vacuum capstan torque and coefficient of friction using back coated tape. Reel motor parameters were calculated and measured as to their acceptability in the system.

3.4.1 Tape Transport

It has been concluded that the optimum transport design would be patterned after computer tape transport technology and thus continued effort need be applied. A preliminary design layout is shown in Figures 41 and 42 for both rotary head and fixed head applications.

3.5 TEST RESULTS AND HARDWARE DEMONSTRATION

On 16 June 1977 RCA performed the requirements of SOW, para. 4.3 by demonstrating several pieces of hardware to J. Petruzelli, the COTR. The project hardware item demonstrated was a partially implemented computer tape station modified for 2 inch tape on NAB reels. The hardware demonstration consisted of reel motors running, vacuum bins loading, vacuum capstan running, capstan vacuum actually pulling tape and unit control operating. Not all of these items were coordinated in their operation. This Fast Access Transport is shown in Figures 43 and 44.

Two other demonstrations were presented to the COTR. The NASA 240 Mb/s breadboard recorder system was operated recording and playing back at full data rate. A data sheet describing this system is shown in Figures 45 and 46. The 40,000 bits per inch demonstration with the new HDMR head/electronics hardware is outlined in Figure 47. These two demonstrations describe results of contract item 0001AA, which is complete.

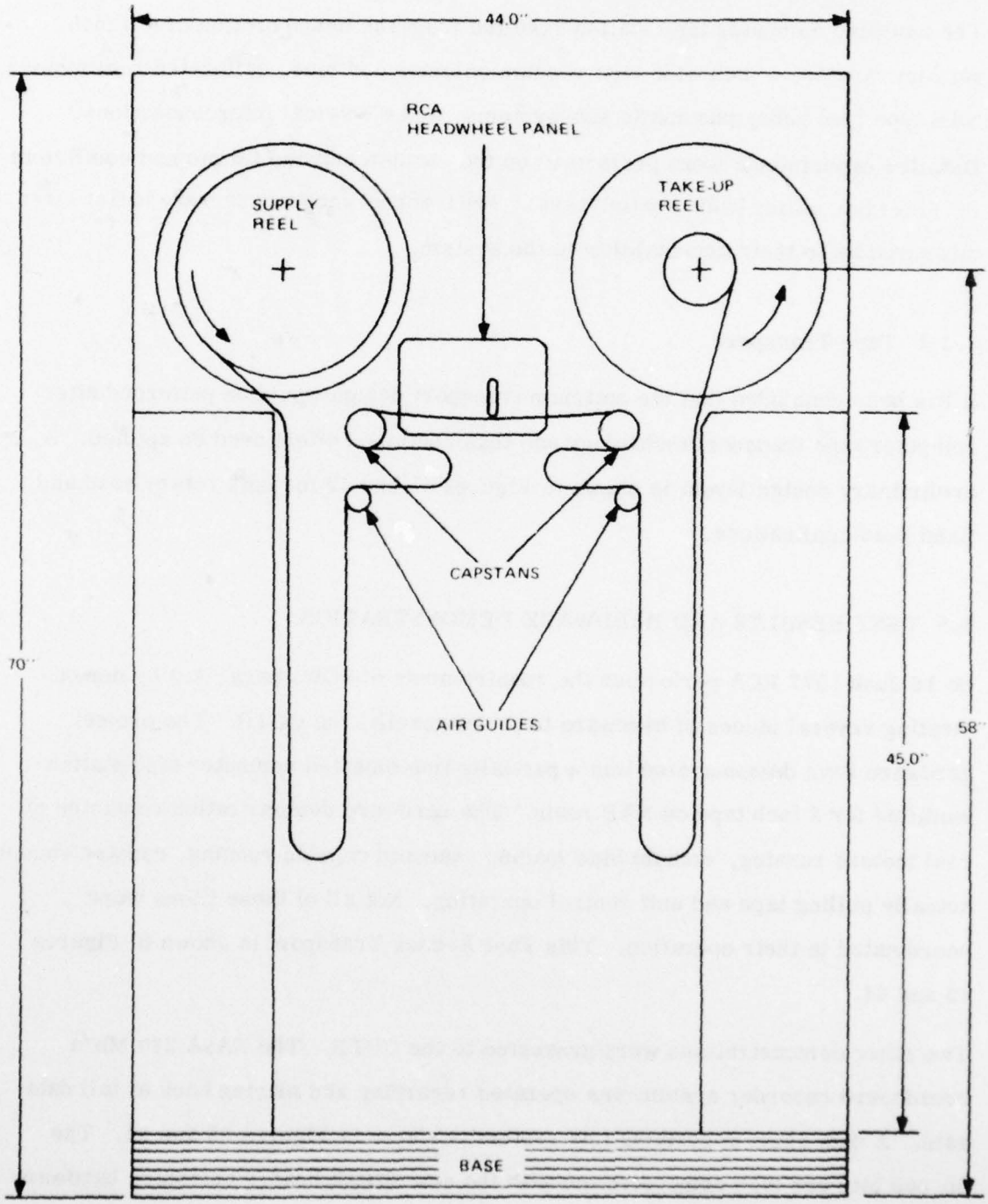


Figure 41. Versabit Type (Rotary Head) Transport

AD-A048 452 RCA CORP CAMDEN NJ INFORMATION PROCESSING AND RECOR--ETC F/G 14/3
ULTRA WIDEBAND DIGITAL RECORDING TECHNIQUES.(U)
NOV 77 O E BESSETTE, L W FERBER F30602-76-C-0183
UNCLASSIFIED RADC-TR-77-356 NL

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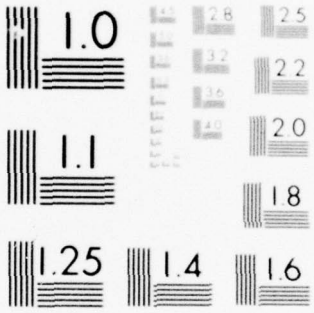


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963-A

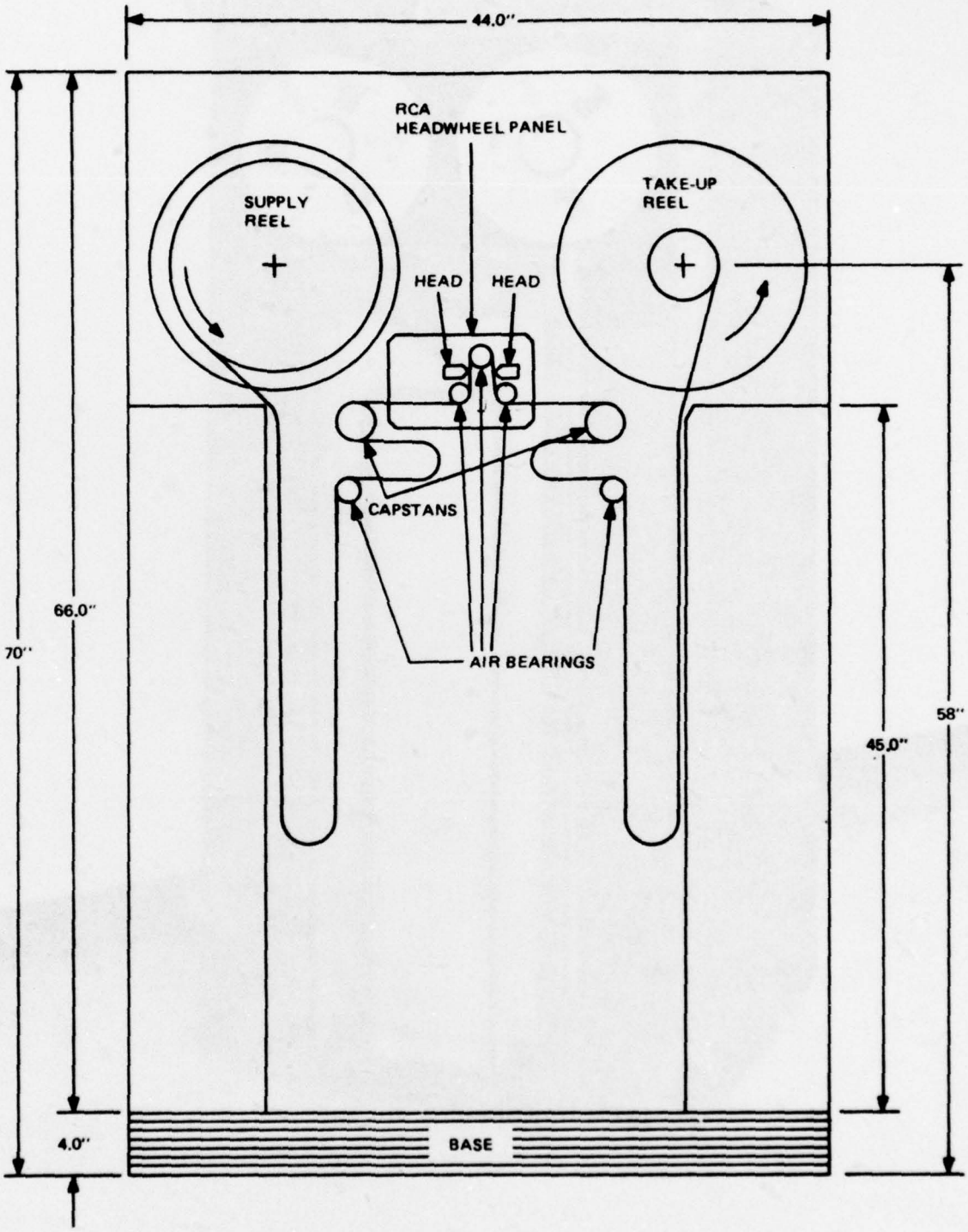


Figure 42. HDMR Type (Fixed Head) Transport

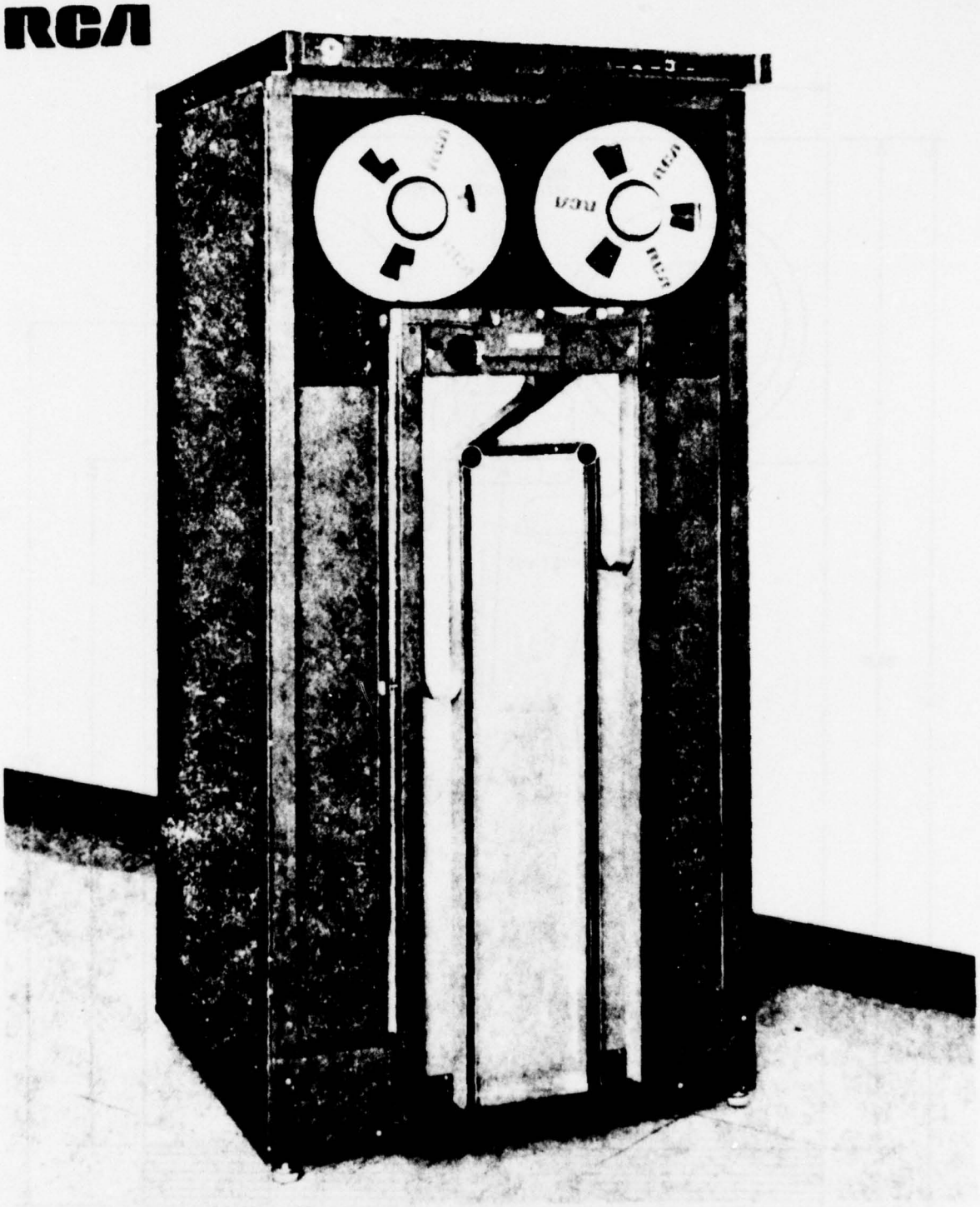


Figure 43. Fast Access HDMR Transport

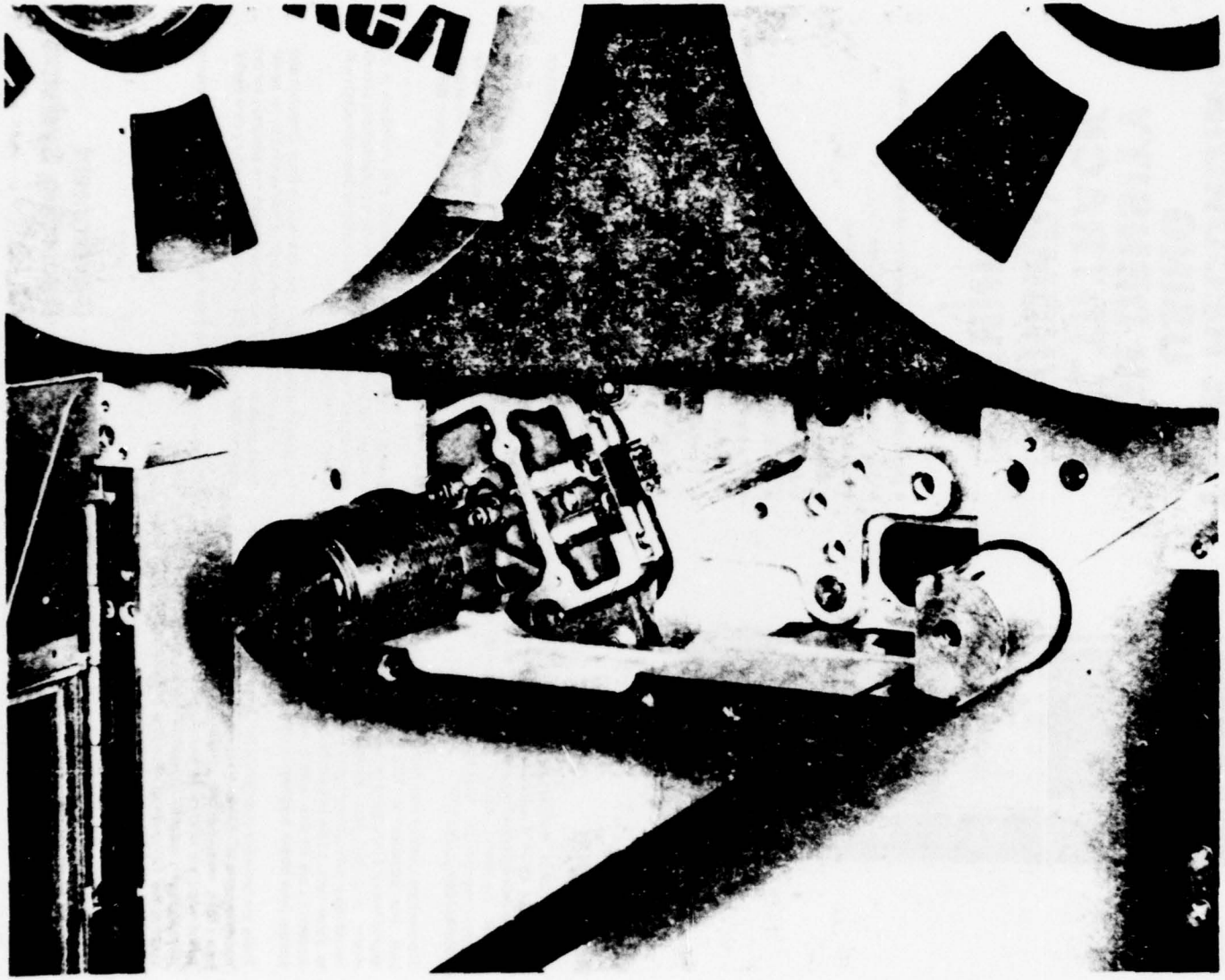
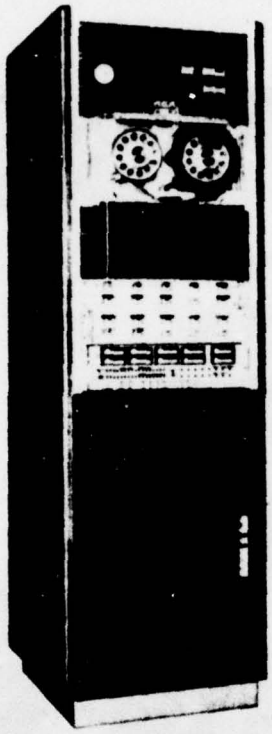


Figure 44. Fast Access Transport Capstan/Head Area

RCA/NASA DEMONSTRATION OF...



240 Mb/s

TAPE RECORDING USING HIGH DENSITY MULTI-TRACK (HDMR) TECHNIQUES

- **Direct 240 Mb/s record/ reproduce using single tape drive**
- **Over 2 million bits per inch of tape**
- **Unique 142-track 2-inch HDMR head**
- **Standard 2-inch magnetic tape**
- **Standard 120 ips tape speed**
- **Full digital deskew/ deflutter buffering**
- **Fully populated 120 channels of record/ reproduce electronics, each handling 2 Mb/s**
- **10^{-4} BER correctable to 10^{-6} with EDAC**
- **On-line BER monitors**

DESCRIPTION

The RCA/NASA 240 Mb/s HDMR demonstration recorder consists of an RCA Landsat 2-inch magnetic tape transport modified for longitudinal recording, coupled to a 142-track, 2-inch HDMR magnetic head, 120 channels of 2 Mb/s record/reproduce electronics, and a 240 Mb/s multiplex/demultiplex I/O.

The modified Landsat transport carries 2000 feet of 2-inch video tape and operates at 120 inches per second providing approximately 3 minutes of recording time. The record equalizers, record amplifiers and playback preamplifiers have been hybridized to minimize the head/electronics interface volume and to allow them to be physically close to the heads. All other electronics are on wire wrap or printed circuit cards. The total system (less power supplies) is contained in a single rack.

There are two input channels to the demonstration system, each accepting data at 120 Mb/s. For operational checks and bit error rate (BER) measurements, these inputs are generated by a pseudo-random word generator. A serial-to-parallel converter (demultiplexer) supplies 120 parallel bits at 2 Mb/s per second each to the 120-channel recording processor. The processor performs the functions of NRZ-to-Delay-Modulation conversion, record equalization and record head drive.

The 120 reproduce channels amplify, filter, limit, demodulate to NRZ, deskew, and deflutter the read head signals. A parallel-to-serial converter(multiplexer) then supplies two channels of data (at 120 Mb/s per channel) to two test stations where BER is measured.

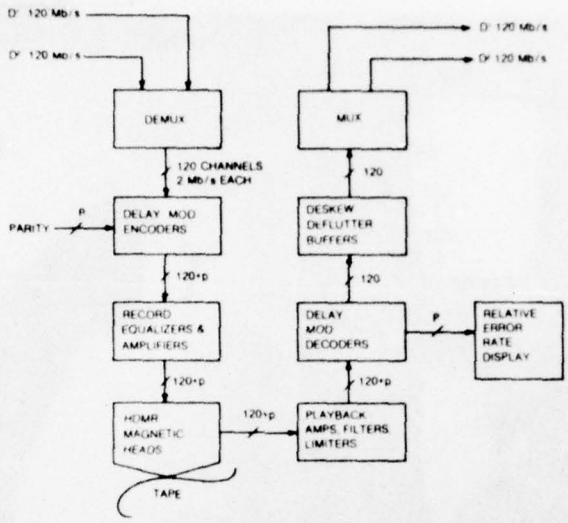
System timing reference for both record and reproduce is an external 120 MHz clock. The reproducer's digital deflutter circuits plus a capstan servo provides absolute time base correction with respect to the reference clock.

The demonstration system does not include Error Detection and Correction(EDAC) circuitry which RCA had verified by an earlier demonstration. Twenty-two unused tracks are allocated for the implementation of EDAC and/or customer auxiliary data tracks.

A block diagram of the basic hardware is shown on the reverse side.

RCA Government Recording Systems

Figure 45. 240 Mb/s Tape Recording System, Sheet 1 of 2



HDMR RECORDER BASIC BLOCK DIAGRAM

RCA's two-inch, high track density HDMR head is the most unique element of the HDMR system. With it, HDMR techniques achieve a tape utilization efficiency of more than 3×10^8 bits/inch by packing over 80 tracks/inch across two-inch tape. A relatively conservative in-track density of 20,000 bits/inch is used to maintain high signal to noise ratios.

HDMR heads are unitized, batch fabricated versions of RCA's standard quadruplex video head used throughout the world in commercial television recorders. This single turn-hot-pressed metal design has had extensive use in severe environments, is not fragile compared to ferrites, and has extremely long life. The integrity of the head-to-tape contact and the life of the head is enhanced by the elimination of all extraneous materials at the interface. There are no shields or pole tip supports -- nothing touches the tape but the magnetic head core itself. In RCA's laboratory measurements, this head configuration has survived the passage of 75×10^6 feet of tape over the head with no measurable head wear, no tape degradation, and no change in recorder performance.

RCA has been continuously evolving hardware-efficient techniques for HDMR digital processing. Coding, decoding, equalization, high rate multiplexing, deskewing, and defluttering schemes have all been designed and implemented to handle up to 160 tracks on 2 inch tape. Error control techniques have also been developed to help eliminate the effects of tape imperfections and provide a BER of better than 10^{-6} at 2 million bits per square inch.

From here, RCA is investigating means of extending HDMR technology to address data rates of over 1 gigabit/second, airborne hardware configurations, and a fast access, ground-based transport. RCA is also involved in environmental testing of HDMR-type tape transports for Air Force MIL-E-5400 application, development of a vacuum bin transport for ultra fast access time and new magnetic head and record/reproduce electronics for 50,000 bits/inch.

HDMR HEAD

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Manager, Marketing, Government Recording Systems
Building 10-5
Camden, New Jersey 08102
(609) 963-8000 Ext. PC-2401

RCA Government Systems Division

Figure 45. 240 Mb/s Tape Recording System, Sheet 2 of 2

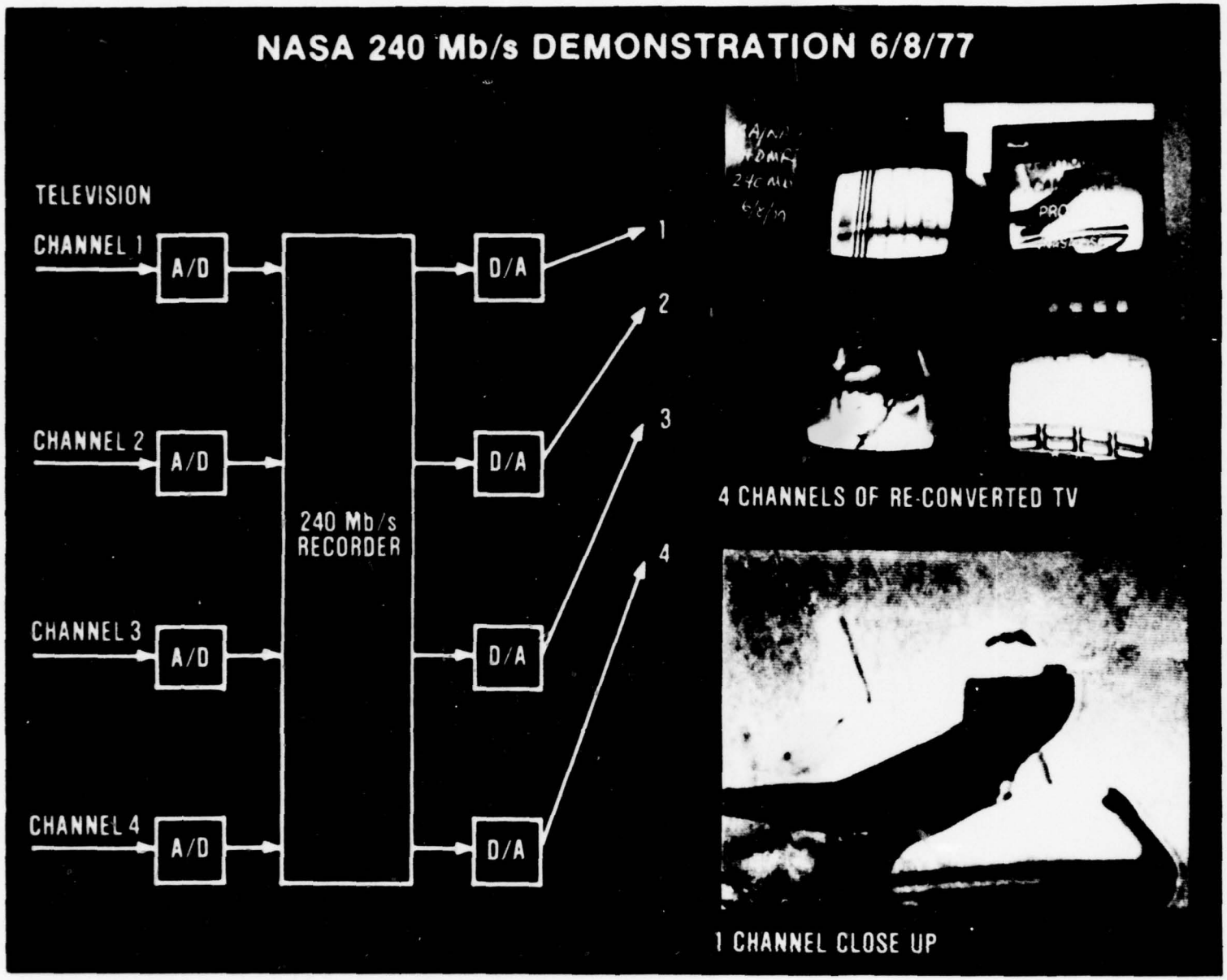

Figure 46. 240 Mb/s Demonstration

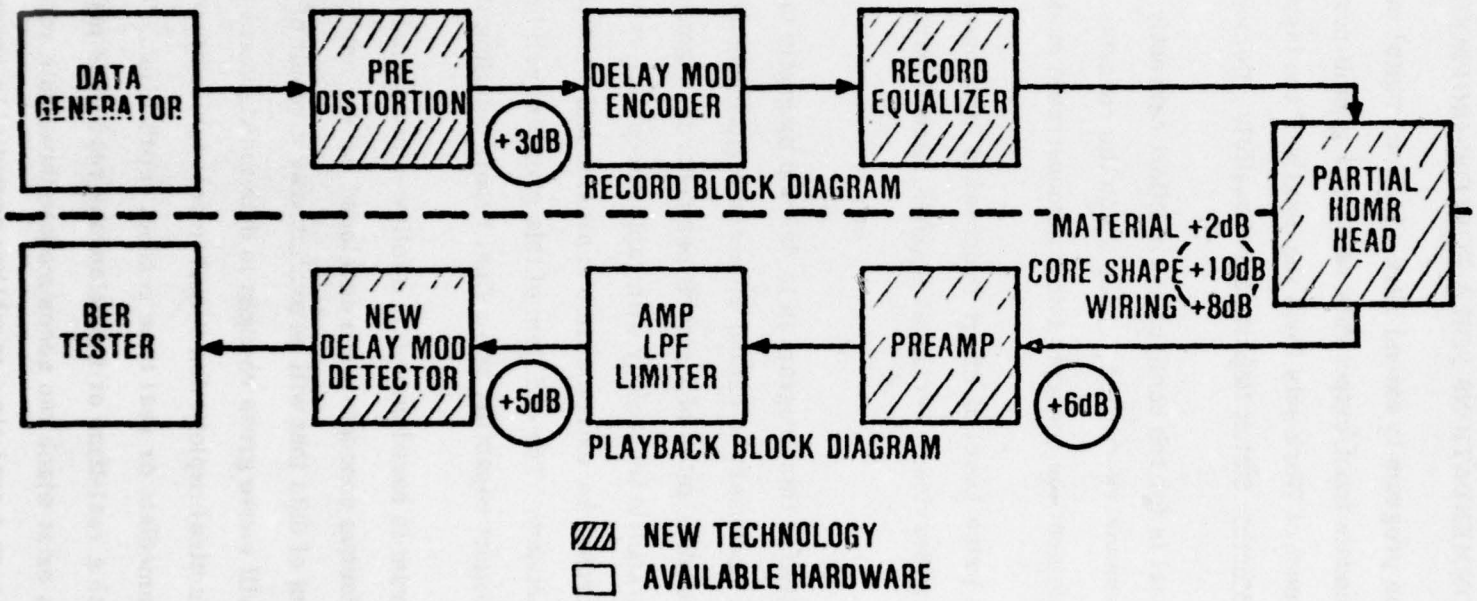

Figure 47. Breadboard Experiment Block Diagram

3.6 RECOMMENDATIONS FOR A FOLLOW-ON PROGRAM

A follow-on program to extend ultra wideband digital magnetic recording technology to accommodate input/output data rates of 1 gigabit per second is herein proposed. The Statement of Work sets forth the details of the tasks which will be performed, including Monthly Status Reports and Feasibility Demonstration.

The proposal is for the continuation of effort currently being performed under RADC Contract F30602-76-C-0183, under which the concepts were developed. This effort would implement the concepts into a demonstrable model.

The Fixed Price Level of Effort Proposal is for a one (1) year program for Engineering Services, Technical Reports, Breadboard Development and Demonstration.

The objective of this program is to develop magnetic tape recording transport technology necessary to extend wideband digital magnetic recording to accommodate input/output data rates of 1 gigabit per record. Concentration will be on fast start/stop/shuttle technology with rapid access for exploitation purposes. Data block recording for extreme time expansion and versatility of computer interaction is of importance. The end item of this program will be a feasibility demonstration of the transport capability and a final report detailing the techniques developed.

This program is based on and is a follow-on of a Contract F30602-76-C-0183 where technique concepts were developed but not implemented into a working model. The amount of data that will be available as a result of high data rate communication systems will cause gross changes in data management techniques by the 1980 time frame. Tactical exploitation requirements for command and control applications demand immediate or real time readout capabilities. The approach most consistent with a real-time or instantaneous readout is magnetic recording. Although techniques exist which can accommodate these data rates (laser holographic), they do not possess a real-time capability essential to several situations.

This program will take the concepts developed under Contract F30602-76-C-0183, with available vendor supplied experimental hardware, develop a working model transport, and evaluate it. The vendor hardware will utilize 10 inch reels, NAB hubs, 2 inch tape and a 2 inch head mount.

The tasks and technical requirements are:

The contractor shall provide engineering services to perform a design, test, and evaluation investigation of the concepts developed on project Contract F30602-76-C-0183 by means of a breadboard development model transport, and a demonstration of this unit.

This new technology breadboard transport shall address the following design objectives.

1. The application and extension of computer transport technology for start/stop rates of less than 25 milliseconds and shuttle/rewind rates of 600-900 ips.
2. Tests will be made at various operating speeds: 12, 24, 120 and 240 ips.
3. Head-Tape interface performance compatible with 40,000 bits/inch, 10^{-6} bit error rate and potential for greater than 1 Gb/s total transfer rates.

Specific sub-tasks are fabrication of hardware designs and concepts from Contract F30602-76-C-0183, including 1 vacuum capstan, transport, reels and magnetic head.

Engineering tests and evaluation of transport performance for:

1. Head-Tape Performance: Measure tape skew, jitter, flutter, tension and wave length response by means of a 2 inch test head and other appropriate instrumentation.

2. Access Time. Measure start time, stop time for operational speeds from 12 to 240 ips. Measure start time and stop time to/from search speeds.

3. On basis of above data, develop design specifications for a 16 inch reel unit.

Data to be provided are Monthly R&D status reports and a Technical report (final report). The technical report shall detail the project results.

Residual hardware: Most of the project hardware will be vendor supplied. The minor remaining hardware purchased on this program will remain with the vendor hardware.

SECTION 4

HAZARD ANALYSIS REPORT

The only deliverable items transmitted by the contractor per this contract are this final report and the preceeding monthly reports and thus there is no need for a Hazard Analysis Report.

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SECTION 7

APPENDICES

Appendix A - Error Rate for Single Channel Failure

Appendix B - Reel Servo Design

APPENDIX A

ERROR RATE FOR SINGLE CHANNEL FAILURE

The Error Detection and Correction technique selected for a 126 track system has the capability of maintaining the specified error rate in one of the EDAC channels and a reasonable error rate in the other channel when a track channel failure occurs. Without the EDAC the failure rate would become very large if one of the recorder channels failed. For no EDAC and the data spread over 112 channels the error rate would become $\frac{1}{2} \times \frac{1}{112} = 10^{-3}$. The 1/2 term considers that even for a failed channel the playback circuitry assumes either a 1 or 0 and thus one-half of the time would be correct. With EDAC, when a channel fails the EDAC system not affected will still meet a 1×10^{-6} bit error rate. The total BER would only degrade to 0.8 P_e of approximately 2×10^{-5} the system error rate would become 1.6×10^{-5} which would still provide operation with a reasonable error rate. Without EDAC the affected channel error rate would be 4.5×10^{-3}, with EDAC the decrease to 1.6×10^{-5} is a 280 to 1 improvement in system error rate. The following calculations show the derivation of the above numbers.

The dropout error model used is that discussed in the analysis of the system error rate for the 126 channel system. The system error rate without a failed channel was

$$P_s = 1.6 \times 10^{-4} P_e + 1.48 \times 10^{2} P_e^{\ 2} + 6.64 \times 10^{-3} P_e^{\ 3}$$

When a failed channel occurs, the data in that channel will be incorrect one-half of the time. If no other errors occur in other channels the EDAC will correct the data in the failed channel. If other errors occur, the EDAC will be unable to correct both the errors of the failed channel and those caused by other sources

such as tape dropout. The number of times that errors occur will be 1/2 P_e; when they occur there will be two uncorrected errors plus an average of 1.2 bits made incorrect by the EDAC subsystem. The overall system error rate becomes

$$P_s = 1.6\ P_e$$

for the EDAC system with the failed channel. The total recorder BER than will be 1/2 the 1.6 P_e bits or 0.8 P_e.

APPENDIX B

REEL SERVO DESIGN

The electrical time constant of the reel servo motor was measured and transient response calculated. Although the electrical time constant is greater than expected, adequate reel servo performance, based upon this motor, will be obtained. The 845X transport reel servo amplifiers are being evaluated to know the circuit details from design, maintenance, and performance limitation standpoints.

1. Electrical Time Constant Measurement - The reel servo loop design requires knowledge of all component parameters. Although fairly complete, reel motor data has been obtained from G. E. (Fort Wayne, Ind.), the electrical time constant was not included.

The test for measuring this parameter was conducted at a fairly high current level to insure that the non-linearities of the computator-brush interface did not mask the results. The rotor was clamped to prevent motion and the field was not connected.

The measured time constant with 1.5 ohms external resistance was:

5.0 ± 0.1 millisec.

Since the armature resistance is 0.44 ohms, the inductance is:

$L = .005\ (.44 + 1.5) = 0.00975$ henry

and the fundamental motor electrical time constant (without external resistance) is:

$0.00975/0.44 = 22.16$ millisec.

2. The above measurement allows calculation of the motor-reel transient response. This gives a measure of upper bound performance.

The subsequent calculations include the electrical time constant but consider the time to reach 240 ips (48 radian per sec) from standstill.

In the following calculations, symbols, values and units are given in Table B-1.

The morot terminal voltage is:

$$V = iR + L\frac{di}{dt} + k_B \tag{B-1}$$

$$= \frac{kt}{J_T}\, i \tag{B-2}$$

In Laplace notation Eq. (1) can be written as:

$$\frac{k_B}{V}(s) = \frac{1}{\frac{LJ_T}{k_t k_B}s^2 + \frac{JR}{k_t k_B}s + 1} \tag{B-3}$$

For imaginary roots of Eq. (3)

$$s = -a \pm jb \tag{B-4}$$

The step response is:

$$(t) = \frac{VE^{-at}}{k_B b}(-a \sin bt - b \cos bt) + \frac{V}{k_B} \tag{B-5}$$

Substituting from Table B-1 and solving for t_1, the time when the motor with full reel reaches 48 radians/sec.,

t_1 = 65.9 millisec.

The peak current and time of peak current can be found by differentiating Eq. (B-5) and using Eq. (B-2). The current peaks to 78.8 amps at 42.7 millisec.

This current appears excessive. Most tests by GE were conducted with one ohm external resistance in the armature circuit. Maximum current was 29 amperes. At this level, saturation appears to have barely started. While it is thermally safe to allow higher currents for short times, the saturation curve is unknown. Based upon the data available, it seems that reasonably linear torque vs. current to 40 or 50 amperes is likely.

The current transient is sketched in Figure B-1. It is concluded that the motor transient response is compatible with tape bin storage and fast loop length control within narrow length limits.

TABLE B-1

MOTOR-REEL PARAMETERS

SYMBOL	DESCRIPTION	UNITS	VALUE
k_t	Motor Torque Constant	in lb/amp	4.25
k_B	Motor Back EMF Constant	volt/rad per sec.	0.48
R	Motor Armature Resistance	ohm	0.44
L	Motor Arm. Inductance	henry	0.00975
J_M	Motor Rotor Inertia	in lb sec^2	0.28
J_r	Reel (Full) Inertia	in lb sec^2	.34
J_T	Total Inertia	in lb sec^2	.368
V	Applied Voltage	volts	48
i	Motor Current	amps	--
(t)	Motor Speed	rad/sec	0.0659
t_1	Time to Reach 48 Rad/Sec	sec.	

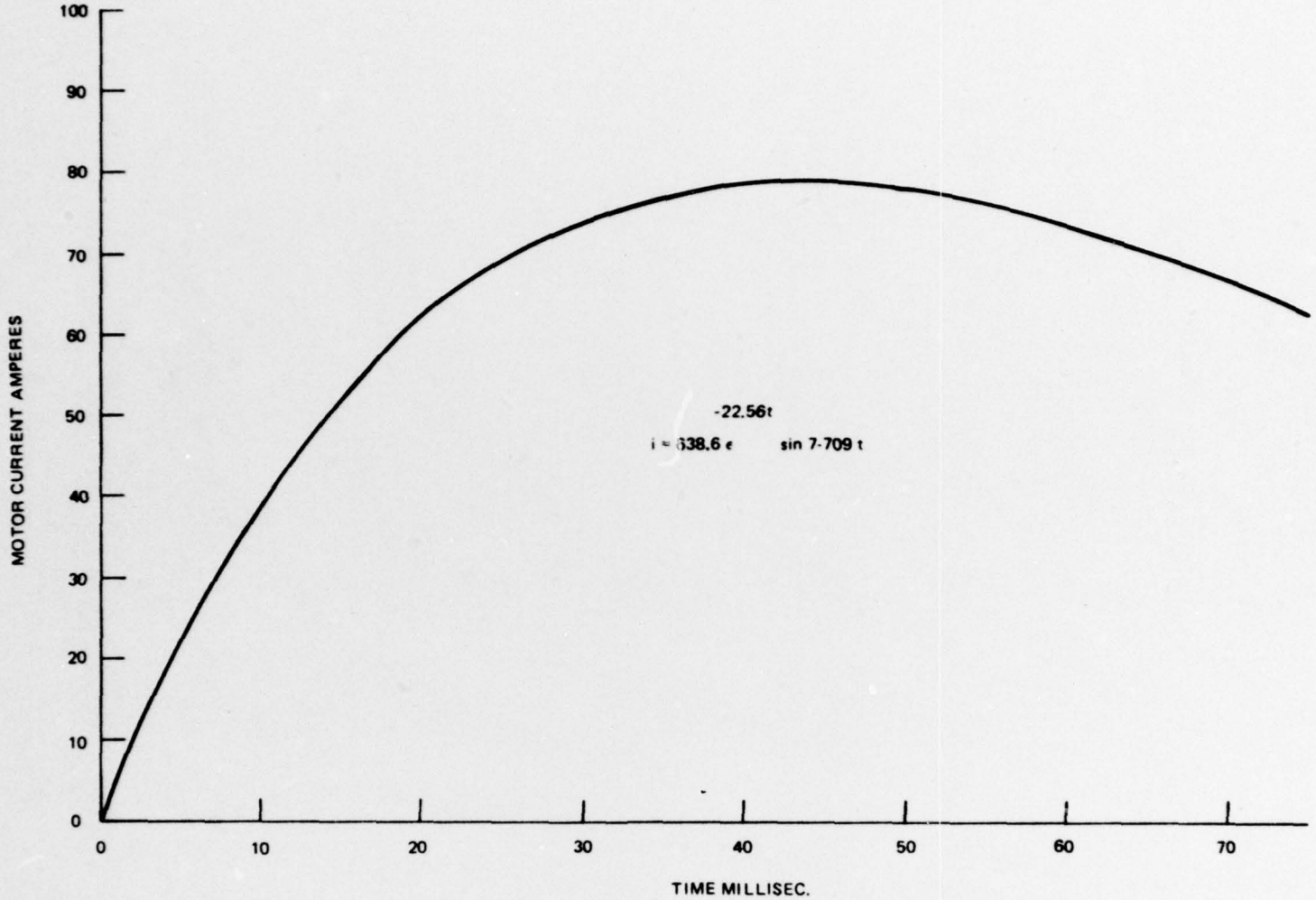

Figure B-1. Calculated Motor Current Transient to Reach 48 RAD/SEC (240 ips) from Standstill