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FINAL REPORT

TAPE/HEAD INTERFACE STUDY

NAS5-26573

PREPARED FOR:

NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION
GODDARD SPACE FLIGHT
CENTER
GREENBELT, MARYLAND 20771

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PREPARED BY:

RCA DIGITAL COMMUNICATIONS
AND RECORDING SYSTEMS

GOVERNMENT COMMUNICATIONS
SYSTEMS

GOVERNMENT SYSTEMS DIVISION
CAMDEN, NEW JERSEY 08102

DATE: May 25, 1983

RCA DOC. NO. 564-727

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SUMMARY

The studies reported on in this Final Report are a result of the combined efforts of NASA, IITRI, and RCA Recording Systems. The overall goal of this study effort was to evaluate and characterize existing high energy tapes, high track density heads, and transport guidance techniques to enable these technologies to be employed in future spacecraft recorders with high confidence.

The results of these study efforts have demonstrated tracking accuracy tape and head density that will support spacecraft recorders with data rates of a minimum of 150 Mbps and storage capacities ranging from 10^{10} to 10^{11} bits.

Description of the work accomplished, study results, and recommendation for further studies are contained in the body of this report. The results and recommendations are summarized here for the readers convenience.

Seven high energy tapes of either 1/4" width, or 1" width, or both, were tested. These are identified as follows.

Type	Width Tested
3M 461 ("Reference tape")	1/4"
Ampex 721	1/4"
Ampex 466	1/4"
3M5198	1/4", 1"
3M973	1"
Fuji H621	1"

All tapes were tested at the same speed (30 ips) and the same packing density (33 KBI). In general, the performance of all 1/4" tapes were similar, and somewhat disappointing. This is believed to have been due to some combination of poor batch control, and some unidentified marginal condition in the 1/4" test setup. The performance of all 1" tapes was considered superior, relative to other comparable test data. Based on overall performance 3M973 was considered the best. Its preference, however should be qualified, pending data on its temperature-coercivity characteristics and its abrasivity.

Recommendations for Future Work

Some recommended future test programs which would be of value to the development of 10^{11} bit storage space recorders are:

1. Complete type testing by IITRI of 3M973, and new high energy tapes which appear subsequently, so that the data is fully correlatable with tape data previously tested by IITRI.

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2. A test program which would be of unique interest to space applications is the measurement of changes in physical and mechanical properties of tape, particularly abrasivity, as a function of increasing the number of passes of the same tape, to a limit of, say, 20,000 passes. This program would best be run by IITRI.

3. A tape guidance study program concentrating on control of 1" wide tape, without edge contact guides, and in the presence of "DC" biasing effects, such as known tape curvature or non-uniform properties of the tape (across its width), or known small misalignments of rollers, which might occur in a space environment. These "DC effects" are cited to distinguish them from cyclic effects which have been studied in the past such as "wobble" of reels. This study could be conducted by IITRI or by RCA.

SECTION 1.0

INTRODUCTION

At the present time spacecraft mounted sensors are being developed whose output rates range from 20 Mbps to 150 Mbps. These sensors require suitable magnetic tape raecorders for delayed data transmission; storage capacities ranging from 10^{10} to 10^{11} bits are required; error rates better than one part per 10^6 bits are also needed. Without additional developmental effort the physical size of the magnetic tape recorders will grow to unacceptable dimensions and weights. Thus, effort is required to increase the packing density of data per volume of magnetic tape that is housed within the magnetic tape recorder. This study program aims to evolve those techniques that currently constitute the high risk technology, so that new magnetic tape recorders can be designed with a high degree of confidence that they will meet the overall mission requirements.

1.1 OBJECTIVES

The objective of this program was to investigate through analysis and test the feasibility of applying current technological advances in the area of magnetic tape, record/reproduce heads, and tape guidance for spacecraft recorders.

In the last five years tapes have been developed for many military and commercial applications. These tapes have not been analyzed for performance in a spacecraft environment, in particular the life of the tape under a high number of tape passes and extended storage conditions.

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The tapes also need to be characterized to their initial and end-of-life performance. New magnetic heads are being developed that have high in-track data density and a high density of the number of tracks across the width of the tape. Again the performance, and in particular the wear rate, of these magnetic heads must be analyzed as applicable to the spacecraft operational conditions. Tape guidance presents a very complex problem which is further complicated by the fact that the width of the tape is increasing. This added stiffness presents new problems. Means must be found that will guide two inch wide tape with a deviation of no more than $\pm$ 0.5 mils. The new guidance techniques must in no way damage the tape or produce debris.

These three key areas are visited in the study and results given in the body of this report.

1.2 Scope of Work

The following constitutes the Scope of Work for this study effort: It includes originally proposed work plus additional efforts added as the program matured. It reflects all work agreed to by the project technical officer.

General - Investigate the field of high energy magnetic tapes and high track density heads. Perform head/tape tests to achieve a head/tape combination which will record and reproduce digital data at a track density of 84 tracks per inch minimum, and an in-track lineal bit density of 35,000 bits per inch, at a bit error rate of 1 X 10^{-6}.

Demonstrate the record/reproduce feasibility at the bit density and

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error rate cited, on sufficient track densities to support a continuous input of a minimum of 150 megabits per second.

Modify a test tape transport for 1 inch wide tape to explore the performance of magnetic tapes which will store date for reproduction at the densities cited.

Investigate a minimum of three tape types, and two head types as specified below:

A. Tape: Explore the field of magnetic tapes, contact tape manufacturers and a tape test laboratory (IITRI) and conduct tests of three selected candidate tapes to evaluate and select the best for the development of high rate recorders. Allow for the cooperative parallel effort of the tape laboratory which will characterize the tapes for magnetics, physical, and chemical properties.

B. Heads: Evaluate and compare high track density record and reproduce heads of different designs and contruction, e.g., ferrite, solid or tipped, and solid hard alloy batch fabricated, using one or more of the tapes under investigation.

C. Head/Tape Guidance: Evaluate the tape guidance for high density tape operating conditions. Measure the maximum tape motion irregularities, tracking and skew to determine an overall system performance for a 150 Mbs tape recorder requirement.

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1.3 Additional Work Performance

Additional work performance which was not originally proposed included the following:

1. Construction of electronics suitable for encoding and decoding digital signals to allow actual bit error measurement to be taken on candidate heads and tape.

2. Modification of a 1/4" STR Tape Transport and electronics to provide up front sample testing on candidate tapes prior to completion of 1" test bed.

3. Inclusion of three additional tape types for evaluation.

4. Error correlation studies on a sample tape.

5. Supplied a 42 track partially populated HDMR Head to IITRI for correlation studies.

6. Sample testing at 34 and 45 Kbpi on highest performing tapes.

SECTION 2.0

TECHNICAL APPROACH AND RESULTS

The investigation of the magnetic heads, tape, and guidance proceeded experimentally and theoretically. The experimental work was based on a transport similar to that used for the ERTS Recorder System. This transport contains negator-coupled reels and thus will reflect a realistic bound that might be placed on the spaceborne hardware. The experimental transport unit was modified to accommodate the 1" wide tape which formed the basis of the experimental work. Initial tape testing was accomplished using an unmodified STR Tape Transport. This approach allowed up front sample testing of candidate tapes while the 1" mod's were completed. All aspects of the work considered the requirement of spaceborne hardware; i.e., a limited range of ambient temperatures and the requirement to survive a rather rigid launch environment.

Candidate tapes were selected from two sources, RCA's High Density Digital Recording Base and IITRI's listing of candidate tapes. Initial listing of tapes were considered but as the program progressed, other tapes were considered and added to the test program.

The magnetic head selection was reduced to the RCA High Density Multi Track HDMR Head which has a proven track record on both space and ground based Recording Systems.

The organization of this section will include the Objectives of the study item followed by background material, description of the Test

Program, test results, and conclusions.

Portion of the study material were in fact gathered as part of the pre-study effort and are included here for completeness.

2.1 Magnetic Tape Study

2.1.1 Tape Study Objectives and Background

The objective of the Tape Study effort is to identify candidate tape types which will support space recording systems with data rates of 150 Mbps minimum and densities of 10^{10} to 10^{11} bits. Additional to fully characterize these tapes in such a manne. that an independent contractor could provide tape certification and screening for recorder manufacturer: on subsequent space projects. To this end an attempt is made to provide sufficient data and support to allow correlation of results with IITRI.

Background

In the development of spaceborne magnetic tape recorders, the tape itself represents the one single component that receives an inordinate amount of attention. Its magnetic properties are important so that data can be recorded, reproduced, and erased in the most advantageous manner. The data must not be weakened by applying excessive stresses to the magnetic medium. Most of these parameters are a function of the temperature at which these processes occur.

The physical parameters are of no less concern. Oxide surface imperfections; i.e., nodules, cause the tape to life off the head

and thus cause "tape dropouts". The tape surface must have the correct smoothness and lubricating properties to maximize the life of the magnetic head. The entire tape, i.e., oxide, base material and backing must be guided with high precision over the full environmental and life requirements. This guidance must be accomplished without exceeding the NASA stress guidelines, without generating debris or causing other deleterious affects.

Tape storage, prior to use or in the recorder, also requires attention to environment, especially humidity, to assure that a successful mission is feasible.

Tape Properties

Magnetic Characteristics

Published magnetic properties which can serve as an aid in the selection of a magnetic tape are the intrinsic coercivity (H_C) and the remanant magnetization (B_r). These tape parameters are obtained from the B-H hysteresis loop of each particular tape. Values of H_C and B_r are used commonly as a quick appraisal of expected playback results. In particular, the coercivity (H_C) is referred to alone when B_r is similar between tape types. The higher values of H_C usually indicate tapes with improved short record wavelength resolution resulting in better SNR for High Density Recording applications.

A more accurate way to predict or compare tape performance is to evaluate the B-H or hysteresis squareness ratio. The squareness ratio is not normally included in published tape data, although tape

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manufacturers use it as a measure of magnetic efficiency. A square B-H loop indicates that the tape retains its saturation level ($B_r = B_{max}$) after the magnetizing field (H_C) is removed. The squarer the loop, the greater the signal output will be during playback. The squareness ratio is defined as the ratio of remanent flux to saturation flux $\frac{(B_r)}{(B_{max})}$.

Values will approach unity as quality goes up.

Tape Chemical Characteristics

The elements of tape which are important to this program are the oxide particles, binder systems, substrate film, and the back coating.

Oxide Particles

Magnetic recording tapes are made with magnetically aligned particles of gamma ferric oxide ($\sqrt{}$-FE$_2$O$_3$), cobalt modified gamma feric oxide CO-$\sqrt{}$-Fe$_2$O$_3$, chromium dioxide C_rO_2, and pure F_e (iron) particles.

Gamma Ferric Oxide ($\sqrt{}$-Fe$_2$O$_3$)

The maximum coercivity obtainable with straight gamma ferric oxide ($\sqrt{}$-Fe$_2$O$_3$) approaches 340 oersteds and is considered a low energy tape. In narrow track recording this particle has fallen from use because of low SNR at the high bit densities.

Cobalt Doped Gamma Ferric Oxide (CO-γ Fe$_2$O$_3$)

The magnetics orientation of tape particles is determined by particle shape anisotropy and crystalline anisotrophy. (Anisotropy is the ability of tape particles to resist switching of polarity under the influence of a magnetic field). It's desirable that the controlling anisotropy be so oriented that after saturation, a minimum magnetization change occurs as the tape moves away from the gap. Normal Gamma Ferric Oxide (O_e = 310) is both shape and crystalline anisotropic. By "doping" the particles with cobalt, the crystalline anisotropy is greatly increased, resulting in coercivities upward towards 100O_e. Just as important, the diffused cobalt narrows the range of coercivity in which most particles switch as shown in Figure 2.1. With a narrow sensitivity to a magnetizing switching field, a greater number of particles will be involved in each recorded field transition which allows for improved record resolution and a resulting increase in playback performance.

Of the two methods of cobalt doping, surface doping and full doping, surface doping is best in that it increases the short wavelength record resolution and at the same time reduces self-demagnetization characteristics of the tape. With this method of cobalt diffusion a very minimal amount of low temperature coercivity differential will exist which has been a problem in the past with some C$_0$ doped tapes.

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Chromium Dioxide

This oxide provides another type of high energy tape. The intrinsic coercivity of this oxide is 600 oersteds. It does not have the problem at low temperatures as does the C_0 doped tape but does have a history of high abrasivity with certain manufacturers. Recent tapes are much improved in this regard and now compete well with gamma ferric oxide. SNR performance and particles dispersion is similar to CO Fe_2O_3 formulations.

Iron Particle

This magnetic surface is generated by using very small particles of iron providing extremely high coercivity upwards to 5000 O_e. Tapes made with this material have coercivity around 1000 and has had its main impact in the audio cassette community providing extended dynamic range over oxide tapes. For instrumentation recorder purposes, it has remained in the experimental stage showing a potential of improved SNR but somewhat poorer dropout characteristics compared to other tapes.

Binders

Hydroscopic Properties of the Binder Systems

The binders used with magnetic oxides is organic in nature and is hydroscopic i.e., it is constantly absorbing and desorbing atmospheric moisture as a function of relative humidity. The presence of moisture in the binder has been shown by studies performed on RCA projects to be an important environmental factor in many head-tape interface problems such as head wear, friction
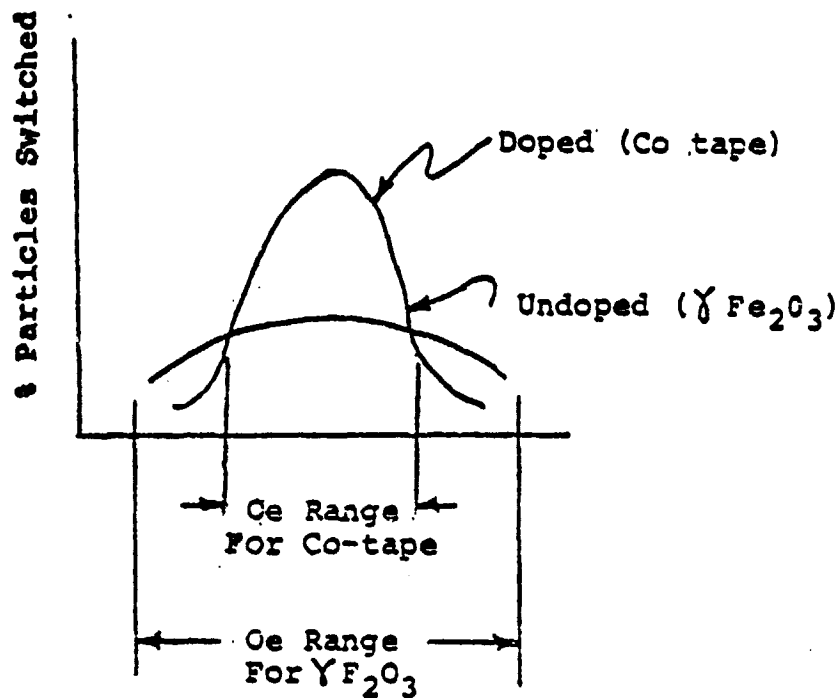
SWITCHING DISTRIBUTION OF DOPED &

UNDOPED Fe₂O₃ PARTICLES

FIGURE 2.1

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staining, tape shed, and generation of loose oxide. RCA is very familiar with tape operated in hermetically sealed cases and also realizes that operation or testing in free circulating air environment will not be demonstrative of flight head and/or tape life characteristics.

Tape Aging

In space recorder applications, due to the extended time demands of long missions, tape aging must be kept to a minimum. Tape aging is caused by a mechanism of oxide binder breakdown known as "Hydrolysis" which is a chemical reaction involving absorbed water. This reaction is a function of the temperature and the relative humidity in which the tape resides. The most serious result of such an aging process is the slow destruction of the binder system, giving rise to an increase of loose tape oxide and resultant dropout errors.

Substrate Film and Back Coating

Magnetic recording tape is constructed having a magnetic coating on a plastic substrate, usually poly(ethylene terephthalate) film (polyester). For some tapes an additional back-coating is added which is intended as a conductive path to drain off static electricity. The tape involved in this study is to be polyester as provided by the manufacturer.

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Mechanical Characteristics

Surface Finish

Many of the tape candidates for this study were originally developed for VHS applications where narrow tracks are already utilized. On RCA VHS programs it was found that a shiny surface finish is demonstrative of a good dropout profile where narrow tracks are used. A very shiny finish may fill the requirement of low dropouts on VHS system where there is air film lubrication between helical drum and tape, but it may cause problems such as "stick slip" on large contacting surfaces such as instrumentation heads. RCA has minimized this problem by the use of the comb structure HDMR head design where the area of contact is kept to a minimum.

Abrasivity

Tape abrasivity studies have been going on for years with no single definitive method for measuring tape abrasivity to fit all applications. It is widely felt, however, that a test involving the actual set of conditions, heads, tape, etc. is the only way to create an accurate abrasivity figure. This figure of merit is described in microinches of head wear per hour.

Dimensional Accuracy

Dimensional accuracy is a key factor when addressing and studying tape guidance. Tolerances on the candidate tape width is published at $\pm$ .001 inches. It has been found, however, that tapes can be culled and categorized to tighter tolerance

less than .001: allowing for still more tracking accuracy.

Candidate Tapes

The candidate tapes in Table 2.1 were selected based on (A) recommendations of IITRI, derived from their testing, and (B) recommendation of RCA based on testing and experiences on space and internal research and development programs.

TYPES	MAGNETIC COATING	THICKNESS MILS	WIDTH
3M 461	CD Fe_2O_3	1.10	1/4"
Ampex 593(721)	CA Fe_2O_3	1.14	1/4"
Ampex 466	CA Fe_2O_3	1.15	1/4"
3M 5198	CO Fe_2O_3	1.04	1/4"
1) 3M 973	CA Fe_2O_3	1.13	1"
3M 5198	CA Fe_2O_3	1.04	1"
1) Fuji H621	CA FE_2O_3	1.08	1"

NOTE 1) 3M 973 and Fuji H621 were additional tapes tested as they became candidte tapes later in the program. Performance results from other RCA and IITRI tests provided inputs that encouraged their selection.

NOTE 2) CD represents Cobalt - doped Fe_2O_3

CA represents Cobalt - absorbed Fe_2O_3

Tapes tested in the program.

TABLE 2.1

2.1.2 Tape Test Program - Magnetic Tapes

The tape test program was configured into two parts. 1) Initial tape sample testing using a STR 1/4" Tape Transport. This test was used to evaluate 4 tape types and selected the best candidate for later testing on a 1" test unit used for guidance studies (see Section 2.3). 2) Final testing was accomplished on a 1" Test Bed. Additional tape samples were subsequently tested using the 1" Test Bed as a vehicle.

It is important to point out that in both cases the Transports used were chosen because of their availability and were used only to facilitate these test and investigations. They are not necessarily RCA's choice for a transport design as that was not the intent of this program.

The following paragraphs describe the Test Beds and electronics used during this study effort.

Quarter Inch Transport

Description

The quarter-inch transport is a Landsat/STR Engineering Model which has coaxial reels that are negator spring tensioned, a single capstan and a tape load of approximately 500 feet. At the 30 ips tape speed to be used in these tests, this tape load results in a recording time of over 3 minutes. (See Figure 2.2)

Preparation

Mechanical and electrical modifications were performed on the STR in order to replace the standard magnetic head with the selected high
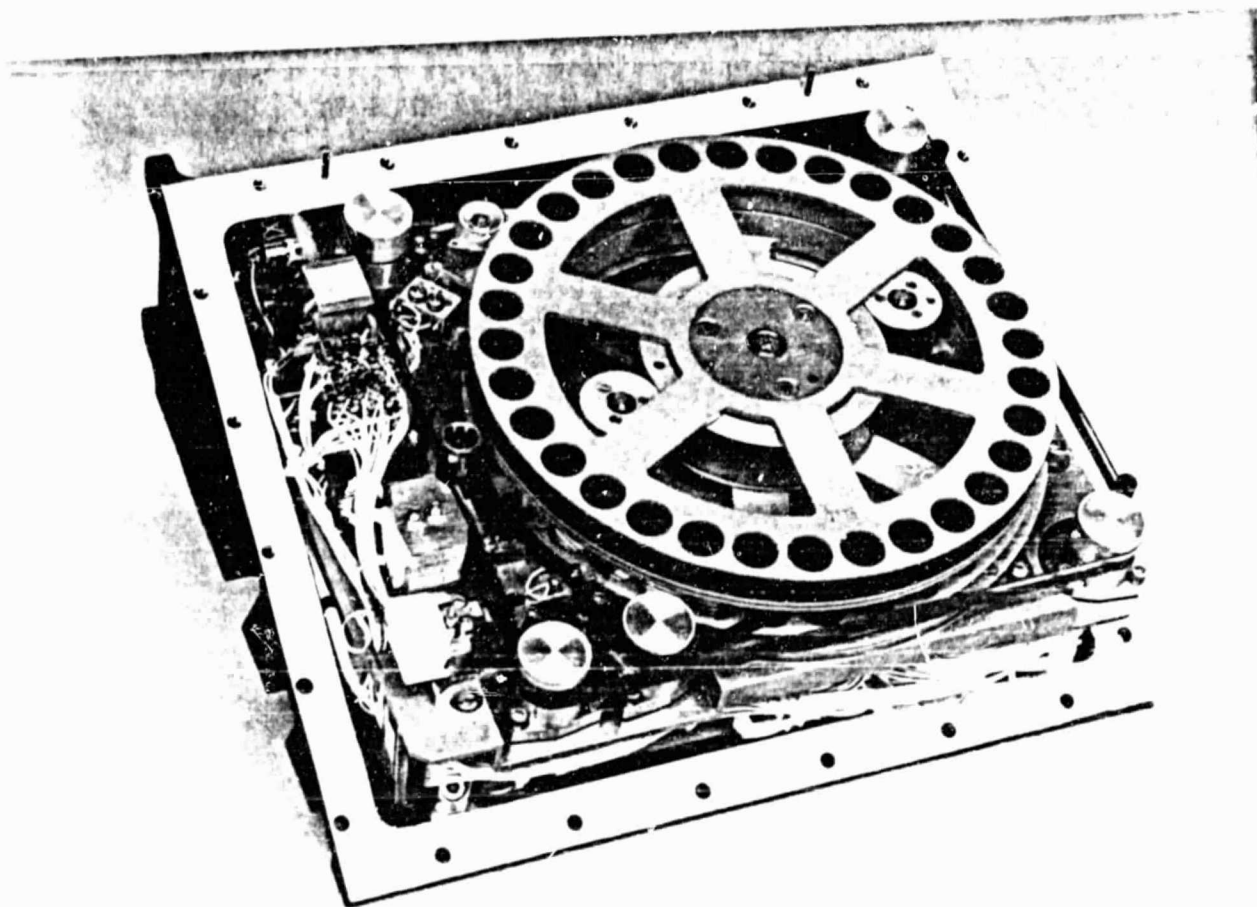
19

FIGURE 2.2

STR 1/4" Transport Test Bed

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density test head, the capstan drive for the correct tape speed and the record head driver, for the appropriate Record Equalized pulse width. The remainder of the record and playback ..lectronics were separate and are described in a later paragraph.

Standard STR alignments to establish tape guidance were made after tape load changes. In addition, a preliminary tape tension measurement was made from end to end in the head space area. See Tension graph. Figure 2.3

One Inch Transport

Description

The one-inch test vehicle is a breadboard transport similar to the ERTS/Landsat Recorder, but which incorporated a new deck and tape path (figure 2.4). It includes ERTS flangeless reels which are torqued by multiple negator springs in order to double the original ERTS tape tension, raising it to an average level of 18 oz. Special 1-inch edge-crowned roller guides replaced the previous edge and face guiding rollers. A double (steel) capstan drive assembly, belt coupled to a single capstan motor, was also added. The urethane tape pack rollers were retained to maintain tape pack integrity. A precision adjustable assembly is used to facilitate positioning the magnetic head. The magnetic head is secured to a head mount plate that is dove tailed to the micrometer adjustable support. This allows the head to be positioned accurately and to be removed for inspection and measurement without disturbing the head position settings. Comprehensive tension measurements were made on this transport, and they are discussed in detail in paragraph 2.3.3.
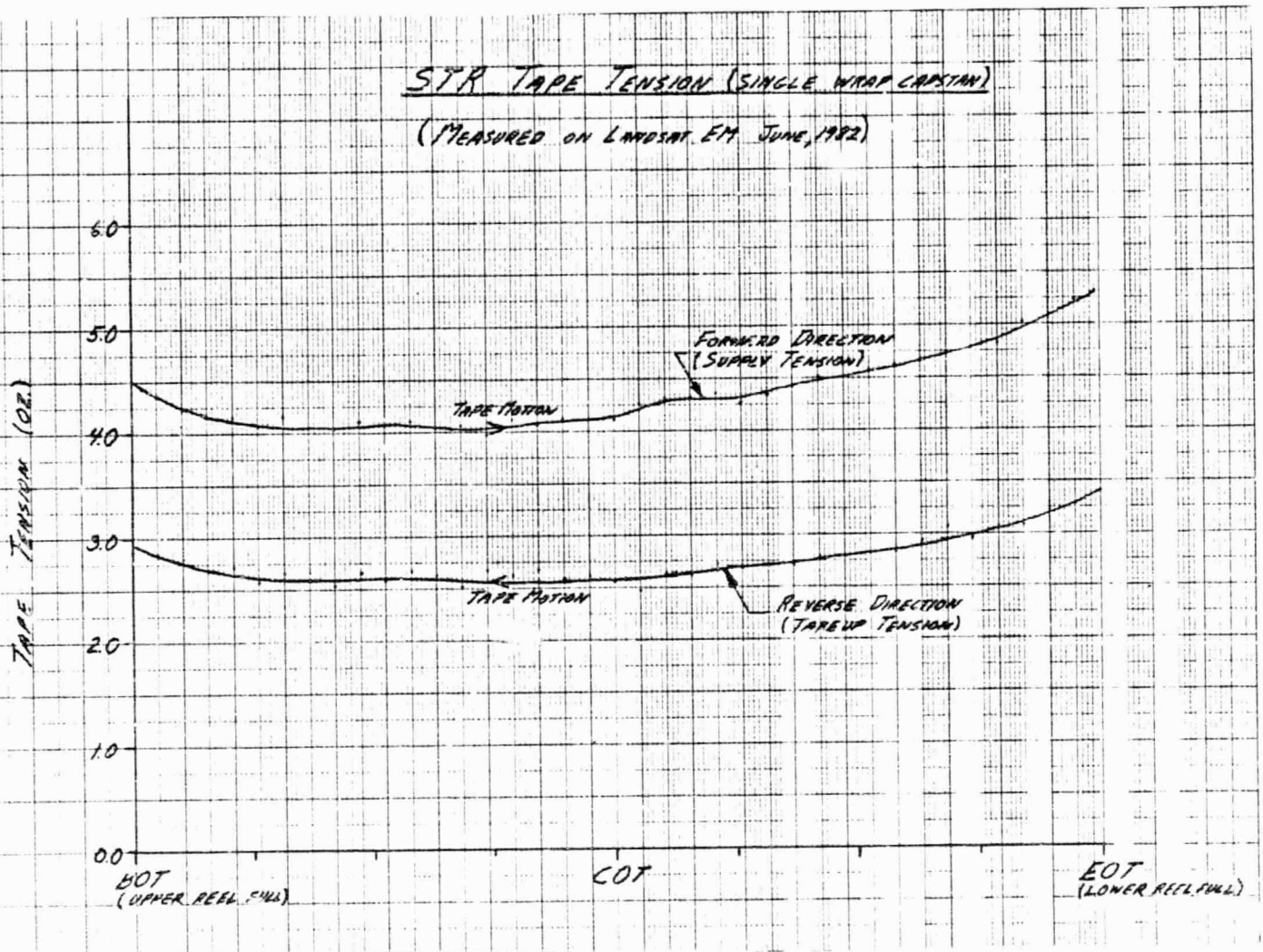
Figure 2.3
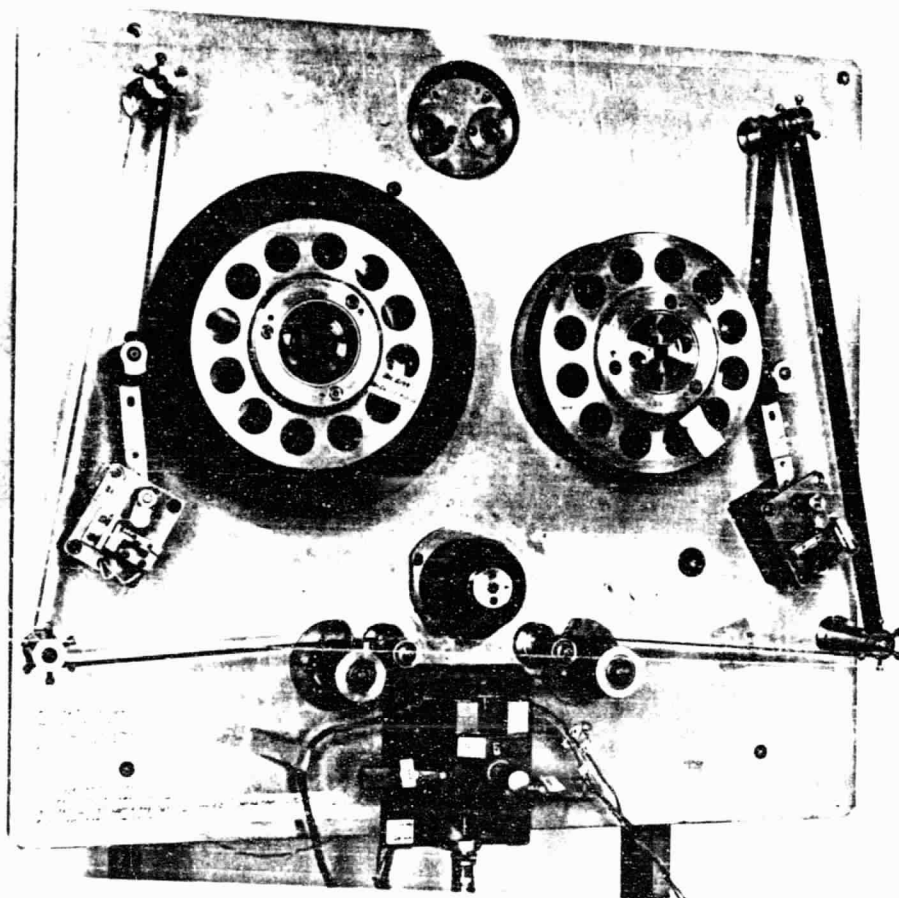
STR TAPE TENSION PROFILE

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Figure 2.4

1" Tape Transport

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Tape Test

Description of Test Electronics

Record - See Block Diagram Figure 2.5

A test oscillator (2.04 MHz) serves as the source for 2X Clock, the primary reference for the generation of data for recording. At the Delay Modulation Encoder, the 2.04 MHz is divided by 2 to become the Data Clock which drives the Word generator (Tautron MBG-1) for the generation of the required NRZ data patterns. In this tape testing, two data patterns are used:

- All 1's pattern - Used in the measurement of the signal to noise ratio.

- 511 bit pseudo random pattern - Used in the measurement of the bit error rate.

The NRZ data is then DM encoded and sent to the Record Equalizer where the data transitions are separated, positive going from negative going and transformed into unipolarity narrow pulses approximately 100 ns wide. The positive and negative edge pulses are then sent to their respective inputs of a balanced head driver circuit. The output is connected in a push-push arrangement with the magnetic head so that bi-directional record currents can be generated from a single voltage power source.

Playback

During playback, the transfer relay switches the magnetic head from the record amplifier to the playback preamplifier. The input of

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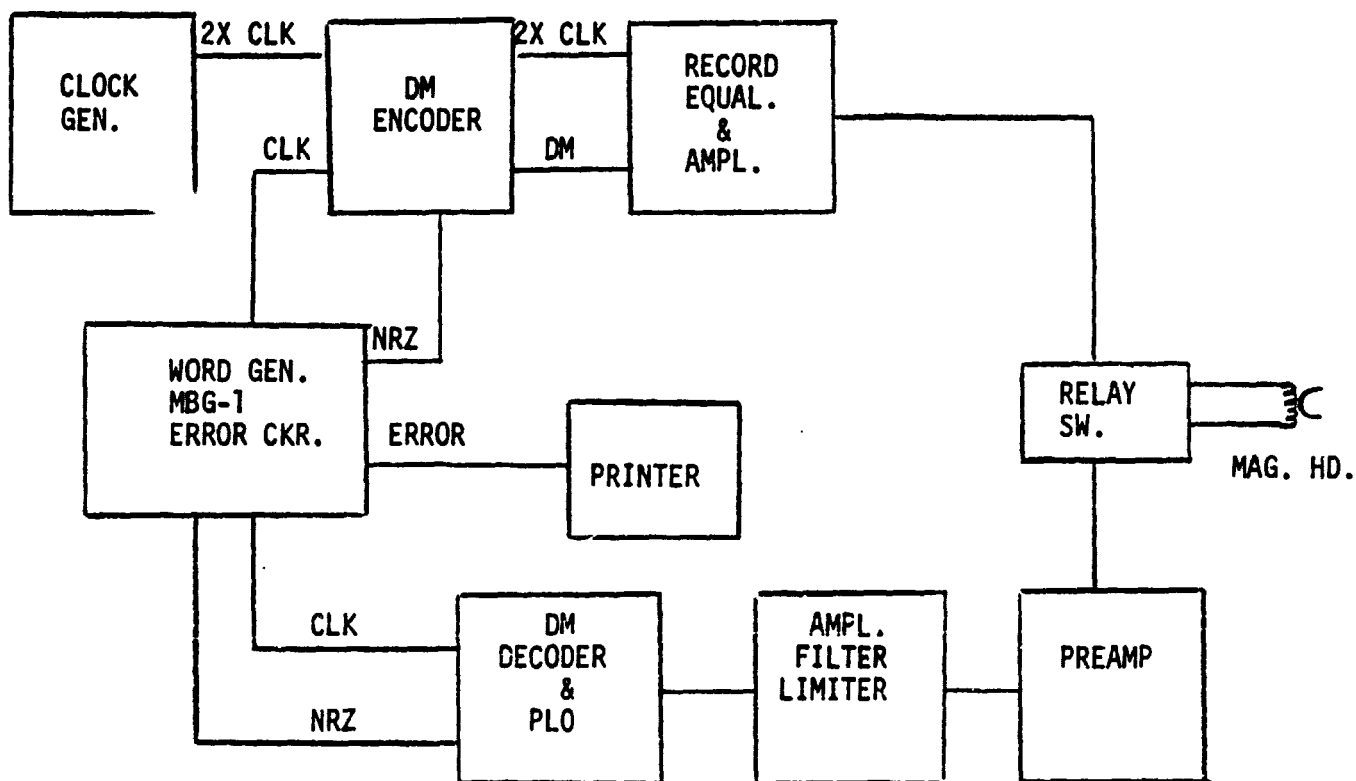
Block Diagram - Test Electronics

Figure 2.5

the preamplifier consists of a step up transformer and a dual FET cascode amplifier. The transformer provides an impedance match between the magnetic head and FET input. After further amplification, the playback signal is low-passed filtered (2 pole RC at 10 and 15 MHz) and then limited to remove amplitude variations. The signal is then sent to the Decoder where zero-crossing information is extracted to lock oscillator running at the 2X CLOCK rate. The PLO output clock is used to strobe and decode the DM data into the original NRZ form. The NRZ data and associated clock is then returned to the Error Checker (Tautron MBG-1) for a bit for bit comparison.

Adaptation of Electronics

All of the circuits described and used in these tests were originally designed for use in a variety of prior recording systems which shared the same recording technique, DM encoded and Record Equalization. They were also designed to operate at higher data rates. The adaptation of these circuits for operation at 1 Mbps generally entailed lowering bandwidths, lowering filter cutoff and PLO center frequencies and adjustments in timing and delays. In all of these areas the modifications were straight forward. In the area of magnetic head coupling or matching to the preamp, additional changes were required. As stated before, impedance matching of the magnetic head to the preamp is controlled by the input transformer. With a lower data rate it was expected that a higher step up ratio would be needed. Using the present transformer toroid core it was found that a maximum ratio of 20:1

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could not be easily exceeded without changing the winding geometry. With such a transformer in place, front end resonance was found to be approximately 1.1 MHz. In addition to the head inductance and transformer parameters, resonance is also influenced by the amount of stray capacity or degree of shielding of the head leads which was not finalized at this point. The 1.1 MHz resonance, conservatively located to minimize phase-shift problems, was judged adequate for tape testing and did not warrant iterative fine-tuning the front end. The first running tests on a 3M 461 setup tape yielded signal to noise ratios of 27-28 dB. Optimum placement of front end resonance would increase that by 2-3 dB.

Another problem in this same area was detected when viewing the composite waveforms of the playback signal. It was noticed that certain waveforms had an obvious assymetry about the zero axis. This distortion was also evident as a left-right assymetry on an isolated transition pulse recording. An isolated pulse is obtained by decreasing the data rate so that any given transition pulse recorded is completely isolated from the preceding and following transition pulses. An amplitude and phase sweep of the head and preamp combination showed poor low frequency (200 KHz and lower) amplitude and phase response. The most expeditious correction was to add some low frequency equalization in the preamp. This was done in preference to making changes in the magnetic head and/or input transformer. Only a partial correction was performed to remove the worse of the distortion since the low frequency boost was accomplished at the expense of overall gain. The approach

for a final design would be to optimize the head toroid and input transformers.

Figures 2.6 and 2.7 are of the complete test setup constructed for these tape tests.

2.1.3 Test Procedures - Tape

A cleaning and burnishing scenario was established based on the initial results of testing needed to bring the 1/4" STR Transport up to speed. Specifically after each new tape was loaded onto the transport 600 passes on the cycler with a cleaning wiper in contact with oxide side of the tape established as a minimum cleaning/burnishing operation before final data was taken on each of the tape samples. Cleaning pads were kept on board and used continually during the test runs. (Note: STR standard practice is 500 passes for burnishing and cleaning on flight tapes).

For each of the tape samples, short recordings, approximately 30 seconds long, were made with different record currents to determine the optimum record current for best BER and SNR. This optimum record current (minimum BER) is then used to record the entire tape length sampie (approximately 3 minutes long) to generate the BER data for the tape under test. This burnishing and Data Recording scenario was used with both the 1/4" and 1" Tape Test Vehicles.

Interpretation of BER Data

The BER data presented in this report consists of a BER Optimization curve, i.e., the BER as a function of record current using relatively short (approximately 30 seconds) segment recordings and a Tape Scan
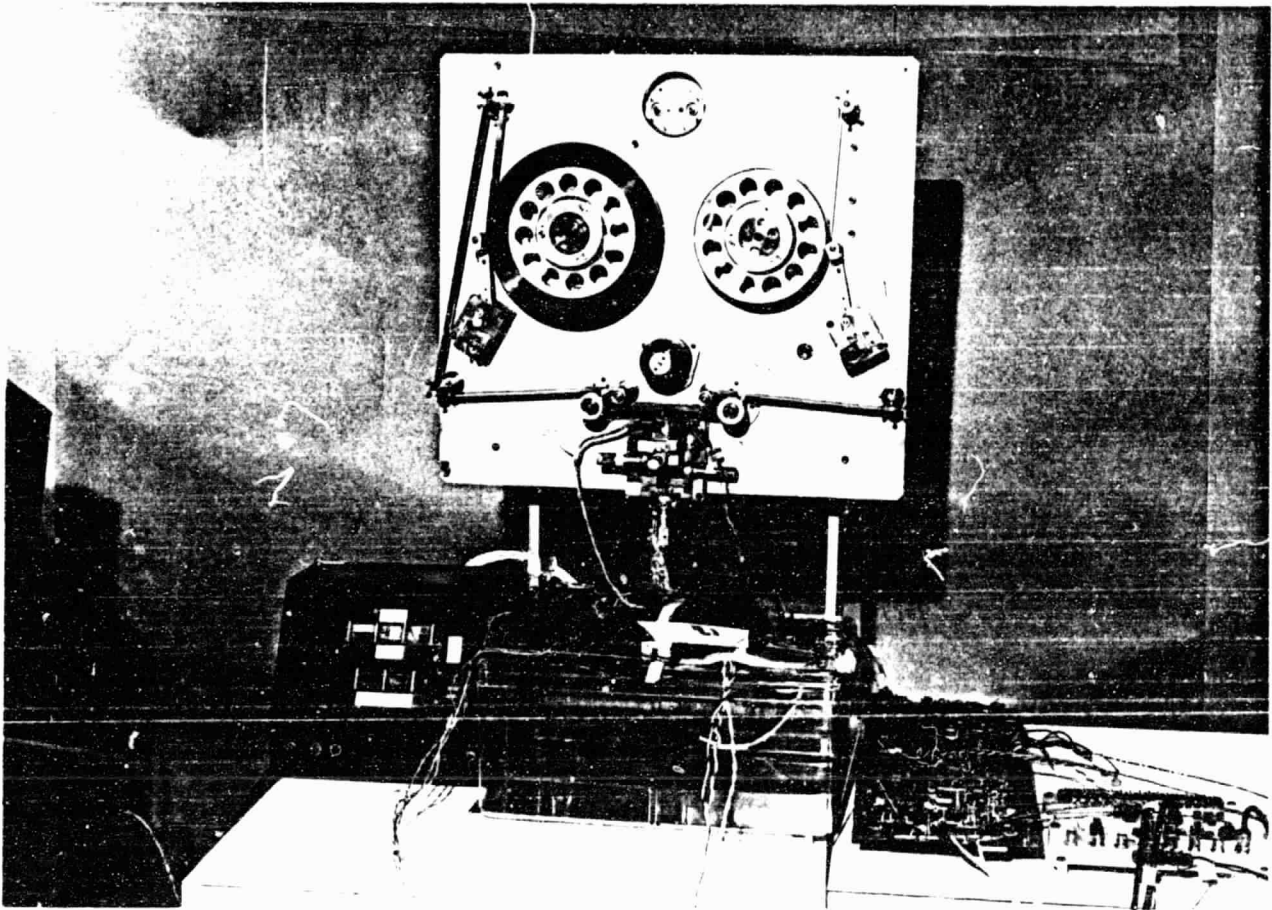
Figure 2.6

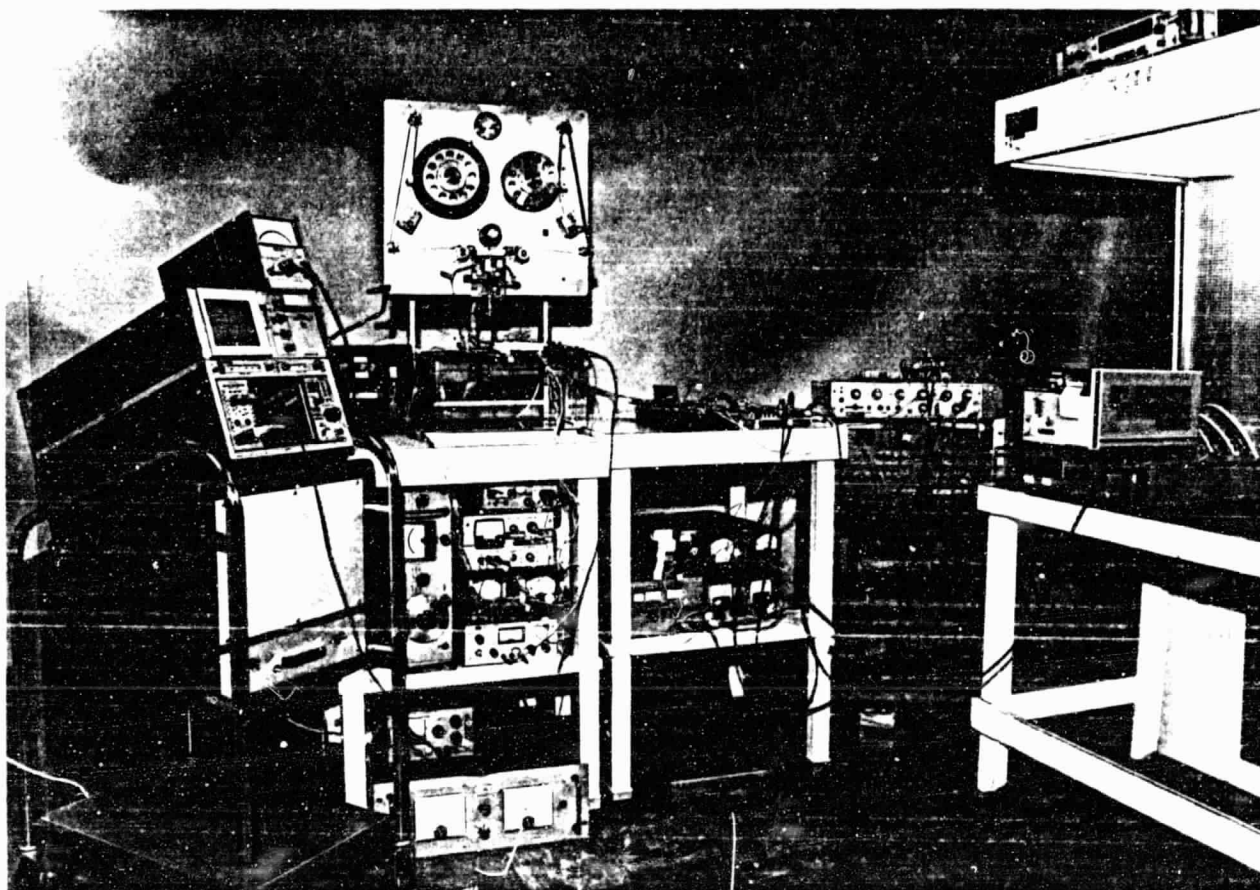Test Record/Play Electronics Transport

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Figure 2.7

Complete 1" Test Setup and Instrumentation

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BER which is the performance of the full test length of tape at the optimum record current as determined by the BER Optimization Curve, shown typically in Figure 2.8.

The BER curve describes the two regions of operation that affect the accuracy of a digital recording. The left or low record current side is the region of SNR limitations. Signal levels change significantly with record current and higher currents tend to diminish the degree of signal loss on minor head-tape separations caused by dropouts. The right or high record current side is the region of record demagnetization where high frequency loss and intersymbol interference is increasing. Whereas the shape and position of the BER curve are a measure of tape parameters such as the BH energy product and surface conditions, it is also measuring the tape handling system for tension and tracking and the magnetic head performance. Tape tests, therefore, involve running a variety of tapes under the same conditions so that the influence of the tape handling system and magnetic head is identical and the resultant test differences are primarily due to the tapes.

BER values outside of a certain range (10^{-5}, to 10^{-7}) are difficult to handle. Very poor error rates are generally associated with lack of repeatability and correlation and vary significantly from run to run. On poor signals, the detection system can be a factor in the number of errors indicated. Amplitude modulation from variations in head-tape contact of signals cause an expansion and contraction of errors because of the V-shaped sides of the signal loss during a dropout. Severe dropouts also cause the PLO to lose sync with the data and continuous errors are generated until relock occurs. The error checker, if it
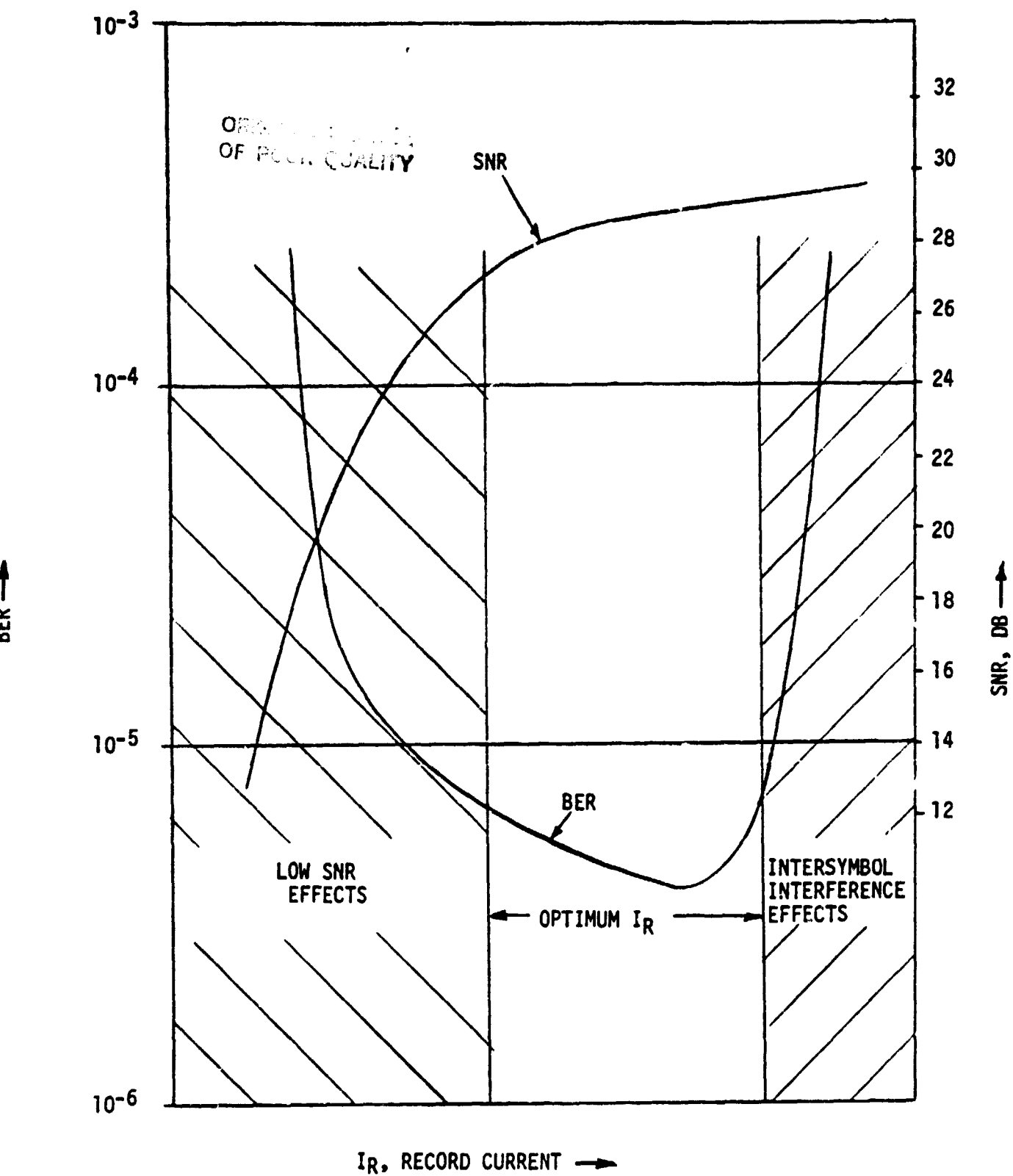
31

Figure 2.8

Typical BER Optimization Current

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loses word sync with the playback data will automatically resync itself but will cause a slight distortion in the error rate while performing this operation. On the other hand, if the error rate is very good, a minimum of several hundred million data bits have to be sampled to even indicate an error rate in the 10^{-9} range. At 1 Mbps, a tape length run of 8 minutes is necessary for this much data. Test tape lengths on both the 1/4 and 1 inch transports were less than 3 minutes long. Therefore, a run of zero errors would only indicate some error rate better than 5 x 10^{-9}. Also very good error rate performance tends to wash out subtle tape differences.

The BER performance for each tape was recorded on a paper tape as the number of errors occurring in successive 1 second intervals.

2.1.4 Test Results - Quarter-Inch Tapes

The quarter-inch tape test results are summarized in Table 2.3. This data attributes the best 1/4" tape BER performance to 3M 461, however, the BER difference between the four tapes tested is not very large. The 3M 5198 required the highest record current, suggesting a higher average Hc. This appears to be substantiated by the manufacturer's data on magnetic properties (Table 2.2). This type of comparative listing, however, should be subject to some qualification. When comparing different tapes, the published values probably show the relative standings more rigorously when the tapes are from the same manufacturer than would be the case for different manufacturers (who may have differing techniques).

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Table 2.2

MAGNETIC PROPERTIES OF TAPES TESTED*

TYPE	H_coe	B_R, gauss
3M 461	500	1350
A 593 (721)	650	1000
A 466	650	1000
3M 5198	700	1350
3M 973	740	1200
Fuji H621	660	1200

*Manufacturer's Specifications

Table 2.3

SUMMARY OF PERFORMANCE

1/4" TAPES

34 Kbpi

Tape	Rec. Current, Ma	SNR, dB	*BERx10^{-6}
3M 461	10	26.2	36
A593 (721)	13	28.0	68
A466	13	28.1	115
3M 5198	15	29.7	80

*Full length error rate performance includes all errors.

In the category of oxide shedding, the two tapes from Ampex continued to leave substantial oxide deposits on the cleaning wipers long after the burnishing and cleaning cycle. Ampex 593 left the heaviest accumulation after the cleaning cycle and Ampex 466 was still losing significant oxide after 820 passes. 3M 461 caused the least accumulation of oxide, while 3M 5198 fell somewhere in the middle of these extremes. The Ampex tapes, (or at least this batch), according to IITRI had poor oxide adhesion and physical durability. There was no quantitative measurement of oxide shedding in these tests and the comments are based on subjective visual observations of the cleaning wipers.

The summary results for the tapes tested on the 1/4" test bed are compiled in Figures 2.9 to 2.12. These display both the optimization run to determine the operating point and the corresponding signal to noise measurement. The "Full Length Error Rate Performance" at the optimum record current setting is given in Table 2.3.
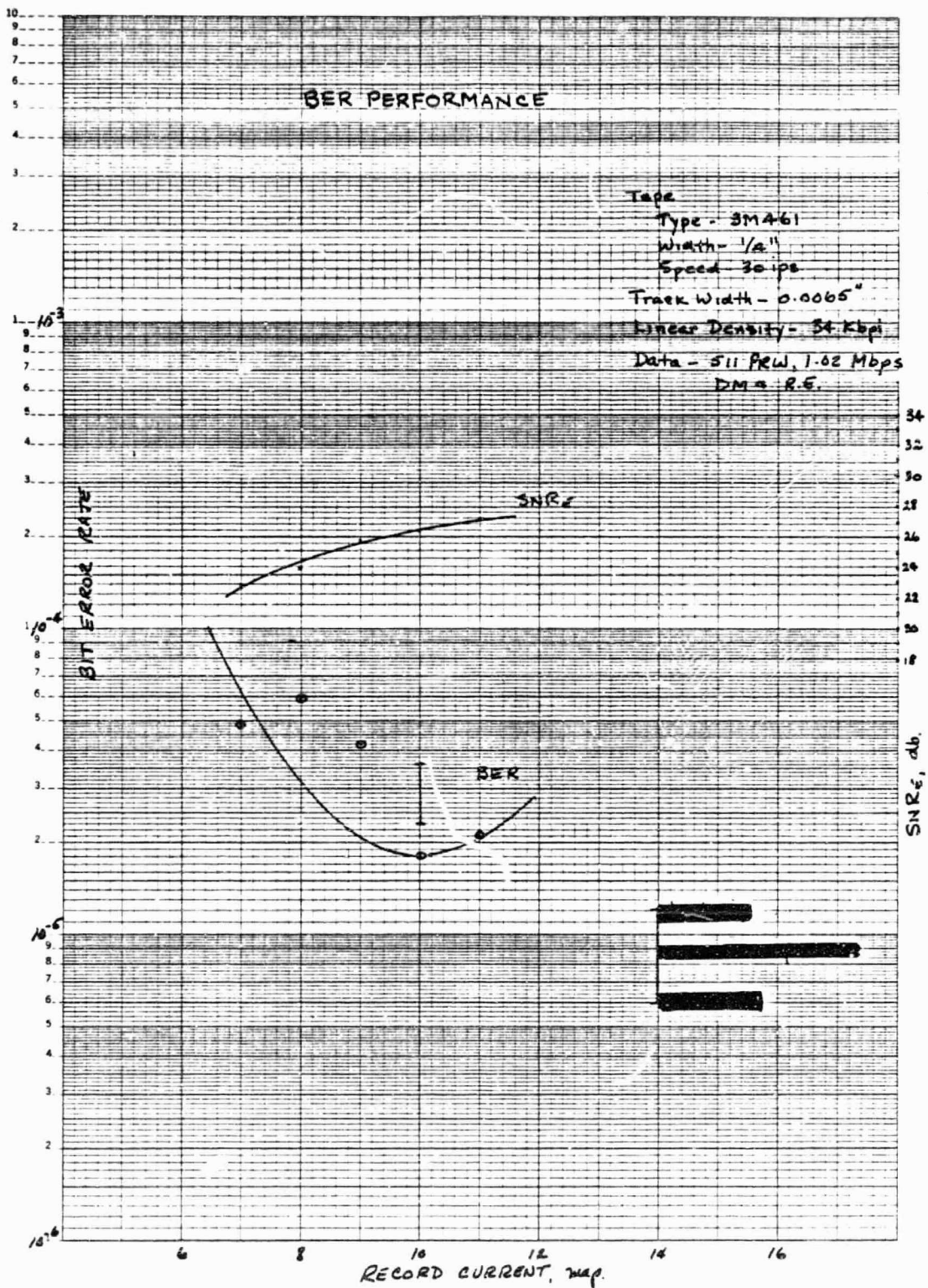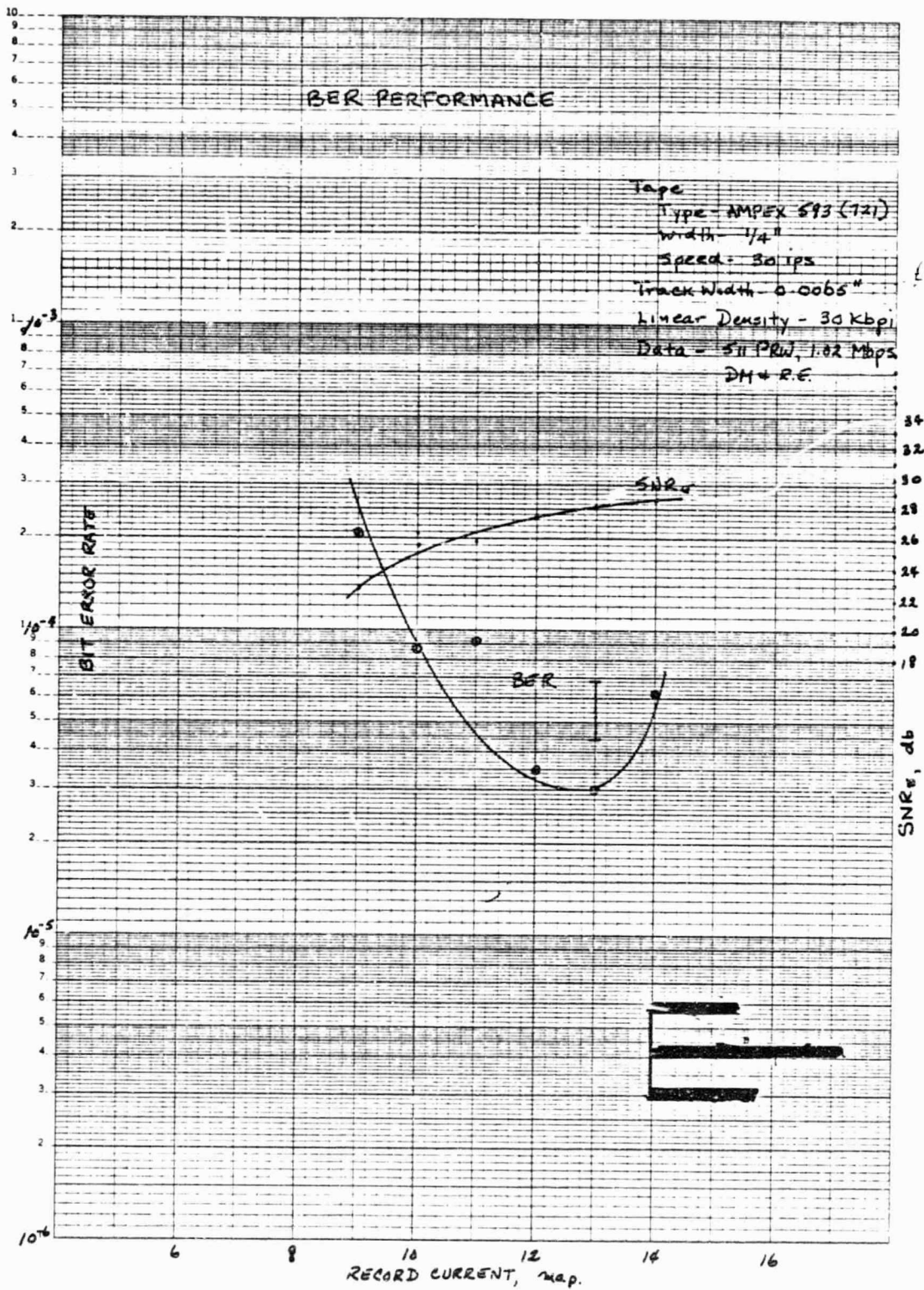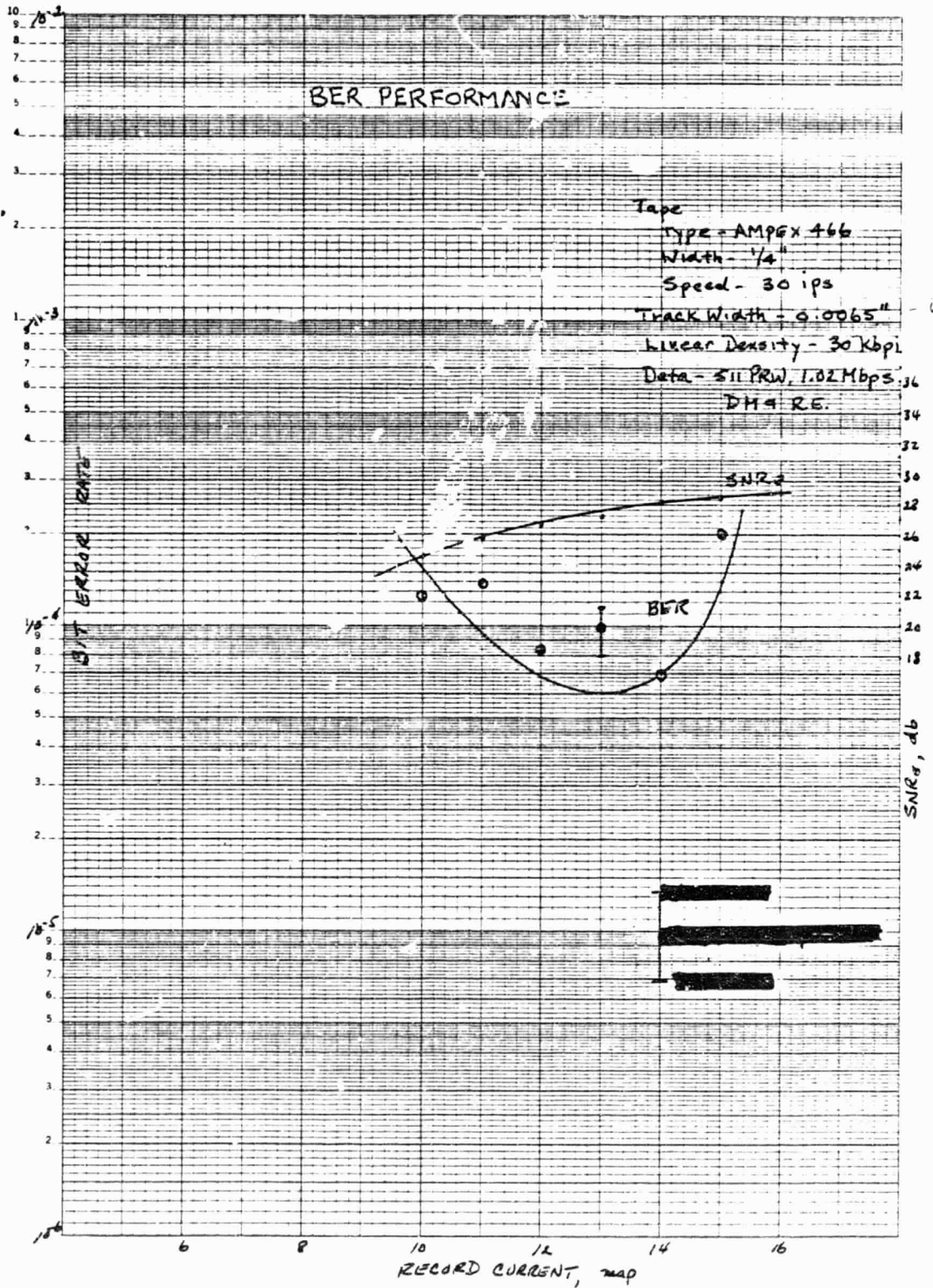
Figure 2.9 - 3M 461

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Figure 2.10 - Ampex 593
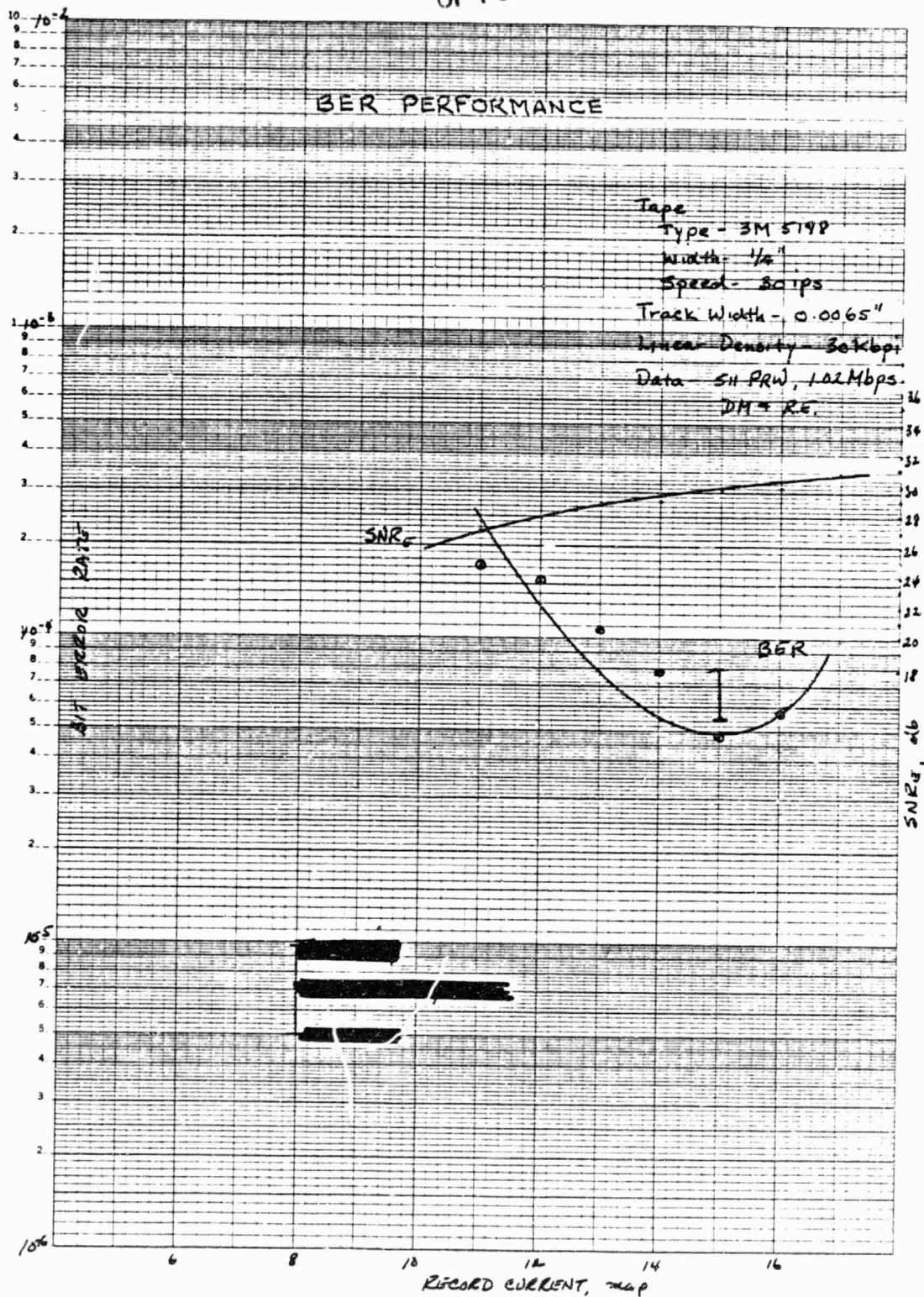
38

Figure 2.11 - Ampex 466

Figure 2.12 - 3M 5198

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2.1.5 One-Inch Tapes

Two samples of one-inch tapes were tested, a 3M 973 and a 3M 5198. See
Table 2.4. The best performance was obtained from 3M 973 with a lower
BER, a higher SNR and a lower record current requirement. It was also
the better of the two in the category of oxide shedding.

An evaluation of the burnishing and cleaning operation was perfomed
while testing the 3M 5198. Record current was held constant and cycling
was extended out to 15 hours (300 passes). Performance was sampled
several times during the 15 hours to measure the progress of the
operation. The initial and final performance data is given in Table
2.5.

Contrary to the results seen in the quarter-inch tapes, very little
improvement in overall BER performance was accomplished by burnishing
and cleaning 3M 5198 even though the wipers showed considerable oxide
accumulation. The BER value was dominated by 2 large dropouts which did
not change significantly with burnishing. Even though the BER
improvement was negligible in this case, burnishing and cleaning is
still recommended as a necessary step for tape.

The summary results for the tapes on the 1" test bed are compiled in
Figure 2.12 to 2.13. These display both the optimization run to
determine the operating point and the corresponding signal to noise
measurements. The full length error rate performance at the optimum
record current is given in Table 2.4 and noted on the graphs.

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Table 2.4

SUMMARY OF PERFORMANCE

1" TAPES

34Kbpi

Tape	Rec. Current, ma	SNR, dB	BERx10-6
3M973	12	34.2	1.7
3M 5198	14	33.1	10.6
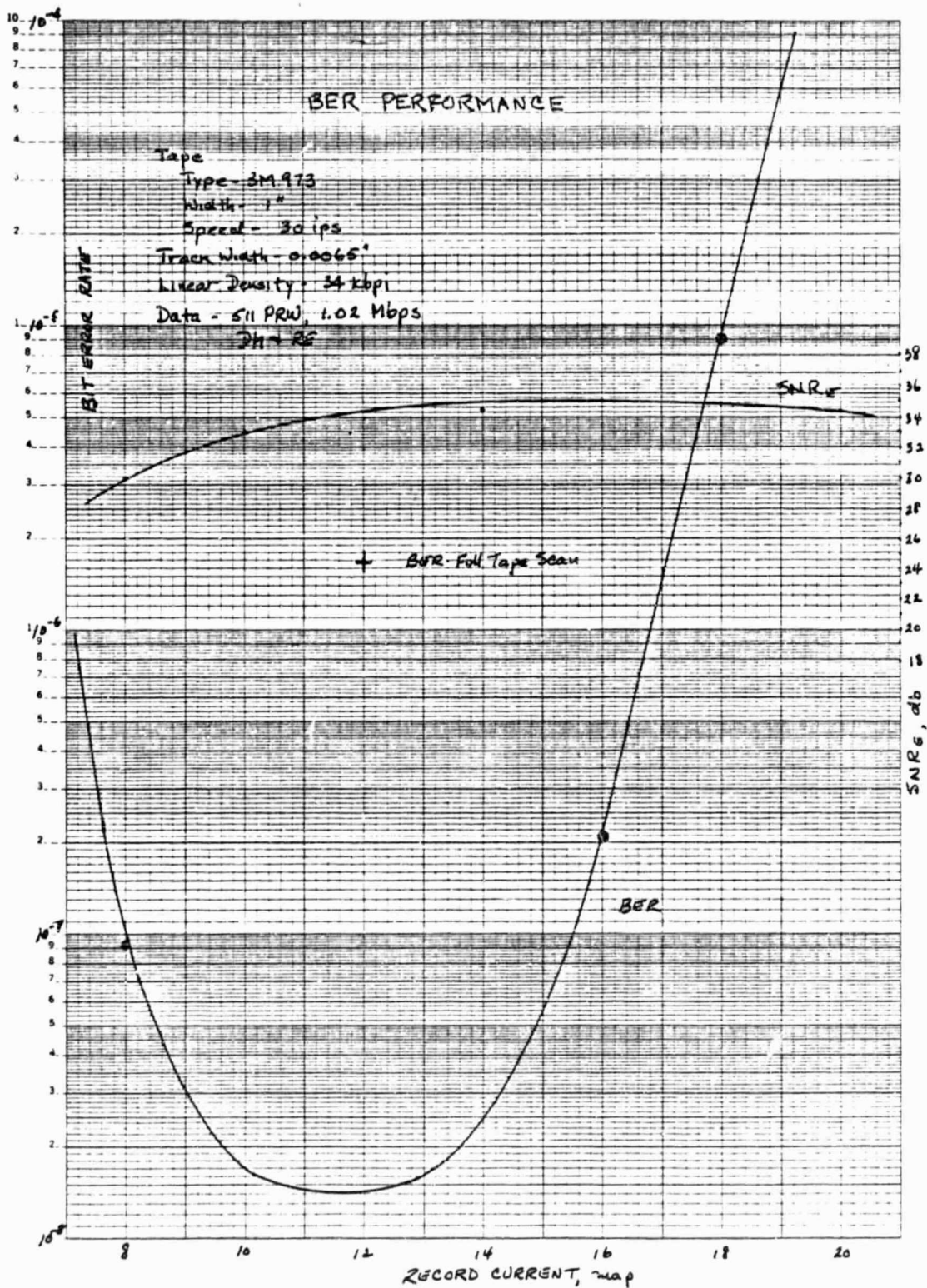
Figure 2.13 - 3M 973

43
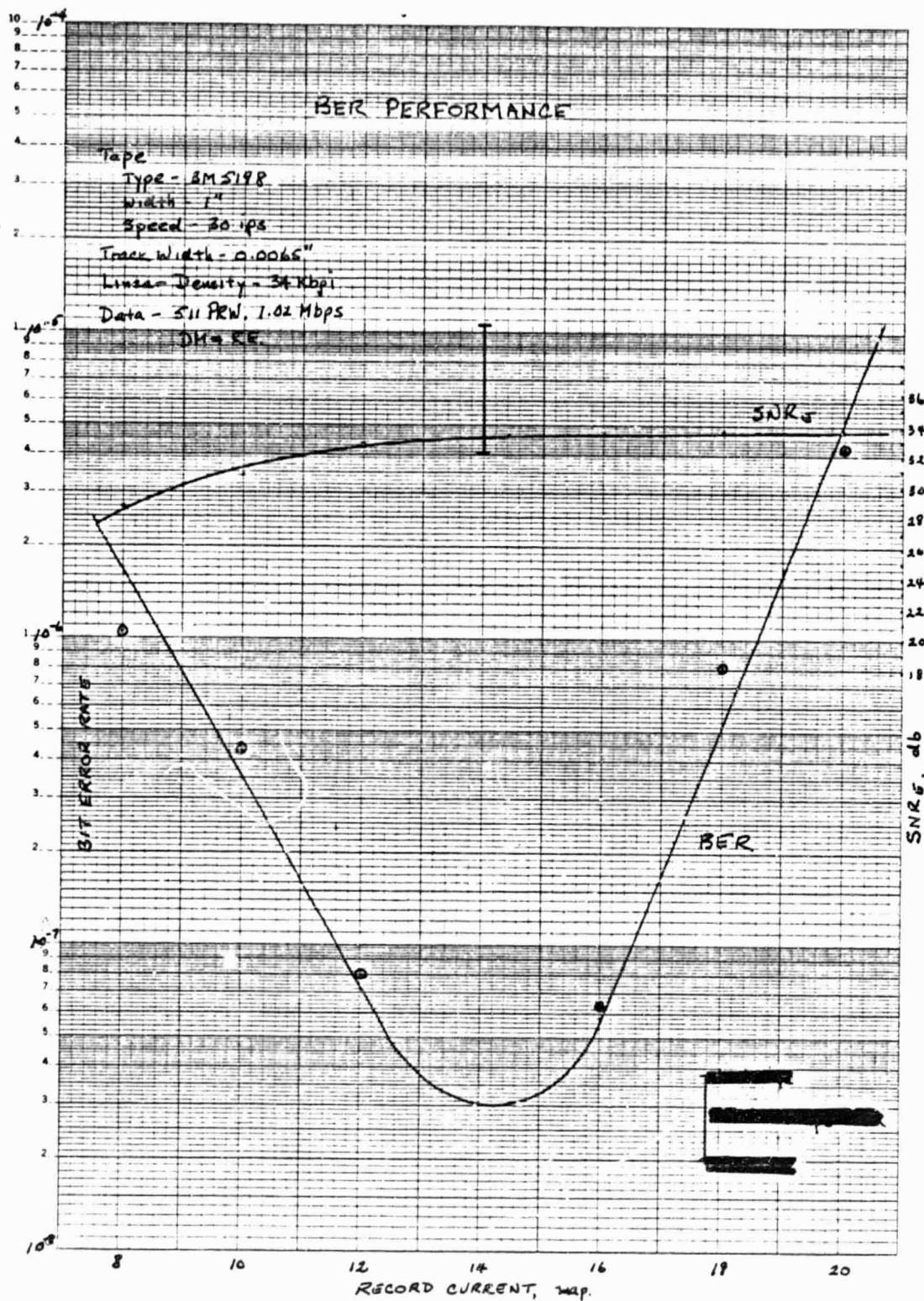
Figure 2.14 - 3M 5198

BER PERFORMANCE

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TABLE 2.5

EFFECT OF BURNISHING ON 3M 5198

# of Passes	NO. OF SAMPLES	BER	NO. OF SAMPLES W/ERRORS	NO. OF SAMPLES W/LARGE ERRORS	LARGE ERROR SIZE
Initial	123	3.7×10^{-6}	16	3	173,180,68
	120	0.28×10^{-6} (BER excluding large errors)			
300 hours	122	2.6×10^{-6}	15	2	145,98
	120	0.63×10^{-6} (BER excluding large errors)			

2.1.6 Tape Test - Fuji H621

At the end of the tape test program NASA requested an evaluation of Fuji H621 based on a favorable review by IITRI.

Purpose

The Fuji H621, favorably rated in a group of tapes characterized by IITRI, was not selected by RCA for testing, initially, primarily because of the lack of availability in 1/4" widths. Dropout tests conducted by IITRI gave the Fuji tape an excellent rating. The later increased availability of the tape also made it a viable candidate. Two reels of H621, that had been tested at IITRI were supplied to RCA with data showing that the dropout activity was lower when compared with 3M 5198. Also reported was the consistency of performance from initial runs to end of tests. This is a unique feature since all of RCA's experience with magnetic tape for space recorders require a period of protracted burnishing before acceptable performance is obtained.

Procedure

'n order to confirm this initial performance of the Fuji H621, a departure from the standard test procedure that we had been using was necessary. No run-in or burnishing was planned and no tape cleaning wipers were to be used to remove loose debris. In a further attempt to isolate "first pass" performance, the optimization runs to deter ⁻⁹ the proper record current were to be performed outside of the defined test tape length area. Only after the proper record current had been determined and tape tracking judged satisfactory would the test section be used.

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An additional change was necessary because of the excellent performance of the 1" transport with prior tapes. Spot or short term BER's could be expected to be better than 1×10^{-7} (the test section is only long enough to contain 165 Mb) and if indeed the Fuji tape was better than what had been previously tested the criteria of BER performance would be limited in measuring the degree of improvement. By extending the packing density to 45 Kbpi, the present test configuration margin of performance would be taxed enough to give BER's in the 10^{-5} range which would statistically give more meaningful data. Test continuity would be maintained by establishing a 45 Kbkpi performance baseline on 3M 5198 and the 34 Kbpi data would also be taken. Packing density was increased by slowing the tape speed from 30 ips to 22.2 ips while maintaining the data rate at 1.02 Mbps. In this way, no changes to the test electronics or head were necessary.

Test Results

During the optimization runs, the Fuji 45 Kbpi performance was found to be poorer than the 3M 5198 45 Kbpi performance, with lower signal to noise and poorer BER (Figure 2.15 & 2.16). While there were fewer dropouts (losses of 6 dB or more), the highest level of modulation noise was seen among all the tapes tested. Lack of dropouts were confirmed by the error runs which gave very consistent error counts with small variations. Performance at 34 Kbpi, Table 2.6, repeated the same observations with the exception that the BER was the best measured (6 errors in 122 count samples over the test section giving a BER of 5×10^{-8}). To sum up the initial evaluation referencing 3M 5198, the Fuji H621 has:

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Lower Record Current

> Lower SNR
>
> Higher Modulation Noise
>
> Lower Dropouts
>
> Better BER at 34 Kbpi (dropout dependent)
>
> Slightly poorer BER at 45 Kbpi (SNR and wavelength dependent)

The *"first pass" (45 Kbpi) in the test section yielded 25.2 dB SNR (lower than the optimization run by 1.9 dB) and a BER of 2.4×10^{-4}. At 34 Kbpi (5th and 7th pass), the SNR measured 32.4 dB with a BER of 0.5×10^{-6}. See Tables 2.6 and 2.7 .

Figures 2.15 and 2.16 show the optimization and signal to noise runs at 34 and 45 Kbpi for H621. After the initial passes it was decided to run multiple passes on the H621 to get a snap shot of its wear and longer term characteristics.

Cycling was started with the 22.2 ips tape speed (45 Kbpi) so that critical performance could be monitored.

---

*NOTE: The BER CHECKER requires the playback of the data bit stream in the exact sequence used in recording. Therefore, record and play are performed with one direction of tape movement. "First Pass" playback is actually the third tape pass.

Table 2.6

SUMMARY OF PERFORMANCE

1" FUJI H621

34 Kbpi

Tape	Rec. Current, ma	SNR, dB	BERx10⁻⁶
Fuji H621	14	32.4	0.5

Table 2.7

SUMMARY OF PERFORMANCE

1" TAPES

45 Kbpi

Tape	Rec. Current, ma.	SNR, dB	BERx10^{-6}
Fuji H621	8	25.5	240
3M 5198	10	30	15.5

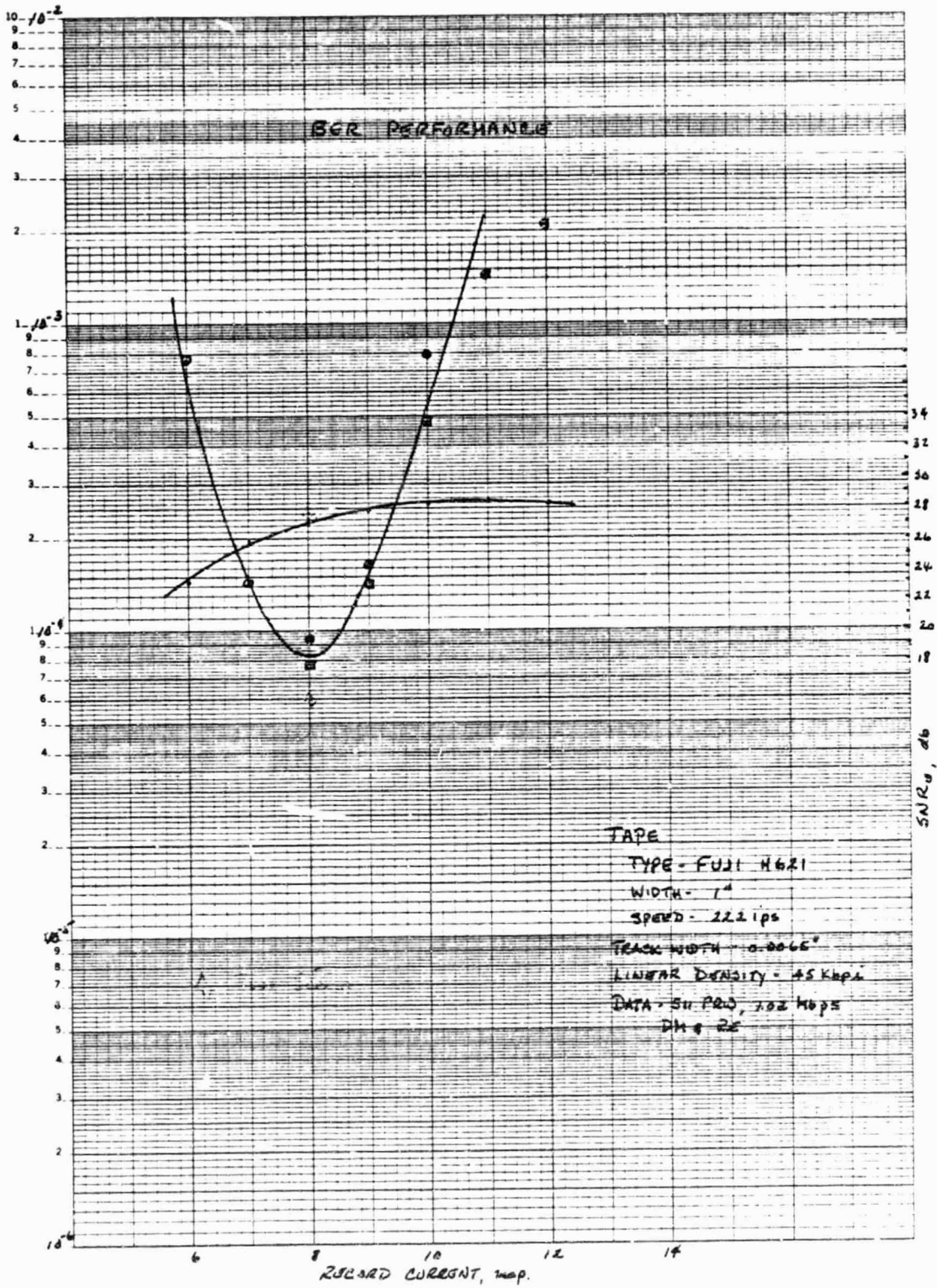Figure 2.15 - H621 at 34 Kbpi

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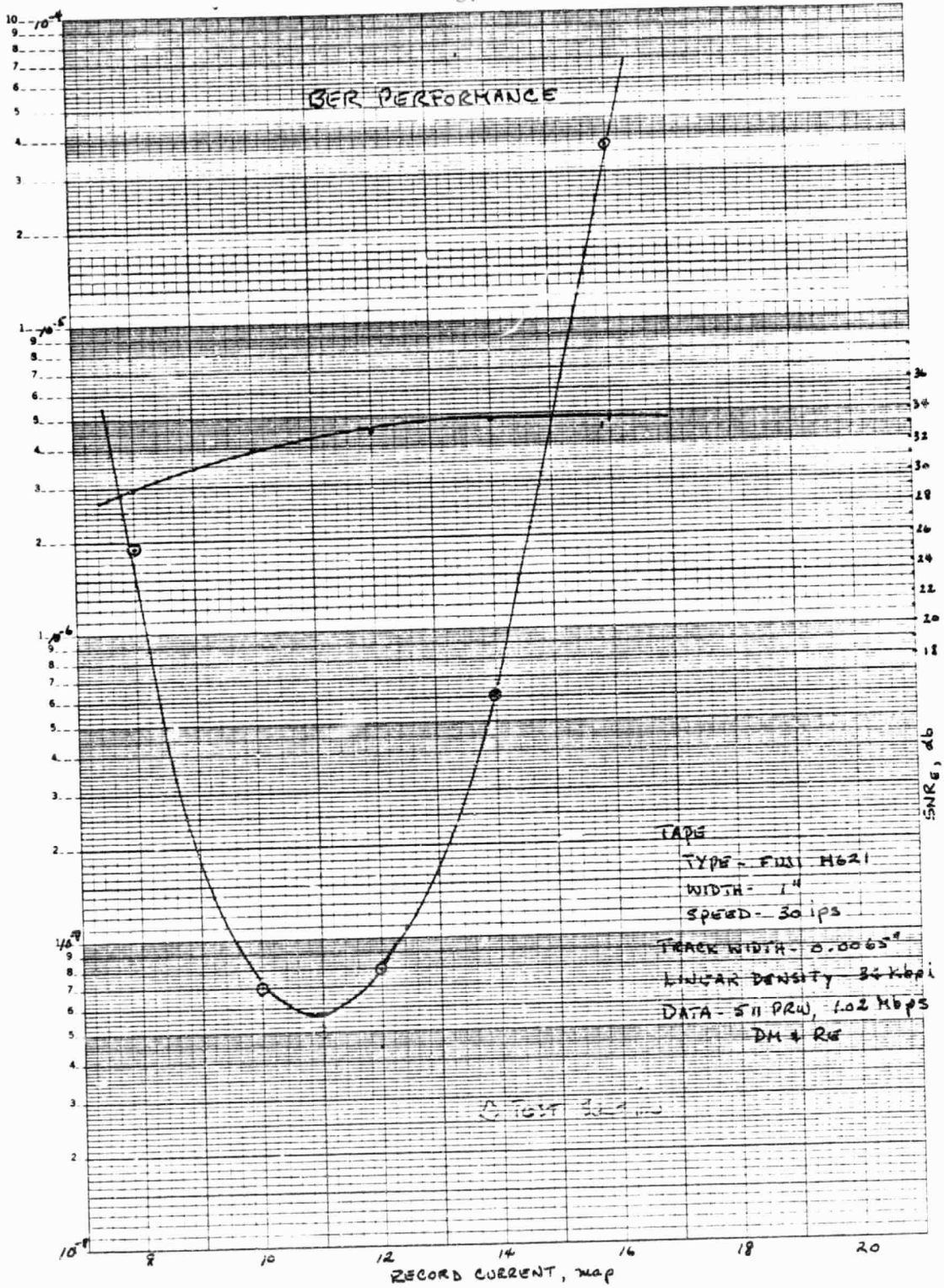
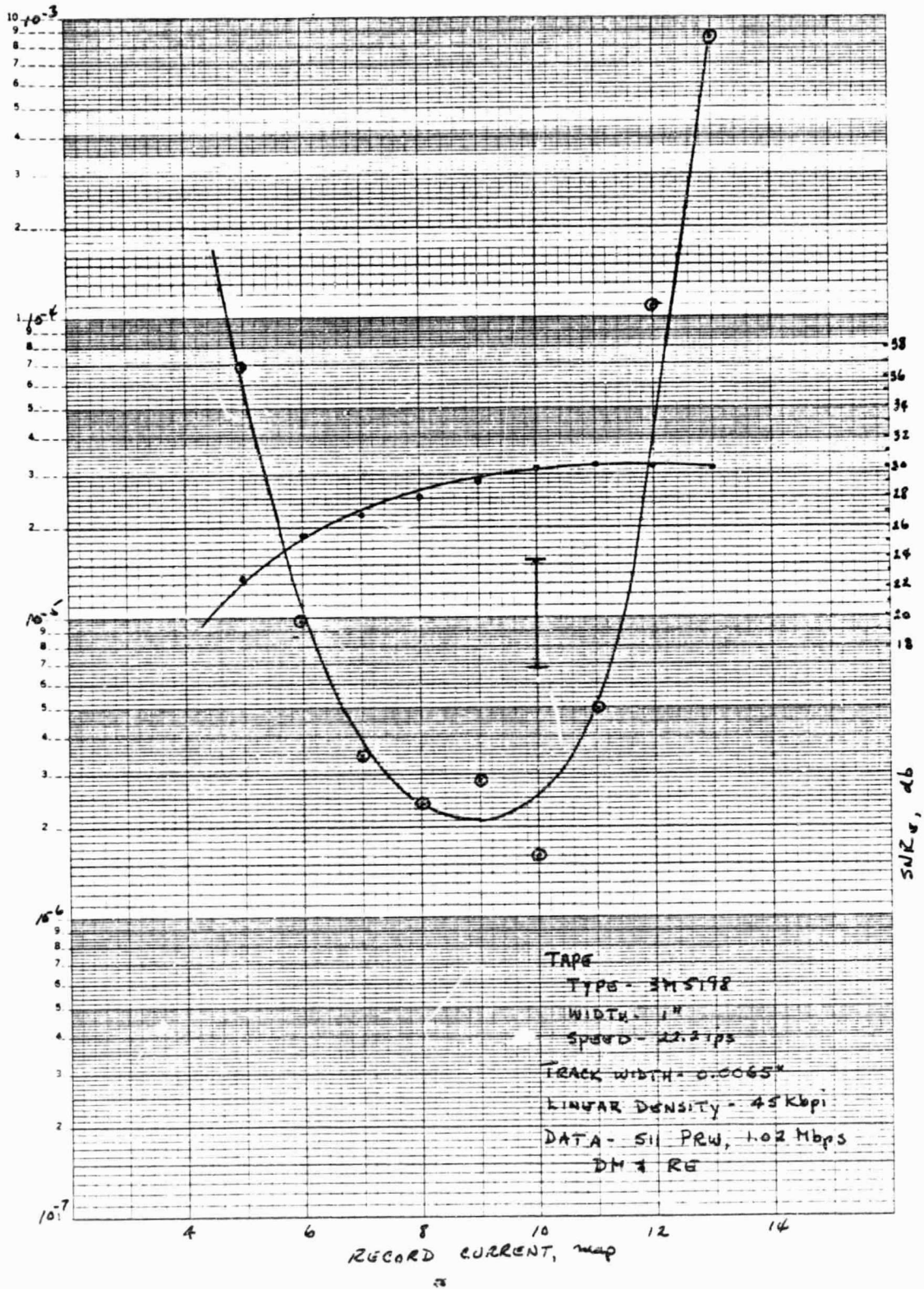Figure 2.16 - H621 at 45 Kbpi

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Figure 2.17 - 3M 5198 at 45 Kbpi

Cycling Log - Fuji Tape

- **40 passes.** BER performance deteriorates, increasing about 5 times to 1×10^{-3}. Also noticed was that the tape is starting to mistrack during a 30-45 second period in the middle of the 3 minute test section. Signal losses up to 2 dB are measured while previous signal variations were less than 0.5 dB.

  A recheck at 34 Kbpi shows only slightly worsened performance, 31.' dB SNR and 8.3×10^{-8} BER. The deterioration was affecting only very short wavelength resolution. A microscopic head inspection revealed that several of the ninety-odd slots between tracks had become filled with oxide debris. In particular, one slot adjacent to the track in use had filled sufficiently to cause tape lifting. The debris was easily removed with an air hose. It was noted that an incipient glazing or staining condition had developed which can be described as a pattern of very small disconnected islands of stain. The air blast was effective in restoring initial performance.

- **270 Passes.** A reduction of 0.5 ma record current improves performance, raising the SNR 2 dB to 26.5 dB and lowers the BER to 6×10^{-5}. Tracking losses of 2 dB are experienced in the middle of the test section making it difficult to get consistent readings. By now the tape pack was showing a "bell-mouth" condition on both edges. "Bell-mouth" occurs when the edge or edges of the tape are longer than the rest of the web (due to permanent elongation) and builds up to a larger radius on the tape pack. This radius

difference is magnified with each suceeding layer of tape so that eventually the tape pack follower roller is resting only on the edges of the tape. With edge crown rollers as the tracking mechanism, tape tracking control is diminished when the tape edge develops permanent elongation.

- **398 Passes.** Cycling speed changed to 30 ips and 45 Kbpi data collection dropped because of difficulty in making consistent readings.

- **490 Passes.** Performance loss again experienced. SNR has dropped to 29.9 dB and BER has risen to 2×10^{-7}. Air hose cleaning has no effect and head is removed again for inspection. This time, slot packing is not significant but head staining has progressed to form a contiguous pattern covering an area on both sides of the gap. Without any remedial action, cycling is continued.

- **620 Passes.** Signal improvement completely restores performance to 32.3 dB SNR and 2×10^{-4} BER.
  End of cycling test.

The most negative finding about the Fuji tape was the base film
distortion that showed up shortly after cycling was started. The
mistracking that occurred was varied and would cause signal losses as
high as 2 dB. Based on a 6.5 mil track width, this magnitude of loss
represents approximately 1.3 mils mistracking. In contrast, previous
typical losses from mistracking while running the 3M 973 and 3M 5198
were less than 0.5 dB which represents less than 0.4 mil track loss. It
could be reasoned that the tape weakness was localized since the
distortion occurred in the middle portion of the test area and
represented only 1/6 of the test length. However, it was also
independently reported by IITRI that the Fuji H621 showed visible signs
of base film deformation after being tested with a single protruding 7
mil wide track test head. The other manifestations of this distortion
were "throw-outs" of the tape pack in the same area and "bell-mouthing"
of the tape pack edges. Both of these can be expected to cause tape
guidance problems. "Bell-mouthing" describes the effect on the tape
pack of a long or stretched tape edge. The long edge winds up to a
larger radius than the rest of the tape and is aggravated by each
succeeding layer.

Another concern is the head staining condition that intermittently
appeared during the cycling test. At its worse, a loss of 2.5 dB in
signal level was measured. No other tapes encountered this magnitude of
loss in the laboratory environment which was maintained at 70-75°F and
45 ± 5% RH. Head staining can be controlled by a specific temperature
and humidity condition.

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The Fuji's higher level of modulation noise coupled with its lower signal level, on average 1 to 2 dB less, would tend to diminish the margin of operation under certain conditions. This is illustrated by the BER performance comparisons between the Fuji and the 3M 5198. At 34 Kbpi, the Fuji had superior BER performance to the 3M 5198 but was decidedly inferior at 45 Kbpi. The main factor leading to its good initial performance is the apparent excellent surface finish which led to an extremely low incidence of deep dropouts.

The head slot packing with oxide debris possibly could have been prevented if the Fuji tape had enjoyed the benefits of burnishing and cleaning that was standard practice with the other tapes. At the moment, there are enough questions raised about the Fuji tape that would preclude it for immediate use.

2.1.7 Tape Event Correlation Data

Because there has been continued interest in experimentally correlating repeatable tape errors in digital tape detection systems with observable or measurable defects in the tape, two sample 1" tapes, tested in this program, were sent to IITRI for further study.

A short test section of Fuji H621 and a 1000 foot (approximate) length of 3M 5198 were forwarded to IITRI. Both had repeated BER runs made of the same recording in one track. The position of the track was identified by its location from one edge. The errors were identified by paper tapes carrying the error count printouts at 1 second intervals. Since the tape speed is known (30 ips) it is possible to identify any error occurrence on the tape with a specific spot on the tape, with some reasonable precision. These paper tapes were also forwarded to IITRI. The results of IITRI's examination of these sample tapes may be of considerable use and interest to the recording community.

2.1.8 Conclusions

The following summarizes the Tape Test Results. Recommendations are made for continuing test efforts.

Magnetic Tape

Three candidate tapes, Ampex 593 (721), Ampex 466 and 3M 5198 were tested initially on the 1/4 inch transport.   Signal and BER performance were similar. See BER Performance Table 2.3. (Note 3M was used as a candidate and a baseline tape for comparison purposes as its performance is well known from the STR program). It was discovered that both Ampex tapes continued to generate noticeably more oxide debris on

the tape cleaning pads than the 3M 5198 and continued to do so,
unabated, throughout the cycling test which lasted 600-900 passes.
IITRI also reported supporting evidence of a possible oxide durability
problem when the Ampex 593 (721) and Ampex 466 scored low on their oxide
abrasion and binder strength tests, part of their comprehensive tape
characterization. Because of the uniquely low scores on those tests, it
was strongly suspected that a batch problem existed in our test samples
of Ampex tapes. Since the 1 inch Ampex tape samples of the same tapes
were intentionally purchased from the same batch number, (the 1" and
1/4" samples of 5198 were not from the same batch) they were not
considered for second phase testing on the 1 inch transport.

On another high density recording project at RCA, good results were
reported using 3M 973. Consequently, 3M 973 was added to the second
phase testing (i.e. 1" tapes) along with the 3M 5198. Fuji H621 was
later included in this test phase as a test addendum. On the basis of
dropout activity at 34 Kbpi, the H621 was undoubtedly the best, 973 a
close second and 5198 a distant last. The BER tests reflect this same
order of performance indicating that the system performance is tape
dropout limited. The 5198, though last, performed no worse than
1×10^{-5} and had equivalent performance in selected areas of the tape.
The other tapes were so error free that one can only say with certainty,
on the basis of the amount of data sampled, that the error rates were
better than 1×10^{-7}. Based on signal to noise measurements, both 3M's
scored higher than the Fuji. The differences in signal to noise is not

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necessarily significant to performance at 34 Kbpi. The Fuji tape besides having a lower SNR also had a higher level of modulation noise which is detectable in the presence of a recorded signal. (The test was not equipped to measure modulation noise as a parameter and this comment represents a visual observation). The Fuji tape developed a localized distortion area in the middle of the test section that give variable signal losses up to 2 dB whenever the area was traversed. Also a head staining condition occurred that caused a temporary loss of signal. None of these problems were encountered with the other tapes, but they are not always unique to a tape type. Additional testing would be required to determine if this is typical of Fuji. Based on laboratory performance (temperature and abrasivity parameters have not been compared), the preferred tape is 3M 973. A reservation is that 3M 973 was not one of the original candidates and therefore did not undergo the characterizations tests at IITRI. It is reported that 3M 973 is scheduled to be tested in the near future. The surviving tape, 3M 5198 is then a second choice, but one with fewer qualifications.

It is recommended that tape type 3M 973 be fully evaluated by IITRI for its mechanical and physical properties. Additional life testing on a suitable tape transport also is recommended.

2.2 Magnetic Heads

RCA's high density multi-track head is considered capable of meeting the program's goals of 80 tracks per inch, 35 Kbpi and bit error rates of 1×10^{-6}.

History

Experience has shown that sensitivity to head-to-tape separation at short wavelengths results in high bit error rate (BER), low reliability of the head-to-tape interface and compromised tape usability. Hence, in development efforts to obtain high packing densities, RCA has devoted maximum effort toward extending the track density while maintaining reliable in-track density.

RCA's success in video head technology has led directly to unique fabrication techniques for ultra high track density longitudinal heads. Applications of these techniques have successfully yielded track densities of 90 tracks per inch.

RCA head technology has evolved around a configuration yielding an extremely high efficiency transducer. A typical video head as shown in Figure 2.18 is constructed with a very short magnetic path length, single turn-transformer coupled-electrical connection, and high wear resistant materials.

This type of construction yields a head structure which very closely approximates an idealized ring-type single turn transducer.
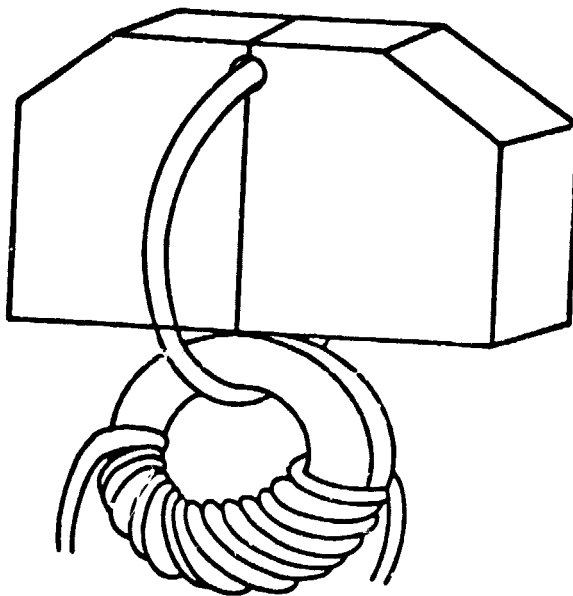
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FIGURE 2.18

VIDEO RECORDING HEAD

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ALFECON II has improved properties for both gap definition and wear resistance. This material is capable of retaining good gap definition in submicron gap lengths and long life with short pole face depths. Thus, high efficiency may be obtained at small wavelengths, or high packing densities.

Multichannel record/reproduce heads have been fabricated at track densities of 90 tracks per inch, yielding track widths of 6.5 mils. The head shown in Figure 2.19 is a batch fabricated, multi-channel, unitized structure consisting of a single mechanical head containing a multiplicity of magnetically isolated transducers. The individual tracks are electrically connected via single turn loops to toroidal transformers located on alternate sides of the head. Because support is not required at the head contact surface between adjacent tracks, there is no extraneous material to contact and contaminate the recording tape.

Description

The magnetic heads used in these tests were derived from 2-inch multi-track assembly, designated as B106. See Dimensional Outline, Figure 2.20 and Head Design Characteristics in Table 2.8. This assembly was made up of four ½" modules with 45 tracks per module. A single module was used in the quarter-inch tape tests and two modules were used in the one-inch tests. Of the wired tracks available, one primary test track was selected on the basis of best performance. On occasion, a second and third track was tested for comparison.
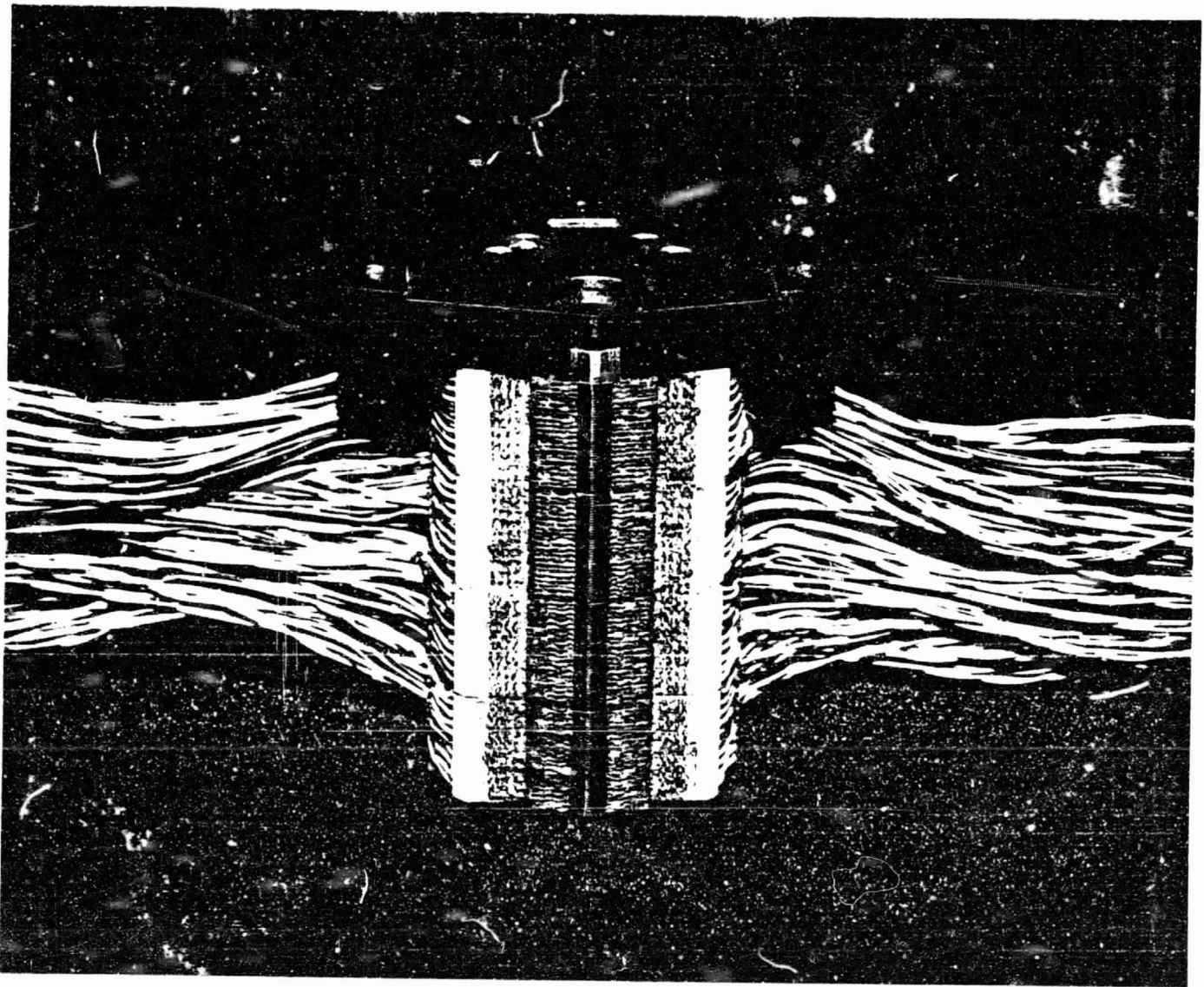
Figure 2.19

HDMR HEAD - 2" HEAD STACK

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TABLE 2.8

Head Parameters

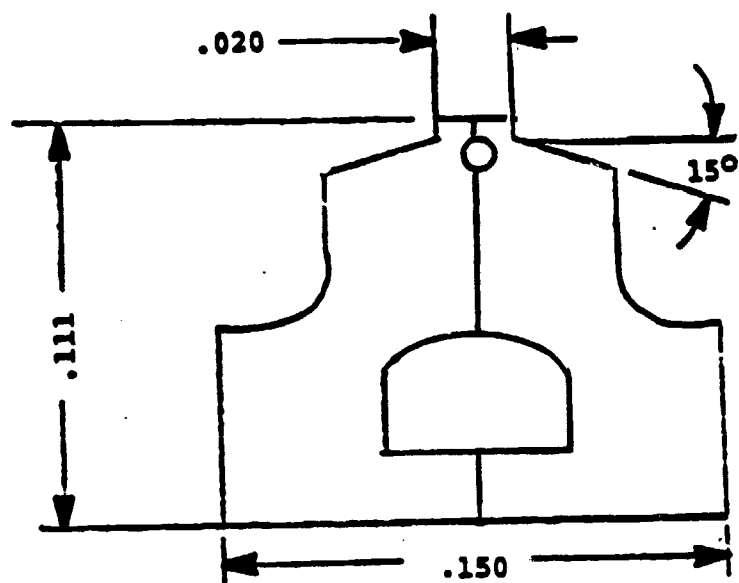|	
Track Width	.0060" - .0065"
Guard Band	.0050" - .0045"
Material	Metal, A II
Head Land Length	.020"
Coil	Single turn-transformer coupled with 20 turn secondary
Gap Length	12 u in.
Pole Face Depth (Start)	.0012" (quarter-inch)
	.0010" (one-inch)

B-106

Figure 2.20

Outline Representation of B-106 Showing Basic Dimensions

Contouring

Quarter-inch

A short "Green" tape lap, (0.5 micron chromium oxide), was performed to round off the corners, and was followed by 50 passes with Crolyn tape. Polishing was accomplished by 600 passes cn magnetic tape, 3M 461. Material removed was .0008" of pole tip, material to reach the starting pole face depth.

One-inch

The head was lapped for 95 seconds at speed with 3 micron abrasive tape with 1 mil backing. Material removed was .0018" of pole tip depth to reach the starting pole face depth. Polishing was done with a 6 hour run-in on 3M 973.

2.2.1 Test Magnetic Head

All tape test work was performed using one type of magnetic head. This was a RCA built high density multi-track head with 90 tracks per inch and gap dimension of 12 u in. The head is batch fabricated in 1/2" long modules of 45 tracks each. A single module was used in the 1/4" tape tests and two modules were required for the 1" tape tests. All of the modules came from a larger head assembly mea ; to be used for 2" tape. This means that all of the modules came from a single source of magnetic material, share matching cycles and undergo all processing together to ensure uniformity of track performance. Limited electronics only allowed single channel testing but at least one head out of each module was tested. The performance level at 34 Kbpi and 1.02 Mbps was

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excellent and tape test results were usually determined by the dropout characteristic. The differences in signal level record current and noise of each tape tested were not factors in affecting performance results. This type of performance testifies to the capability and efficiency of this type head in handling the data rates and densities of the tape test. Generally, the record currents were low, never more than 20 ma peak at pole face depths greater than 0.001". The highest coercivity of 740 oersteds (3M 973) showed no signs of head tip saturation limiting.

There was no indication of abnormal head wear. Though head wear tests were not specifically conducted, final measurements at the end of tests on both head assemblies showed negligible wear. This represents approximately 148 hours ($\approx$3000 passes) on the 1/4" module and 106 hours ($\approx$2100 passes) on the 1" module. See Table 2.9 and 2.10.

HEAD WEAR, TABLE 2.9

Quarter-Inch Module

	"Wear	PFD
Initial, After Contouring	0.0008"	0.0012"
Final, After all tape tests	0.0008"	0.0012"

Tape Type	Hours of Use
3M461	32.5
A 593 (721)	34.0
A 466	43.5
3M 5198	37.5
Total	147.5

HEAD WEAR, TABLE 2.10

One-Inch Module

	"Wear"	PFD
Initial, After contouring	0.0018"	0.0010"
Final, After all tests	0.0018"	0.0010"

Tape Type	Hours of Use
3M973	8.4
3M5198	50.2
F H621	47.9
Total	106.5

2.3 TAPE GUIDANCE

2.3.1 Background

The need for accurate control over tape tracking increases directly with the track density. If, for example, the track width is halved from previous reference, a given mistracking error will cause the percent lost track width to be doubled over the previous reference value. For our present minimum track width of .006" it is felt that the maximum mistracking should not exceed one mil, and preferably not exceed 0.6 mil for adequate margin in signal level and S/N ratio.

Tape mistracking can be caused by a variety of causes, of which the most prominent are:

1. Errors in alignment of rollers and guides: non-parallelism between axes of rollers which should be parallel, tolerances in the angles of rollers which should be tilted, etc.

2. Unintentional slight tapers in roller surfaces which should be perfectly cylindrical.

3. Non-straightness in the tape (under tension) due to inadequate slitting procedures, non-uniform viscoelastic properties of the mylar across the tape width, differential temperature effects, etc.

Close control over tape tracking is conventionally provided by some form of edge guidance. In the specialized category of spacecraft recorders, however, there has been a longstanding avoidance of edge guidance. This is based on the peculiar need of spacecraft recorders to record and play on the same tape many thousands of tape passes, with minimum degradation of performance. Where edge guidance is used, and where the tape edges

encounter significant edge pressures, tape degradation begins early in the life of the mission. The continued edge pressure tends to overstress the edge material and to generate debris, thus causing deterioration of performance of the tracks near the edge. Continued generation and dispersal of tape debris will ultimately degrade the performance of other tracks also.

To avoid this source of early degradation and achieve 20,000 tape passes or more, crowned rollers have been used in spacecraft recorders as a primary means of guidance control. With proper deployment, crowned rollers have the property of developing a restoring action on a tape which tends to mistrack due to any of the several causes. The effectiveness of the crowned roller is dependent on tape tension, tape width, the length of the tape span, and the geometry of the roller. With reduced track width, the demands on the restoring action of crowned rollers become more stringent, and their ability to meet these new requirements must be reaffirmed.

A third category of guidance control may be referred to as active control. This, most typically, refers to one or more rollers placed on a mounting which is pivoted. Intentional slight rotations about the pivot axis will bias the tape tracking to one side or another. By sensing a mistracking error and introducing an appropriate tilt to the rotor the mistracking can be eliminated or minimized.
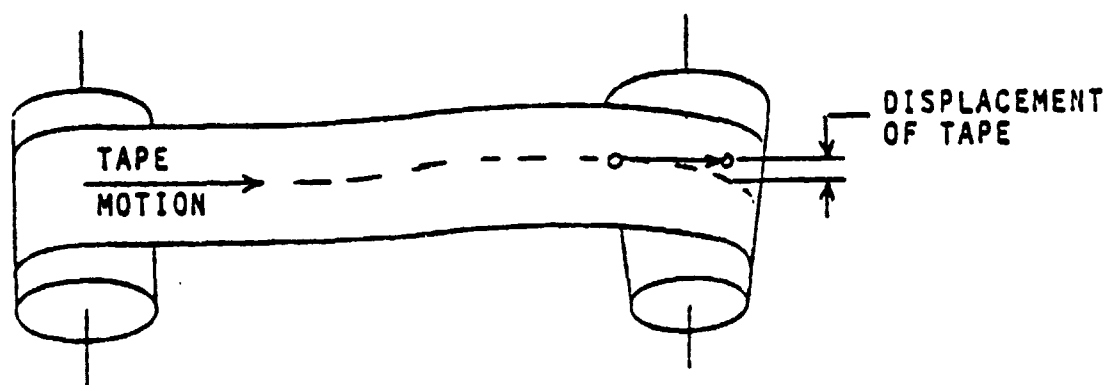
The Causes of Tracking Errors

The most common causes of tape mistracking may be categorized as tolerances and errors in mechanical dimensions and alignment. Some of these causes are shown in exaggerated form in Figure 2.21.

1. **Non-Perpendicularity of Roller Axis** - is shown in Figure 2.21(a) Here, the tape is shown approaching a roller on a tilted axis. The peripheral motion of the roller has a transverse component which will lead the tape off axis.

2. **A Tapered Roller** - is shown in Figure 2.21(b). This unintentional taper will induce greater speed and tension in the upper half of the tape width, with a consequent curvature of the tape. The tape curvature will cause the tape "ride up the larger diameters" of the rollers.

3. **Non-Straightness of Tape Under Tension** - is shown in Figure 2.21(c). The non-straightness may be due to improper slitting practice, or to variations in elastic properties of the tape. The tape backing is slit from a wide web of mylar which has some variation in elastic modules across its width. The tape curvature will cause the tape to ride off the intended center line.
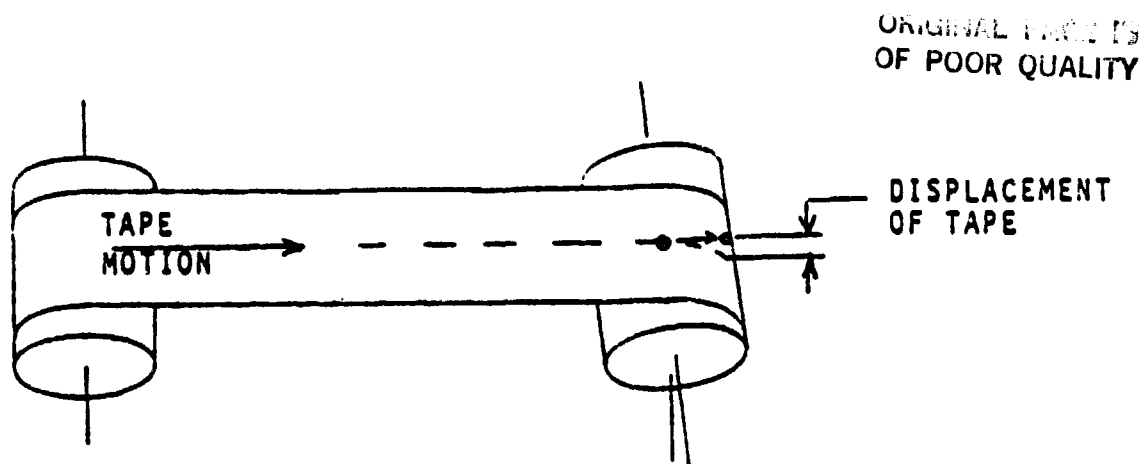
(a). Effect of Tilted Roller Axis

(b) Effect of Tapered Roller
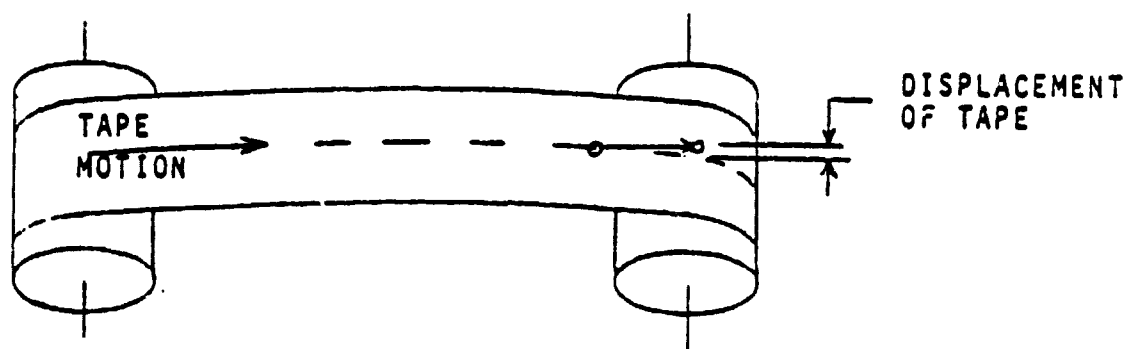
(c) Effect of Non-Straight Tape

FIGURE 2.21 . VARIOUS CAUSES OF TRACKING ERRORS

Candidate Methods

1. __Edge Guidance__ - Edge guidance may be considered to fall into one of
   two categories. (a) Two fixed guides which have a space between
   them which is slightly larger than the greatest width of tape. (b)
   One fixed guide and one spring-loaded guide (the "soft button")
   which exerts a continual soft pressure against one tape edge. This
   keeps the opposite tape edge in contact with the fixed guide, which
   is the reference position.

   Both of these techniques may be acceptable, provided the sources of
   mistracking, outlined previously, are kept at a low level by high
   mechanical precision and close control of tape quality. We must
   assume that there will always be some residual tendency toward
   mistracking. This will cause some pressure against one or both
   edges of the tape. The greater the mistracking tendency the
   greater will be the edge pressure. With high precision of
   mechanical components and assemblies and selecting of tapes to be
   used the edge pressures can be kept low enough to avoid degradation
   for the life of the mission. The tradeoffs between the two types
   of edge guidance may be considered as follows:

   __Two Fixed Edge Guides.__ Since these must have a very slight
   clearance over and above the maximum tape width, the tape can have
   tracking excursion equal to the clearance over the minimum width.
   While commercial tapes have a .004" tolerance on width the
   variations in width of any given reel have been found to be
   extremely small. On the positive side, it must be said that the
   edge guide forces are no greater than those low forces

required for a high precision assembly. Also the edge forces need not be continuous, if the mistracking tendency is discontinuous.

The "Soft Button". This eliminates the slight tracking excursion which is associated with the clearance of fixed guides. It does, however, mean that there is a continual edge pressure equal at all times to that required for an occasional peak mistracking tendence. Again, this edge pressure can be minimized for a high precision transport assembly.

2. Crowned Rollers - Crowned rollers have been used for many years to control the tracking of various moving webs, in equally varied industries. The published papers related to the subject have generally provided a theory of a qualitative or semi-quantitative nature, coupled with some test data for specific configurations. A brief description of the action of crowned rollers follows.

Figure 2.22(a) shows moving tape approaching a crowned roller. When the tape is on the roller surface with a tight frictional grip, it may be assumed to be moving with the velocity of the surface it touches. Since the crowned roller has its maximum diameter at the cente. plane, it also has its maximum velocity there. Where the roller diameter is decreased due to the crown contour, the velocity of the roller surface and the accompanying tape is also decreased, proportionately. (Up to a point, of course: when the roller diameter decreases enough, the frictional grip between the tape and roller surface is lost and the tape

velocity is not necessarily that of the roller surface.) The
moving tape is actually a steady state flow system in which a
constant "flow rate" of mylar exists at all points. Where the tape
temporarily moves faster, it must be slightly elongated (i.e.,
develop an increased tensile strain) in order to maintain the same
mass rate of flow. The result of this is that the tension profile
across the tape width, while on the pulley, becomes somewhat of an
image of the velocity profile of the pulley.

When the tape has some mistracking tendency, its center line will
be displaced slightly from the center plane of the pulley, as shown
in Figure 2.22(b). The velocity profile, however, is not
displaced, as is true for the tension profile. The center of
tension, therefore, tends not to shift with the tape center line,
and a bending moment is developed at the tape end approaching the
roller and producing a curvature at that end. This curvature
induces a counter-tendency for the tape to track to the opposite
direction from that of the original mistracking -- in fact, a
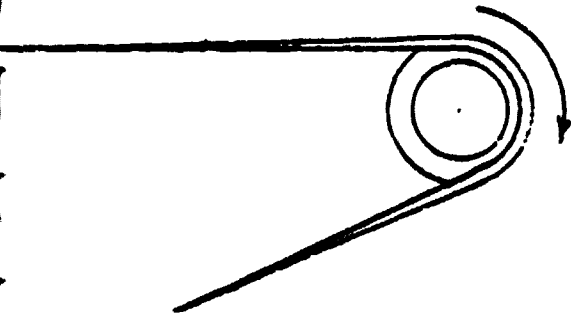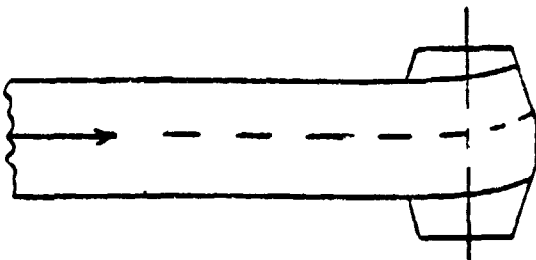restoring action has been developed.
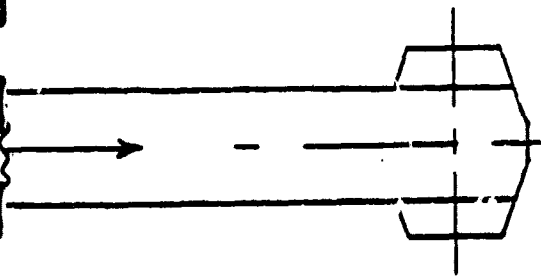
TAPE VELOCITY
ON ROLLER

TAPE TENSION
ON ROLLER

(a) CENTERED TAPE APPROACHING ROLLER

TAPE VELOCITY
ON ROLLER

TAPE TENSION
ON ROLLER

(b) OFF-CENTER TAPE APPROACHING ROLLER

FIGURE 2.22
THE ACTION OF CROWNED ROLLERS

Quantitative estimates of this effect are usually based on the theoretical equations for beams under tension, with various end conditions assumed to simulate the causes of mistracking. In general, it can be said that the effect increases with tension, decreases with tape width, and is influenced by the length of tape span approaching the crowned roller.

The contour of the crown profile is of importance, also. In our most recent experience, however, several different profiles were found to have essentially the same guidance capability. Other consequences of these differing contours became the basis for selection, such as: the ease and/or precision of fabrication, the stress induced in the tape, and (for cases where the head was close to the crowned roller) residual tension profile in the tape causing a varying contact pressure (and wear) across the head width.

3. <u>Active Guidance</u> - This technique involves the placement of one or more rollers (uncrowned) on a mounting which is pivotable. When the assembly is pivoted, the approaching tape span has its direction angle changed s   ly while the departing tape span is merely twisted about its center line. This action, then, is a deliberate misalignment which causes the tape to track to one side. By sensing some initial mistracking and introducing an appropriate tilt to the rotor, the final mistracking can be compensated and minimized.

This action may be achieved by either of two techniques:
(1) A fully active servo system involving a powered transducer

to implement the roller tilt and a tracking error detection circuit, and (2) A non-powered mechanical device which uses the offset tension of the displaced tape to produce the desired rotor tilt.

Early in the program it was recognized that the limited scope of the effort did not permit any realistic testing of two of the guidance techniques, viz. edge guidance, and active, servoed tracking correction, for different reasons: Evaluation of edge guidance would require life testing of tapes with a second one inch transport comparable to the one used in evaluating tapes and heads. This was not provided for, and without such testing, the degree of distortion of tape edges with continued usage could not be established.

The testing of an active guidance technique would require the development of a new major subsystem, including the development of a new power transducer and a feedback loop, involving substantial design and analytical effort.

For these reasons it was decided to concentrate the study activity on guidance by crowned rollers of 1" wide tape (there is extensive history of guidance of ¼" tape by crowned rollers, but less quantitative information is available on such guidance of wider tapes).

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2.3.2 Test Program

The experimental effort involves 1" wide tape, moved on an experimental coplaner reel transport at 30 and 50 ips. The tape guidance error is measured directly using an optical transducer centered on one tape edge.

The transport was designed to permit modular changes of the various rollers and edge guidance components. The effect of changes in tape tension were experimentally assessed.

In order to assess any increased problems for bidirectional operation (Record and Playback in opposite directions), the tracking error was tested in both directions. Guidance techniques were designed with this requirement in mind.

Test Facilities

The test vehicle was implemented by modifying an existing coplanar transport which currently handles 2000' of 2" wide tape. This transport was based on the ERTS transport design and has been used for a number of HDMR experimental programs.

The transport uses flangeless reels which are torqued by a cluster of four Negator coils. Urethane coated rollers are spring-loaded so as to exert uniform pressure against the changing stack diameters of each reel. This technique has been most valuable in assuring a tight tape stack on the reels and, apparently, improving guidance at high speeds. The reel and Negator subsystem is used as is, for operating 1" tape.

The four-negator coil cluster facilitates testing with incremental changes in tape tension (by disconnecting one or two negator coils).

Since it is known that for any number of Negator coils used, the profile of tension variation as function of tape footage will have a similar percentage change, short tape length runs were used to more nearly approximate constant tension conditions. Tension transducers were used to map curves of tension vs. tape footage. A portion of the full length run was selected for minimum tension variation, and the end of tape switches were reset for the shorter limits.

The operating speed was reduced to 30 and 50 ips by a combination of reduced motor driving frequency and changed belt-pulley ratio. The test bed is shown in Figure 2.23.
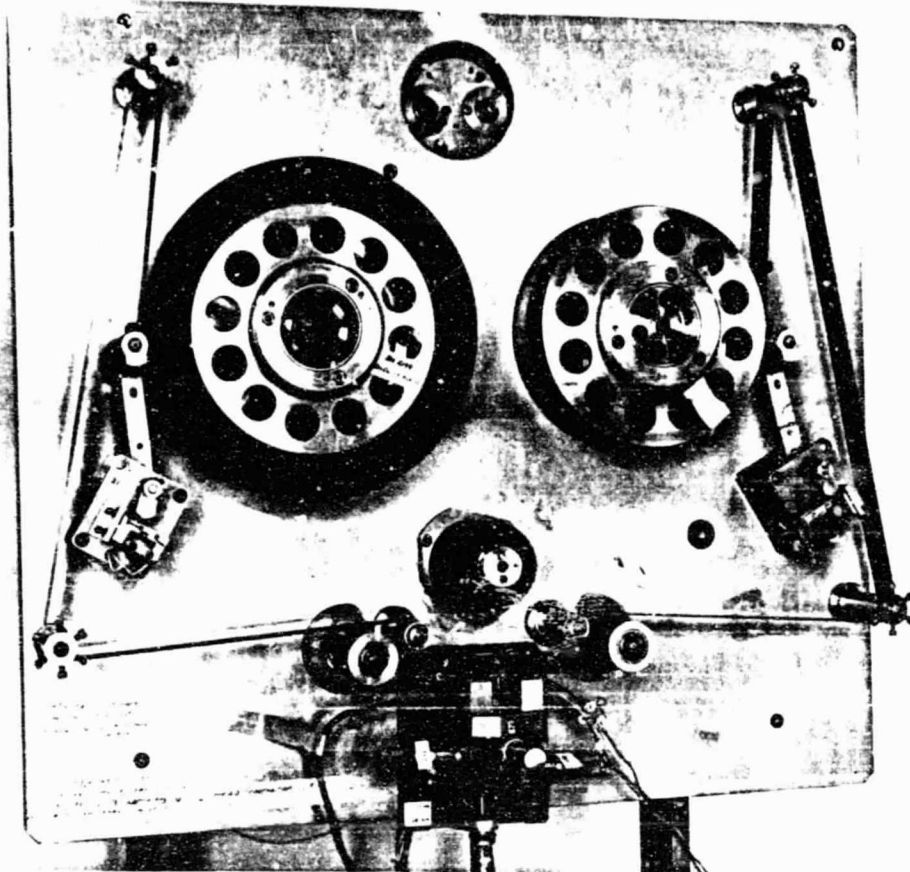
Figure 2.23

One-Inch Tape Test Transport

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2.3.3 One-Inch Transport Performance Results

The one-inch transport mechanical performance was evaluated by measuring the tape tension profile and tape edge tracking from end-to-end with over a 1000 feet of tape load.

Tape Tension

After initial assembly of the modified transport, the tape tension was found to have a differential of 8-9 ounces when tape direction was reversed.

Because of a possible low value of slippage torque in one belt, a new tension adjusting eccentric was made, and the two belts were adjusted to suitably high slippage torques. The tape tension, however, continued its shift of 8-9 ounces with motion reversal; this is considered excessive. Measurements were made of the diameters of the two capstans, the two capstan pulleys, and the long motor pulley which drives the two belts simultaneously. The motor pulley was observed to have a slight taper in its nominal .442 diameter which might have caused an effective difference of 0.2 to 0.3 mils between the diameters in the respective planes of the two belts. The two capstans had diametral differences of about 0.3 mil, due to too loose tolerancing on the shop sketches, and, also due to not being finished at the same setup. The two capstan pulleys were more difficult to measure since each pulley has a double crowned surface. It is believed that three of the crowned diameters were matched within less than 0.1 mil, and the fourth may have differed by 0.1 to 0.2 mils. Since the nominal diameter of the crowned pulleys is 1.794, a differential of 0.1 mil causes a smaller percentage effect

than is the case of the other two smaller components. The two capstans and the motor pulley were reworked, while the two capstan pulleys were not.

When the components were reassembled and tested, the tension differential was found to have decreased to 2 ounces. This probably could not be further improved, short of making up completely new and matched components. For interest, two curve sheets are included showing tension measurements, while running the tape at a speed of 47.3 ips. The first curve sheet (figure 2.24) shows the tension measured between the dual capstans for each of the two directions of tape motion. The second curve (Figure 2.25) shows tension measure outboard of the two capstans, and represents, essentially, the tension at one reel while serving, respectively, as the supply reel and as the take up reel. The large variations in tension with tape passage are, of course, due to the characteristics of this particular negator and gearing assembly (including some significant hysteresis). It is obvious, however, that the dual capstan arrangement causes a substantial improvement in matching the two profiles of tension for the two directions. Another improvement, not shown in these curves, was quite apparent in the continuous analog recordings of tension made on a chart recorder. These recordings were made with the tension transducer at three different locations, and with the two opposite directions of tape motion at each location, and are shown in Figure 2.26 to 2.31, inclusive. Tension fluctuation due, probably, to the gearing (which is no longer new and

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probably higher in noise) were considerably reduced between the two capstans, relative to those outboard of the capstan. The ripple reduction ratio was estimated as roughly 3 to 4 times smaller, confirming the theory of a dual capstan acting as a mechanical low pass filter.
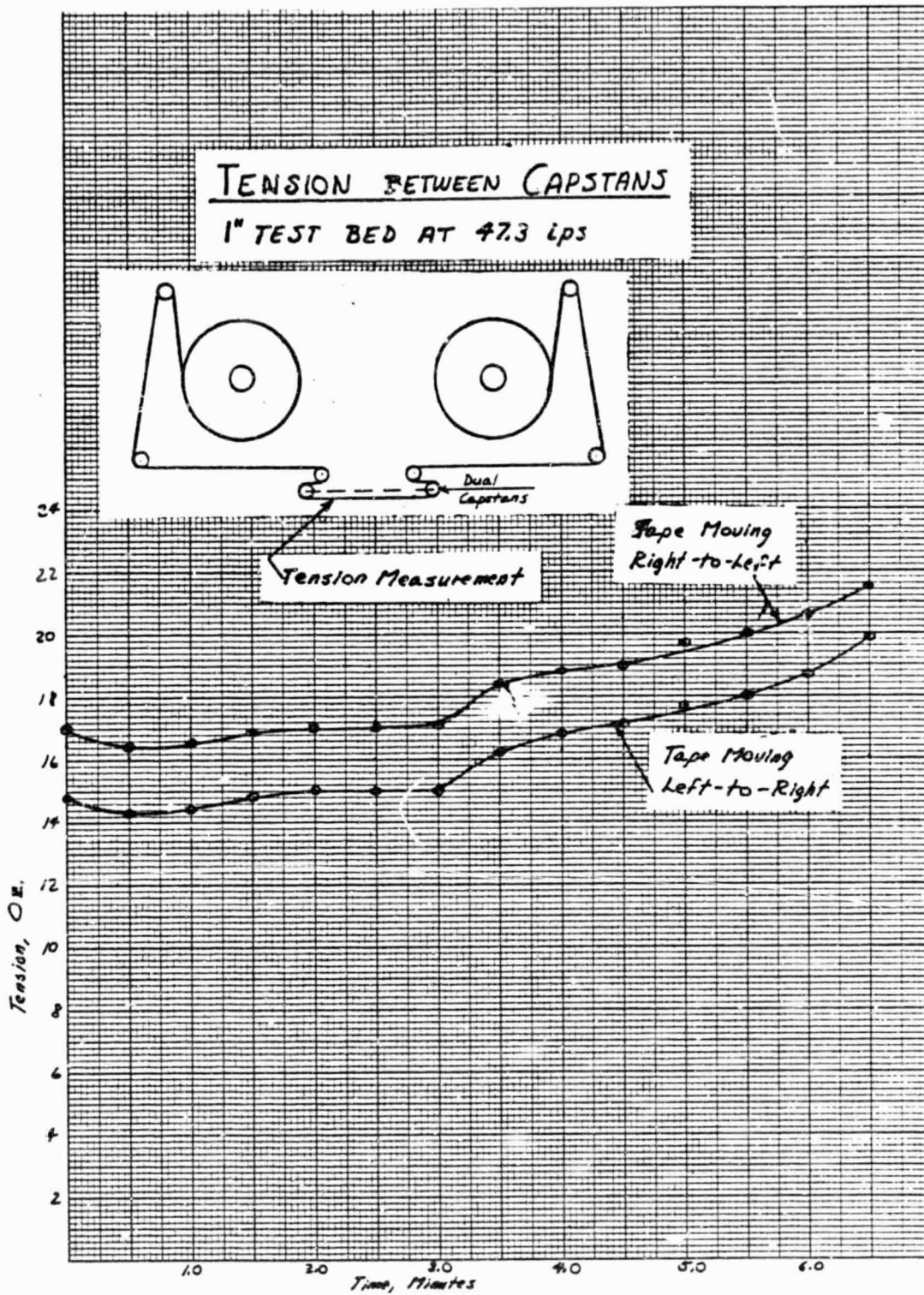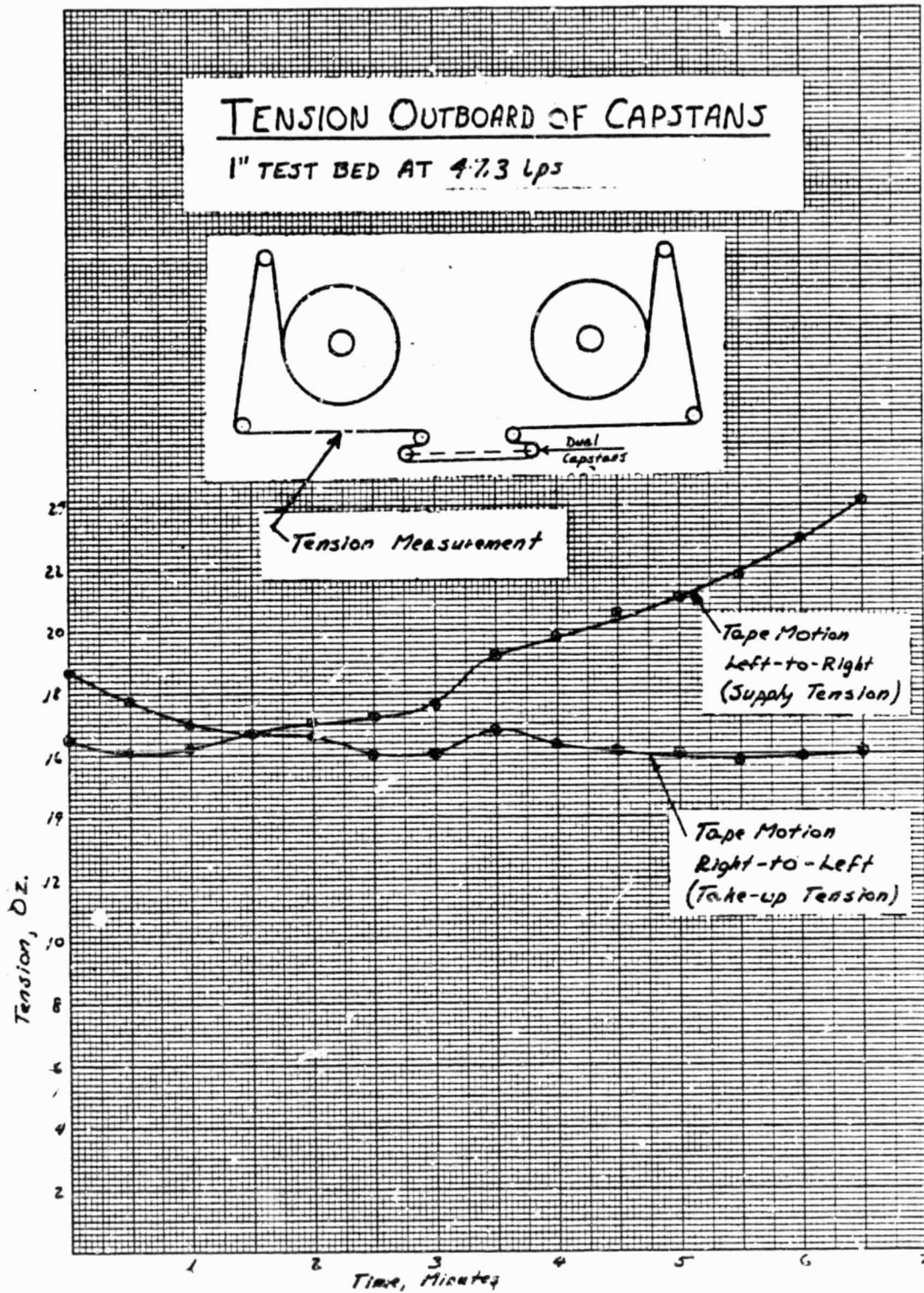
Figure 2.24

Figure 2.25

2.3.4 Tape Guidance Results

Preliminary observations (visual) of tape guidance, made on the outer corner rollers, where there was a clear optical path, had seemed promising. In order to observe tape guidance at the all-important head span between the dual capstans, a sensor from an optical tachometer was clamped to the head mount, and centered over the outer tape edge. The sensor output was calibrated using the head mount micrometer. A reasonable linear response over a range of .035" was obtained, with constant of .0477 volts/mil. Use of this setup indicated edge tracking to be extremely poor, with both short-term and long-term variations. This was confirmed for the normal negator-gearing tension variations, and also for intentional, incremental tensions, induced by manually torquing a roller. Since the two idler rollers closest to the capstans were adjustable rollers (of the type used in ERTS and DSU 2), they were investigated. These rollers had been designed for 2" wide tape. An analysis of their stiffness had been made during the ERTS program, and was reviewed. For a nominal force of 1 lb. at the outboard end (approximately 2" from the base) the calculated tip deflection was 0.75 mils. The associated change in tilt angle was 3.75×10^{-4} radians (0°, 1', 17"). A theoretical calculation made of the tape mistracking which would be caused by this change in roller axis (due to elastic deflection) forecast a tape shift of 1.9 mils (on the roller). Further, the roller bearings were found to be slightly loose, instead of properly preloaded. This could add some unknown, further angular shift, in addition to the elastic deflection.
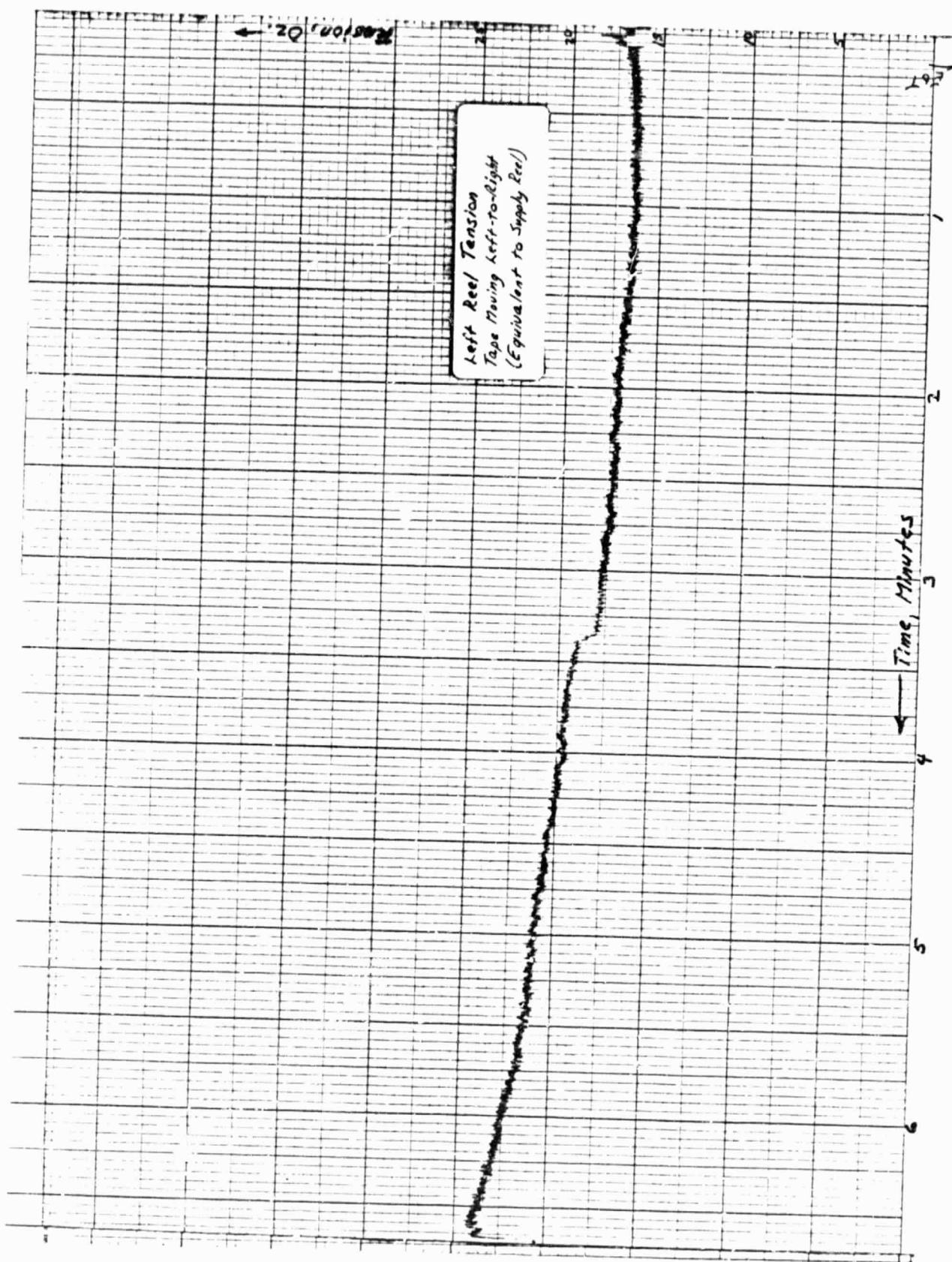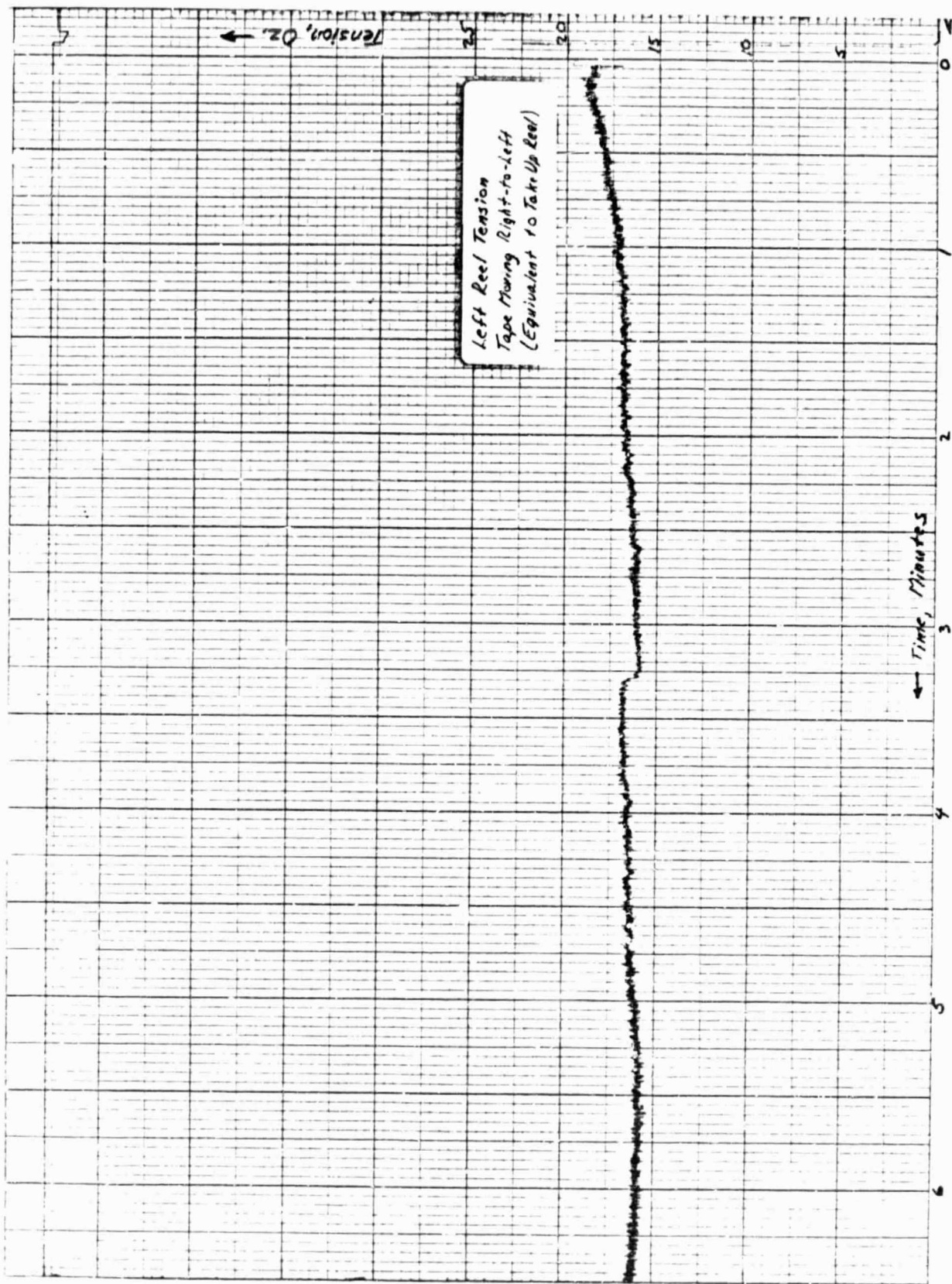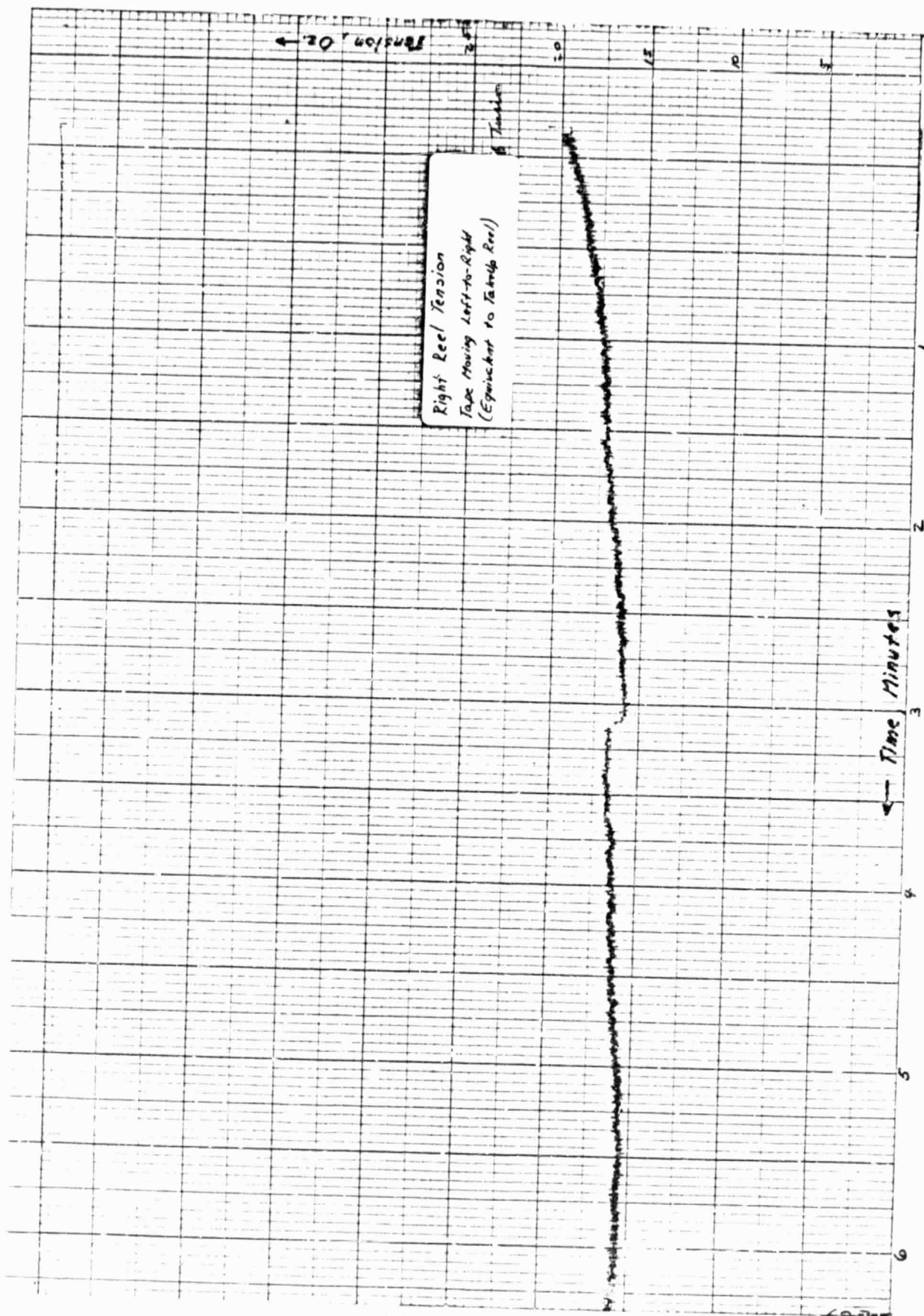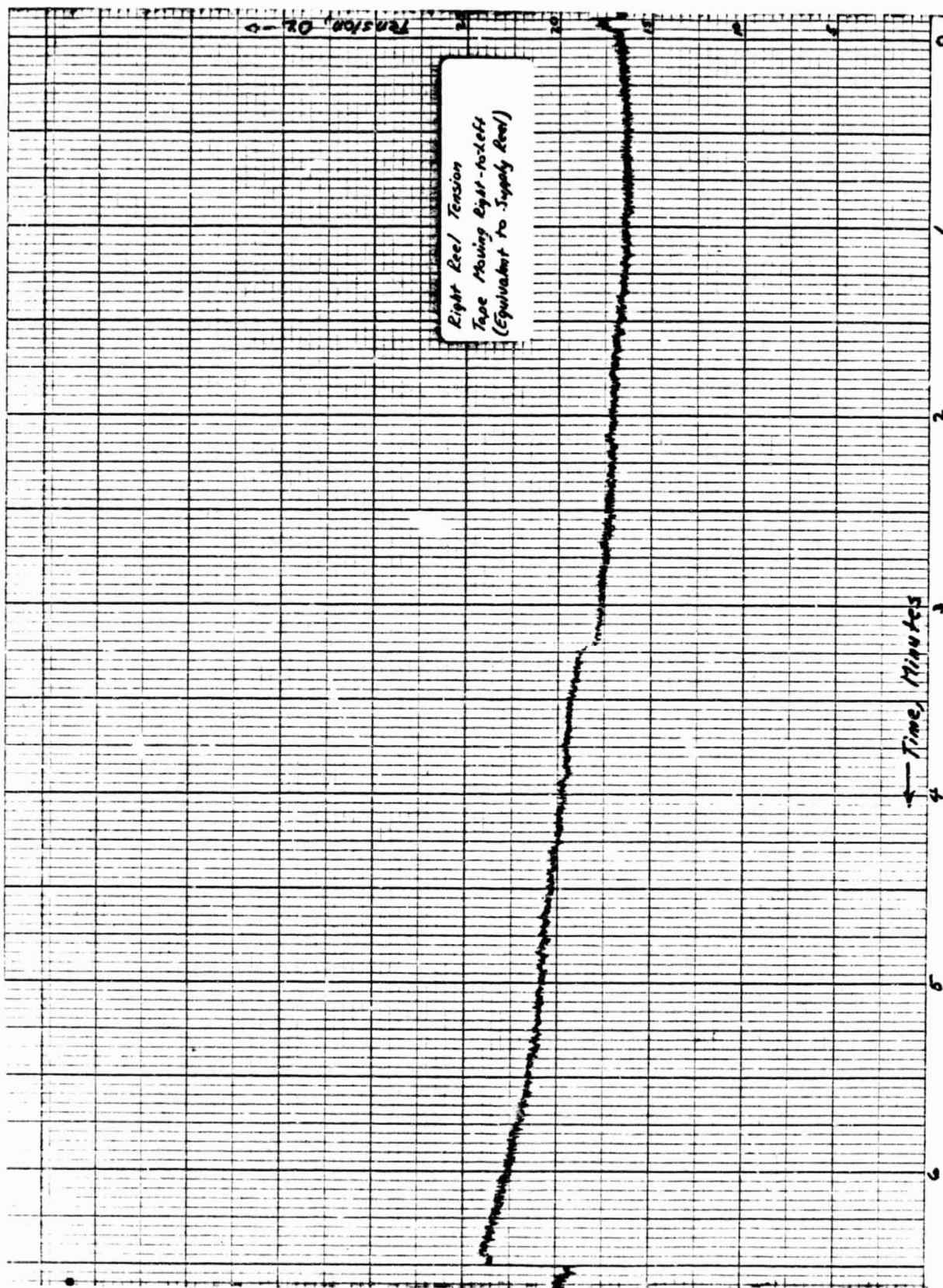
88

Figure 2.26

Figure 2.27

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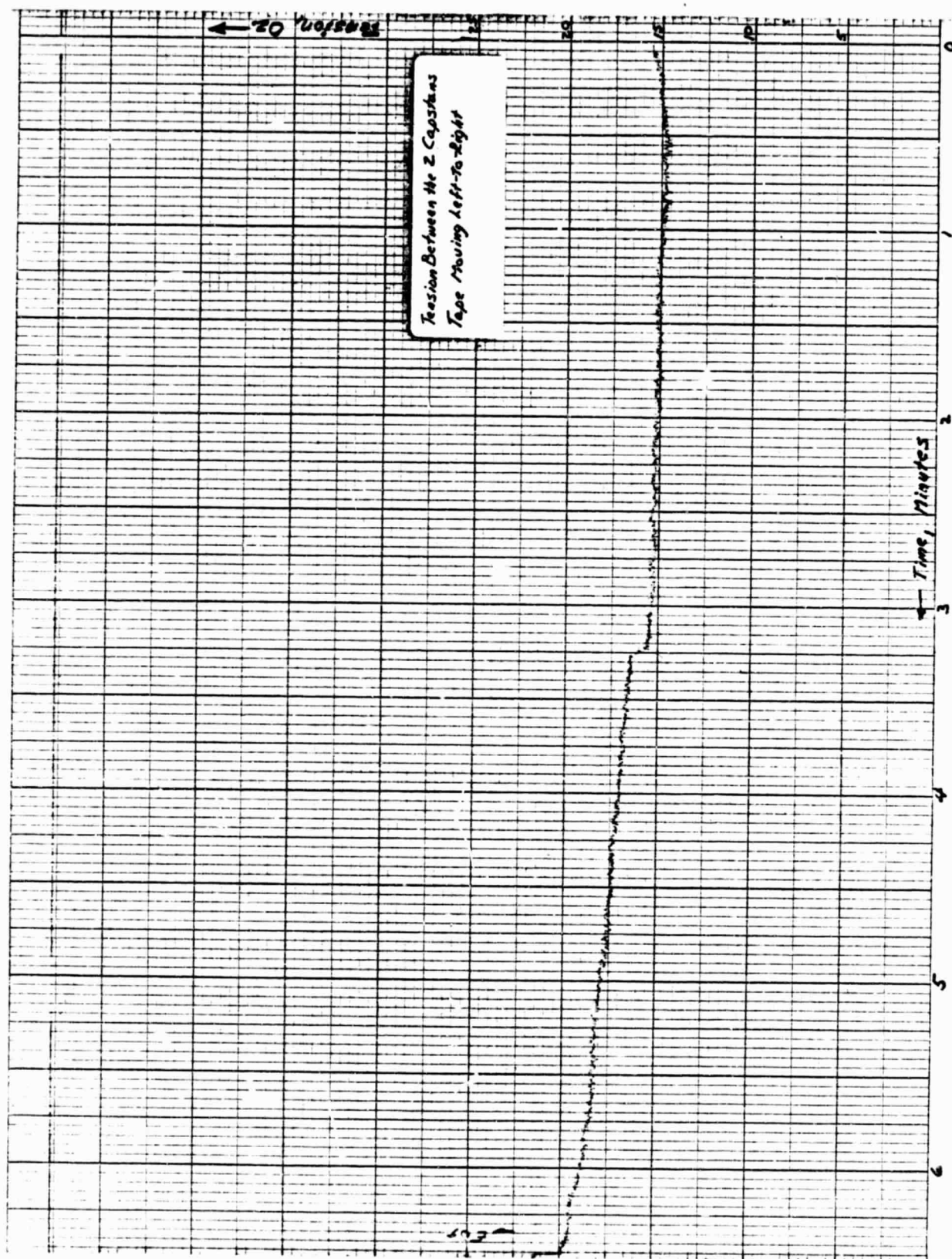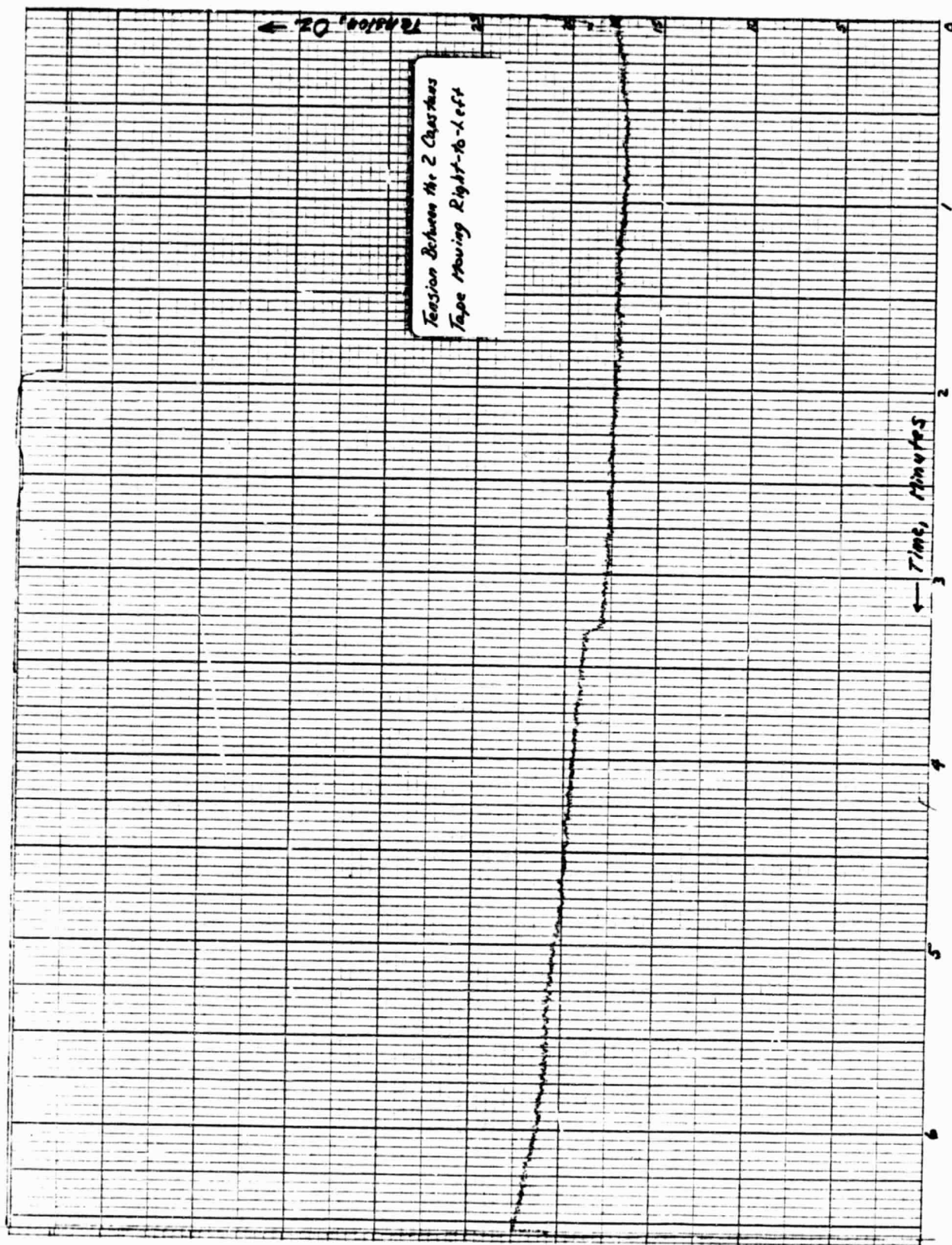Figure 2.28

Figure 2.29

92

C-2

Figure 2.30

93

Figure 2.31

94

The adjustable rollers were removed, and non-adjustable rollers were substituted at the two critical areas near the two capstans. These non-adjustable rollers are estimated to be 3.7 x stiffer than the adjustable rollers. Testing of tape guidance was continued, using the optical transducer to measure the location of the outboard tape edge. Chart recordings (See Figure 2.32) of the transducer signal indicated short term fluctuations and long term variations. The short term fluctuations showed maximum values of 2-3 mils peak-to-peak, and are assumed to represent the "edge signature," and, as such, would have little effect on the head-tape interface of a non-edge-guided system. The long term variations are quite important, particularly the repeatability of tape edge location as a function of tape passage.

The initial tests were made after the four adjustable rollers had been optically aligned for perpendicularity. The first tape load used in testing was 1500' of 1" Ampex 787 tape. The first test data was extremely bad: the absolute variation in one direction was .012". The repeatability was not identified, however, the motion reversal shift at one end of tape was as much as .010". Interchanging two adjustable rollers with 2 fixed rollers, with the hope of benefitting from stiffer roller axes near the capstans, produced little improvement.

At this point the tape was replaced by 1180' of 1" 3M 5198 tape (from the reel procured for the program). Interestingly, with no change in transport adjustments, the absolute variation in one direction was reduced to .007" and the EOT reversal shift (at the same end of tape) was reduced to .005". This confirms the generally held opinion that

selection of tape may be important for guidance, as well as for magnetic performance. A variation in elastic properties across the tape width will cause an initially straight tape, under tension, to have a slight curvature. Also, if the tape has some slight initial curvature this will change under tension. Both of these effects will vary if the tension varies.

The original dual capstans, which were simple cylindrical elements, were replaced by crowned capstans. This produced little improvement, however, the crowned capstans were left in the assembly.

The last change made was a fine "tuning" of the adjustable rollers in an appropriate sequence for direction of tape motion. This improved performance substantially. The absolute variation in one direction was reduced to .003", and the EOT reversal shift was reduced to .0015. The repeatability of edge position appears good. See Figure 2.32.

At this stage it was felt that any further tracking assessment should be done after the head has been lapped and is in position. The tracking losses of the head will depend on the repeatability of the absolute position.

In general, it is now felt that crowned roller guidance of 1" tape can provide suitable tracking precision. What has been clearly established is that the guiding elements must be suitably rigid so that there will be negligible change in their alignment with variation in tape tension forces. Optical alignment of rollers, etc, with the tape removed

(i.e. zero tension load) would be feasible only when deflections under tape tension loads can be restricted to very small angular changes (witness the calculation, cited earlier, of a shift of 0o, 1', 17" of roller axis causing an estimated tape lateral shift of 1.9 mils).

Vertical Scale: .005"/Inch
1" Wide 3M5198 Tape
Tape Speed: 47.3 i.p.s.
Tape Length: 1180 Ft.

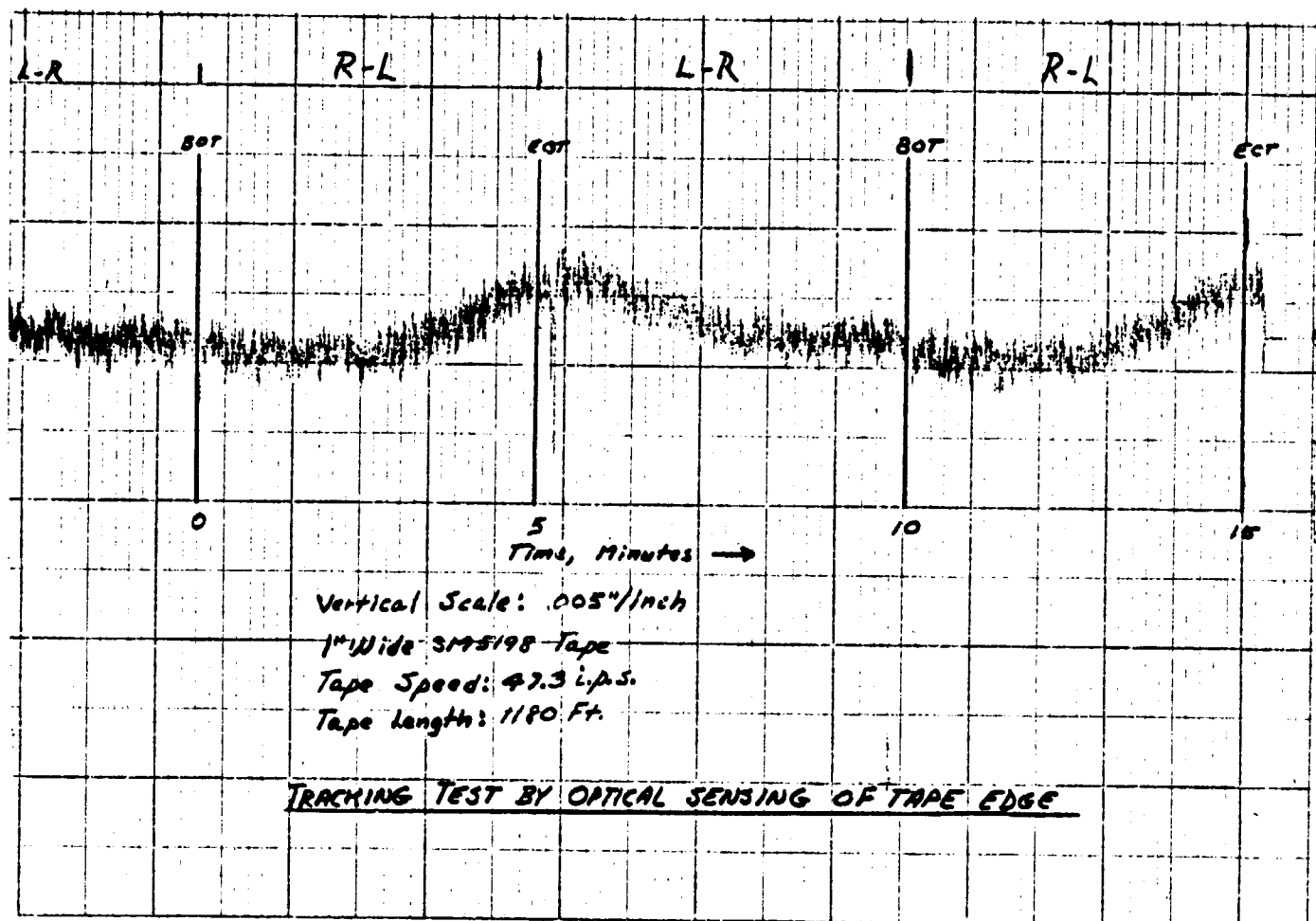TRACKING TEST BY OPTICAL SENSING OF TAPE EDGE

Figure 2.32

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2.3.5 Conclusion

Tape Handling/Guidance

Fixed edge guides, crown rollers and active guidance methods were originally considered. The use of fixed edge guides was not in harmony with the life requirements of 20,000 tape passes. The continued edge damage is a potential source of a great deal of debris. Active guidance employing tape position sensors with servoed training mechanisms were considered too complex for satellite use. It was decided to concentrate on employing crown rollers as the training mechanism. To reduce the stress level on the tape an edge crown profile was used.

The edge-crown roller tape guidance technique proved capable of tracking tape with better than 0.5 mil variation as measured by the signal level changes during playback.