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FINAL REPORT FOR

ANALOG-DIGITAL DATA ARCHIVE STUDY

(30 June 1964 - 10 October 1964)

Contract Number: NAS 5-9710

For Goddard Space Flight Center, Greenbelt, Md.

LINK GROUP OF GENERAL PRECISION, INC.

WDR-96-3

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PREPARED BY

LINK GROUP, GPI
1451 California Avenue
Palo Alto, California

FOR

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

SUMMARY

The Link Group of General Precision, under contract to the National Aeronautics and Space Adminstration, Goddard Space Flight Center, has conducted the Analog-Digital Data Archive Study for the purpose of determining the most suitable method for recording, storing and retrieving of telemetry data. Extensive investigations have been conducted into the problem areas of the present data storage and processing system. The data presented in this report will show methods which would be used to alleviate these problems.

With the advent of high data rate satelittes, the problem of storing data becomes extenisve. Not only does storage space become a vast problem, but also, as the original study specifications point out, magnetic tape must be exercised at least once per year to preserve reliability. Therefore, as years pass by, the problem becomes increasingly complex for exercising tapes. Because of these problems, inducement for immediate exploration of new ideas for reducing storage space and elimination of exercising magnetic tapes has been warranted.

Since a relatively small amount of work has been done in these problem areas, new concepts and ideas will be necessarily advancing the state-of-the-art. Link has emphasized and based its study program for applicable storage media on the specification of having the capability for reliable recovery of data over periods <u>longer than five years</u>. Even though some of the ideas and solutions to the problem of archival storage are advancing the state-of-the-art,

the thought is always present that these methods could be immediately implemented into hardware and be able to solve the immediate storage problems for NASA, and still maintain archival quality for a long period of time. Investigation has been made into a type of medium for long term storage, how the data could be transmitted from magnetic tape to this new medium, a way of providing short-time accessability to the data stored on the new medium, and integration of a data reduction device into the overall system of data processing.

After extensive examination of alternate media, the conclusion was made that photographic film represented the optimum archiving medium. Using this information as a point of departure, a thorough investigation of film chips, disks, and reels was concluded. Mathematical analysis pointed to the use of reel film for the specific task outlined by GSFC. Previous experience and knowledge gained from similar company funded studies, and a breadboard, used in the role of verification of theory, (but not necessarily designed to produce the ultimate in technique), and rigorous mathematical calculation has shown film in the form of reels to be the best method to record telemetry data. Past experience has shown that, with reasonable care, the reliability and fidelity requirement can be met for data retrieval after several decades of storage.

In spite of twenty years use of magnetic recording in a large variety of applications, the recording process on magnetic tape is still not well-defined. Problems in magnetic print-through, cross-talk, and demagnetization must be overcome before magnetic tape can be considered as an archival storage medium. Photographic film was chosen as the storage media because its parameters permitted a thorough quantitative analysis leading to a design of a film recorder and complete system which could be utilized by GSFC.

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I. STATEMENT OF THE PROBLEM

At the present time the GSFC has about 44,000 analog and 10,000 digital magnetic tapes in storage from various satellites. During the next few years high data rate satellites will be launched which will increase these numbers considerably. Calculations have been made which indicate, based on available figures, five years after the launching of the first OGO satellites there would be a total storage requirement from all sources for 240,000 analog tapes and 75,000 digital tapes at the GSFC. Using common practice methods now used in tape libraries, the storage of 7 tapes per cubic foot on shelves seven feet high with 100% additional floor space allowance for aisles would result in a requirement of 12,600 square feet of building space. This corresponds approximately to the useful space in one of the GSFC multipurpose buildings. One reaches the obvious conclusion that an immediate problem is the vast storage area required as the data accumulates. Further, an estimate of the requirement for the near future shows that 130 analog tapes and 45 digital tapes will have to be stored every day; therefore, some immediate solution must be found to reduce the storage space and still retain the data in its true form after several years of storage.

Another problem associated with magnetic tapes is the layer-to-layer magnetic "print-through." Tapes stored over a long period of time tend to be unreliable because of "print-through" or other aging effects. The present solution is to exercise the tapes about once a year to relocate the layer-to-layer magnetic fields and thus minimize the "print-through" effect. However, as large volumes of data accumulate, this operation becomes increasingly difficult. Some other means of storage must be found to eliminate the "print-through" problem.

In summary, immediate solutions must be found for the problems listed which are associated with the present storage methods:

1. Excessive storage space requirement.
2. Periodic exercising of magnetic tapes.
3. Lack of automatic indexing.
4. Manual operations involved in retrieval.
5. High cost of material.
6. Less than optimum reliability.

II. FACTS DOMINATING THE PROBLEM

GSFC specified that this study should center around the following essential characteristics of the data storage system:

A. A volumetic improvement by at least a factor of 100:1 must be achieved.

B. An electronic output from a device must be available to provide an input to the data processing equipment.

C. Magnetic tapes have hand written log information identifying each reel with a particular satellite, pass number, signal quality, etc. Some means should be found to record this information on the new storage medium where it could be reproduced when processed in the data processing equipment.

D. A basic analog storage capability is preferable. An absolute accuracy of ±1.0 percent is required. Higher accuracy of up to ±0.1 percent is desired. The bandwidth capability of the storage medium should not appreciably degrade that available from magnetic tape;

i. e., response to 500 kc when the magnetic tape system is played at 120 ips (inches per second).

E. A new device approach must be operationally more attractive as a system than the existing magnetic tape oriented approach.

Other factors involved which are considered desirable:

A. Capability for automatic access without manual intervention to all data in storage.

B. If complete automatic access is not feasible, capability should be provided for automatic indexing to minimize the likelihood for human error in data retrieval.

C. A significant decrease in the cost of expendable material.

D. Significantly improved reliability (the maximum magnetic tape standard of approximately one bit in error of 10^6 must be maintained.)

E. A capability for reliable recovery of data over periods longer than five years is highly desirable.

III. DISCUSSION

The study program was performed in essentially three parts: (1) search for a desirable archival base material which had excellent storage characteritics and remained dimensionally stable after several years storage; (2) emulsions or magnetic oxide films which could be bonded to a base material and, combining one of these, become the actual storage media; (3) investigation of the problems associated in recording and reproducing on various storage media.

A. Archival Base Material

Some of the various base materials were eliminated at the onset of the study because of obvious limitations. A paper base, for example, deteriorates with age and mildew. In addition, with the current application of paper in the form of punched tape and punched cards, the end result is a low bit storage capacity per unit volume and further limits both recording and reproducing modes. Some other configurations were not considered applicable for archival storage because of one or more of the following listed characteristics:

(1) Low storage efficiency per unit volume.

(2) Poor expandability, that is the system is not open ended.

(3) Ease of handling the material

(4) High accuracy in the construction of reading and writing equipment.

(5) Permanency of the record.

(6) Suitability to variable record length.

(7) Limited reading and writing speeds.

(8) High cost of storage media.

(9) Flexibility of use compared with access time.

(10) Adaptability to future information storage equipment.

(11) Compatability with future improvements in the state-of-the-art of recording and writing methods.

The investigation finally centered on two different materials, glass and polyethylene terepthalate. Polyethlene terepthalate is known by the more familiar names of "Mylar" (Dupont) or "Estar" (Eastman Kodak Company).

1. Glass has yet to be surpassed as a base material in critical applications where dimensional stability is

paramount. This applies when exact register of size holding is essential, or when temperature, humidity, and other factors make it difficult to hold size accurately. Glass has even greater dimensional stability then the steel gage blocks used for standardized measurements. Its humidity coefficient is nil and, possessing a thermal coefficient of expansion of only 4.5 microinches per inch per degree Fahrenheit, glass is roughly three times as stable as aluminum in this respect, twice as good as bronze, significantly more stable than "stable" plastic bases, and excels hardened steel. Any dimensional changes due to temperature effect are truly reversible.

Thus, subject to the usual limitations of weight and fragility, the three unique properties of glass-base plates which can be used to solve design problems are:

(a) no measurable humidity coefficient of expansion.

(b) The thermal coefficient of expansion of glass is the lowest of any of the base materials investigated.

(c) A degree of flatness can be provided with glass, when required, that is unattainable with other base materials.

2. Since the purpose of this study program is to provide the best means possible of storing data for periods of several

years or into the decades, the moisture properties, mechanical properties, dimensional stability, etc., of polyethylene terephthalate were taken from the Kodak Estar specifications since their familiarity with archival storage would be extensive, and the base characteristics of the polyester base would apply in the final analysis along with the material or materials bonded to it.

The polyester base material is almost completely a function of the relative humidity of the atmosphere to which it is exposed, not of the absolute humidity. In other words, the base has its own equivalent relative humidity which is the relative humidity of the air with which the base is in equilibrium, rather than to its moisture content. The physical behavior of the polyester base is a direct function of its equivalent relative humidity.

When Estar base is changed from one relative humidity to another, a certain amount of time must elapse before it establishes equilibrium in its new environmetal relative humidity. Figure 1 shows the moisture gradient of a roll of processed film of Estar base when changed from $70^{\circ}F$ - 50% RH (relative humidity) to $70^{\circ}F$ - 5% RH. One must conclude that a polyester base should be kept in an atmosphere where the RH is 45 ± 5% in both the record and reproduce modes. If the humidity differential is not minimized, such conditions as curl effects, frictional differences or dimensional distortions occur.
If, for example, the polyester base is wound in reel form, a lengthwise curvature results because the inside surface is under compressive stress and the outside surface under tensile stress. This

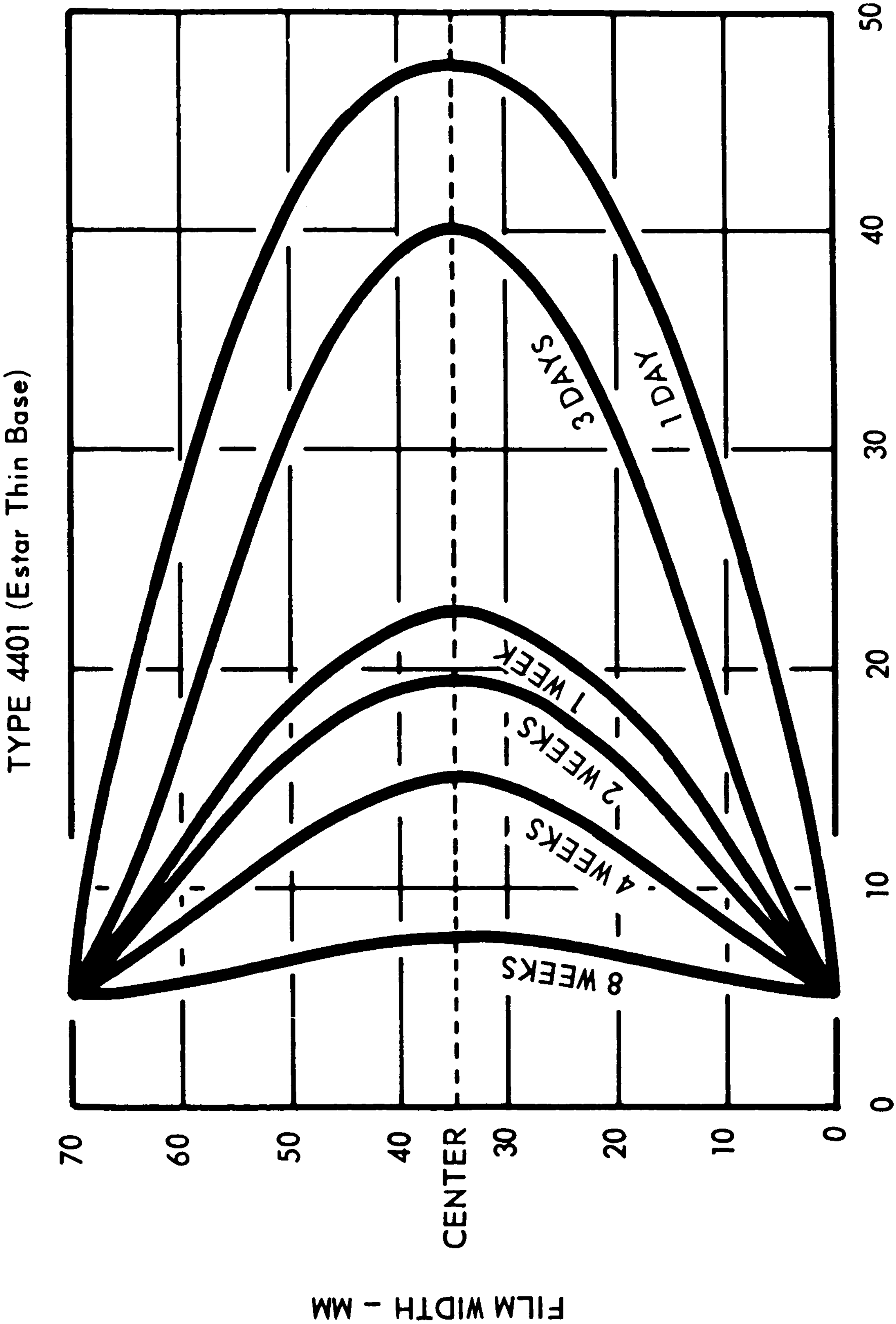


Figure 1 Moisture Gradient of Estar Base

phenonmenon of lengthwise plastic flow of a base that is held in rolls is usually referred to as "core-set" and will result in a curl effect.

Extensive dimensional stability measurements were made by Kodak. Unless otherwise indicated, all measurements were made by the pin-gage method as described in "American Standard Method for Determining the Dimensional Change Characteristics of Photographic Films and Papers, PHl. 32-1959, " with a 10-inch gage length on strips 35 mm wide. Estar polyester bases are manufactured with a high degree of uniaxialism, i.e., it is stretched in both the length and width directions. Consequently, any slight preference in molecular orientation in one direction in the plane of the sheet may not be in the length or width direction. The maximum dimensional change may lie in some direction between the length and width, for example, in a diagonal direction. However, the base is manufactured so that any difference in properties is quite small. Experimently, using the pin-gage method, the thermal coefficient of the Estar polyester base is 0.0015% per degree F measured between 70F-20% RH and 120F-20%RH. The aging shrinkage is the result of plastic flow and some mechanical strain release of the base. The shrinkage of the Estar base is 0.06% after three years at 78F-60% RH, as shown in Figure 2. Most of the shrinkage takes place in the first year, since after one year of aging, a 0.05% reduction was noted with storage at 78F-60% RH.

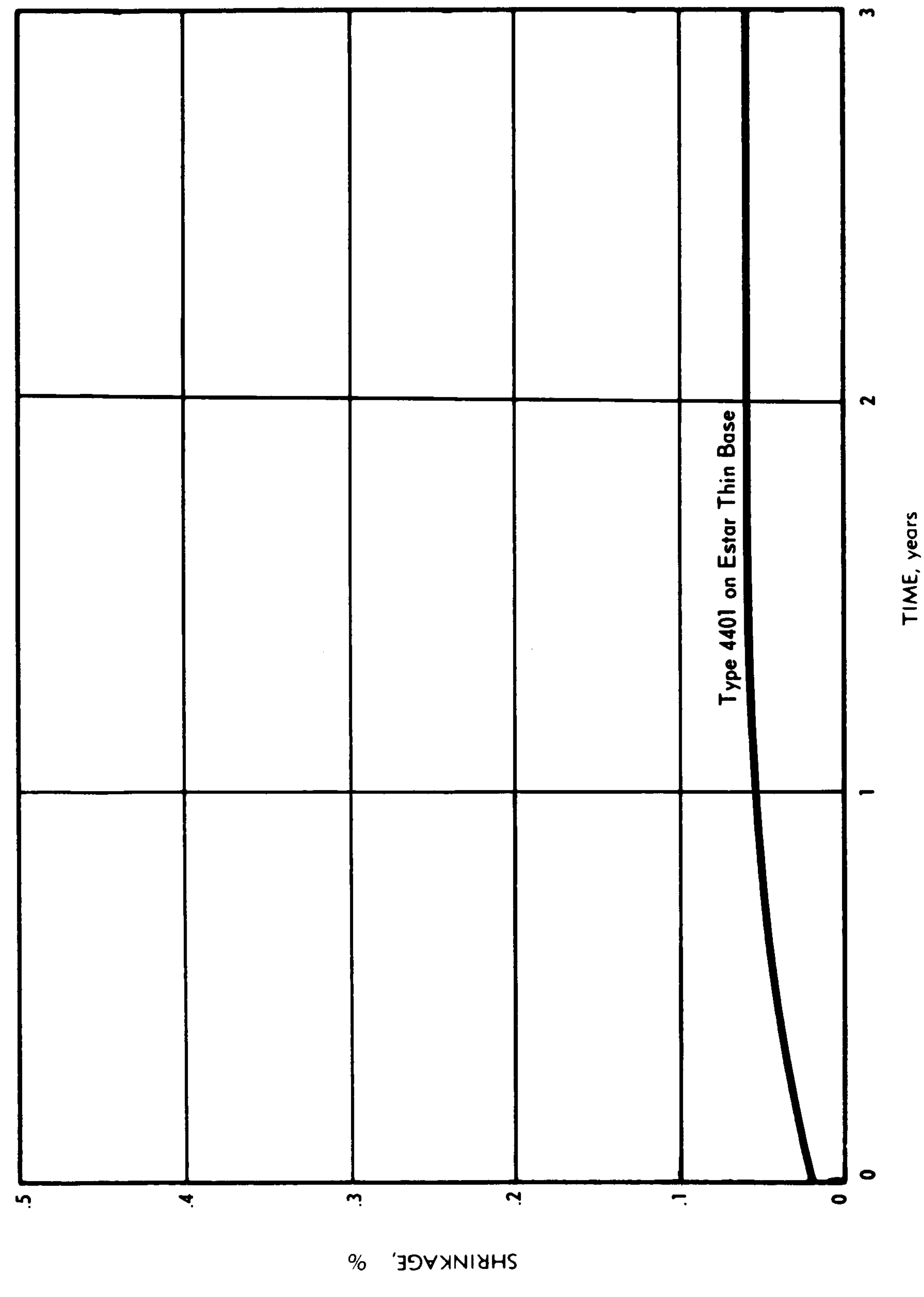


Figure 2   Aging Shrinkage of Estar Base

B. Investigation of Complete Storage Media

Basically, two different methods of recording and reproducing of high speed data are used. These are the electro magnetic and the optical methods. Pure mechanical methods must be discarded. For example, some punched tape systems have used plastic tape which is considerably stronger than paper and is more permanent for archival storage, also, this material can be transferred at high speed; however, it is more difficult to perforate in the recording process. Stainless steel ribbon has also been tried but aside from its excellent storage life characterisitcs it has the same limitations and storage capacity as other punched tape media. A thermal mode might be used where a Laser beam could etch in some material; however, this method was not investigated because of the limited amount of time for the study.

With the two above different methods of recording and reproducing being used, (electro magnetic and optical), the investigation of a complete storage media was directed toward magnetic tape, photographic glass disks, and photographic film in reels.

1. Magnetic Tape

The majority of magnetic tape used today has a polyester base for use in high grade high resolution applications. The general construction of most tapes comprises a magnetic coating adhered to a flexible plastic carrier: a single magnetic coating is generally used. With a very few exceptions, the magnetic material used is gamma ferric oxide in the form of needle shaped particles.

A paper presented at the International Conference on Nonlinear Magnetics in April 1963 [1] gives detailed data on magnetic tape recording materials. Both base and coating are made as thin as possible to achieve a maximum volume density of information in a recording. Provided equivalent physical properties can be maintained in thin base layers, the limiting factor will be the magnetic printing effect between adjacent layers in the wound tape. As the magnetic coating thickness is reduced an additional problem arises due to a relatively greater undesirable amplitude modulation of the reproduced signal caused by mechanical flaws in the coating.

Not only must a magnetic layer be considered from the viewpoint of maximum surface field for reproducing, but also, a large field is undesirable with respect to the printing of signals between layers of tape. In addition, the magnetic material of the tape should be insensitive to remagnetization by small d. c. fields, which may be accompanied by other energies such as temperature rise or external a. c. fields. The basic phenomenon involved is magnetic viscosity due to thermal fluctuations. When a magnetic field is applied to a material consisting of single domain particles, the resulting change in magnetization may take a finite time due to relaxation effects. For the same reason, when the field is removed, the magnetization may gradually decrease with time. The magnitude of this phenomenon depends critically on the particle volume and the temperature. In general, if the volume is small enough to be in the range where single-domain properties give way to superparamagnetic properties, then applied fields smaller than those necessary to switch the single-domain particles can, in time, produce further magnetization in the field direction. Low susceptibility to unwanted printing effects during tape storage would then seem to be obtained if the particle volume distribution can be restricted.

The trend towards high resolution tapes on which shorter wavelengths are recorded reduces the severity of the print-through problem since the printing field from adjacent recorded layers in a tape is reduced when the ratio of recorded wavelength to layer separation is small. New oxides are being developed which may reduce the magnetic layer thickness and still produce the required recording and reproducing characteristics. Another paper presented at the above conferece [2] gave data pertaining to saturation recording using chemically deposited cobalt. This material could potentially be a new magnetic tape medium.

At the 1964 INTERMAG Conference, a paper was presented [3] where a nickel-colbalt material was discussed. As stated, a thin magnetic surface not only facilitates sharper magnetization reversals by the writing transducer, but it is also better able to resist demagnetization. However, at very high densities (bits per inch), self and adjacent bit demagnetization become increasingly significant with a subsequent fall-off of the output signal. It is this critical demagnetization region that is considered in this paper. An expression is derived for the density of the recording as a function of the magnetic parameters of the recording medium and the thickness. Using saturation recording, the equation is tested against several Ni Co surfaces where composition and thickness are purposely varied. A favorable agreement is found between the densities calculated and those achieved experimentally. As shown in Figure 3, frequency response curves of output versus density were measured for the various recording surfaces, where Vs is playback voltage, H is oersteds, M is in emu, and the numbers on the graph represent various samples of the magnetic material. The measured bit density, the maximum density before the signal drop-off, was selected. In other words, the measured bit density corresponds to the knee of the frequency response curve. The signal at densities lower than the optimum bit density would be constant because demagnetization does not seriously alter the magnetization of the recorded bits at these densities for square loop materials. Therefore, the calculated density is the optimum density before appreciable signal fall off.

One of the most complete derivations on magnetic print-through was done by E. D. Daniel and P. E. Axon of the British Broadcasting Corporation in 1950. Even though magnetic tape design has advanced considerably since then, the mathematical derivations relating to print-through are general enough in nature to be applied to present day tape design. The report is printed in its entirety in the Appendix. An approximate analysis of this derivation shows that the ratio of printed to recorded magnetization should first rise with frequency at approximately 6db per octave, reach a maximum, and then decrease rapidly as the frequency is raised still further. At a given frequency, the print level should decrease exponentially with distance between layers, the attenuation per layer being proportional to the frequency.

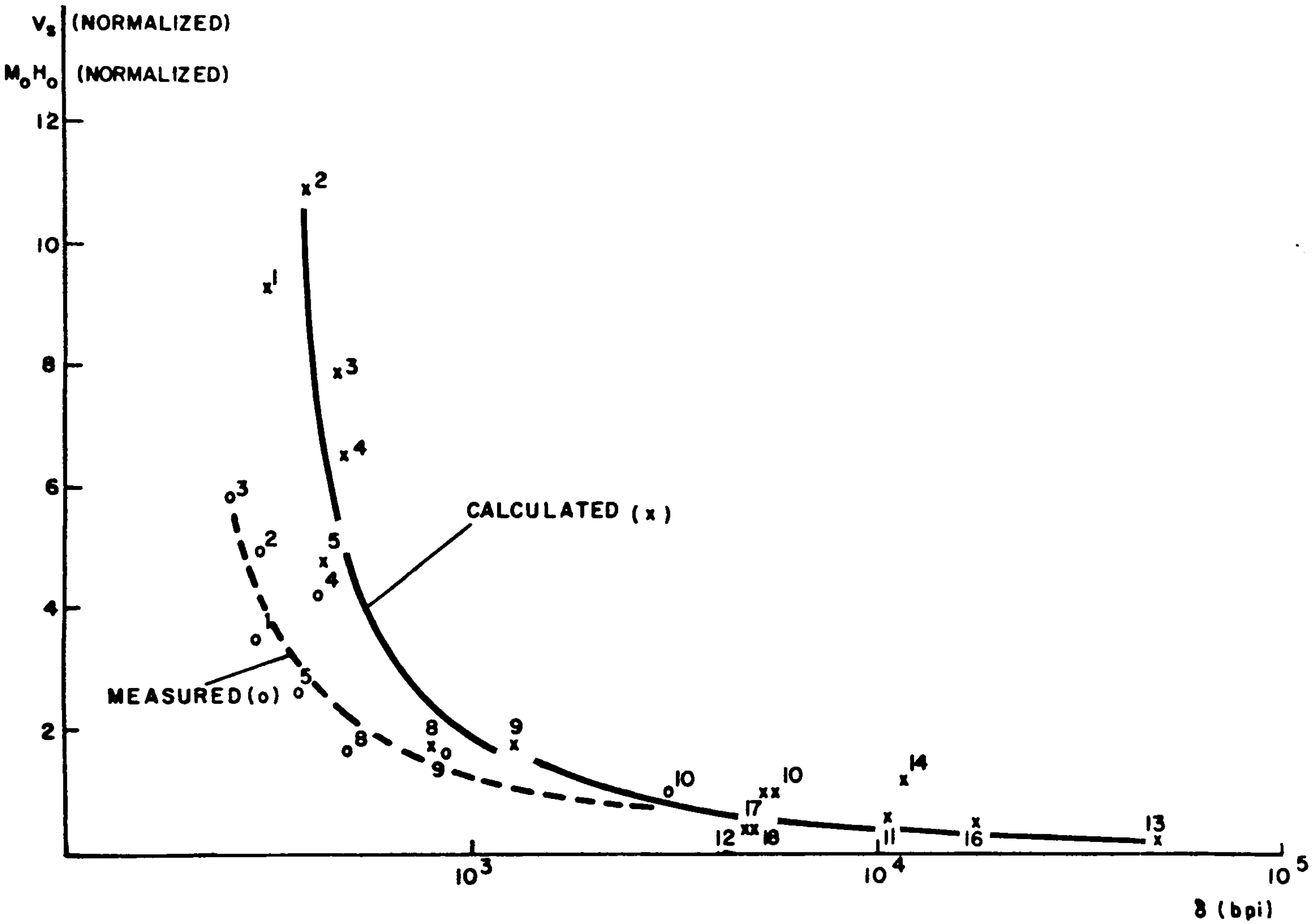


Fig. 3 Normalized output vs bit density.

New techniques are being developed for making magnetic tape withstand higher environmental, mechanical and electrical stresses. A report by the U. S. Army Electronics Research and Development Laboratory analyzes present day magnetic tapes for dimensional stability when subjected to extreme environmental conditions. Results of some new tapes being developed are included in the discussion. Since the polyester base is discussed rigorously, the report is included in the Appendix as a supplement for both the Complete Storage Media and Archival Base Material sections.

2. Photographic Glass Disks

Photographic glass is a highly transparent, amorphous (or non crystalline) material that is rigid at ordinary temperatures and melts at about 2,600F. Glass has no definite freezing point but becomes solid because its viscosity increases progressively to infinitely high values at ordinary temperatures.

Glass for photographic plates is of the soda-lime type. The main glass-making constituents - soda, lime and silica - are melted at high temperatures in enclosed refractory furnaces or tanks. The sheet is formed at the surface of the melt and the glass is drawn from the fluid melt in a wide, continuous, flat, clear sheet by mechanized drawing equipment which controls the width, thickness, and other physical characteristics of the sheet. The surfaces on the drawn sheet are produced as a brillant fire-polish as the sheet is being formed.

The glass sheet solidifies as a supercooled liquid, and a crystalline structure is prevented from forming by the infinitely great viscosity of the material. For this reason, photographic glass has no grain or molecular orientation. The final sheet is highly transparent, flat, strong, and free of strain.

Photographic plates have several emulsion or gelatin layers which fairly readily absorb and release water. Depending on the initial conditions, and their later treatment and processing, the gelatin layers exhibit a strong tendency to expand or contract with changes in relative humidity.

These forces, in the case of flexible supports, give rise to tensions or compressions between the base and gelatin layers which, in turn, can cause dimensional changes because the base cannot resist the stress. In the case of photographic plates, however, the base is inherently very strong and has a very high yield point. The emulsion and gelatin layers are bonded firmly to the glass base, and thus are prevented from expanding or contracting. In turn, the high strength of the glass base is capable of completely resisting the tensile or compressive forces exerted by the emulsion or gelatin layers which would otherwise lead to dimensional changes.

Since the photographic emulsion is firmly attached to a glass base, it changes only in accordance with the temperature coefficient of expansion of the glass. During process, the wet emulsion layer swells vertically, but other dimensional changes are restrained as outlined above. During the drying process the lateral dimensions of the layer remain essentially unchanged, but the vertical dimension may vary according to the treatment. Thereafter, the layer does not change dimension independently of its glass base.

Photographic glass has a useful transmission from approximately 350 millimicron wavelength in the ultraviolet region of the spectrum to the 2,500 millimicron wavelength in the infrared region. Except for some absorption at 900 millimicrons, the transmission is in excess of 85 percent throughout this wave-length region.

3. Photographic Film in Reels

Three different materials were considered for use in archival storage which could be bonded to a polyester base. The materials are silver halide emulsion, Kalvar and Diazo. They will be discussed later in detail.

Initially, two parameters must be considered in the study of various films, along with the various environmental characteristics. They are the spectral transmittance and contrast characteristics. Spectral transmittance will not be discussed in great detail since, obviously, the film and the light source exposing it must lie in the same well-defined area of the spectrum for optimum energy transmittance. Comment will be made in the discussion of each material indicating the spectral-transmittance properties.

Contrast in film technology is referred to as the sensitometric properties pertaining to the response of the film in terms of the degree of blackening, or optical density, of the developed image produced as a result of exposure to radiation.

The best method of presenting sensitometric data is with the characteristic curve. This is a plot of the response, optical density, versus the logarithm of the exposure. Such a curve is obtained by subjecting the photographic material to a series of exposures, each greater by a constant factor than the preceding exposure, and then processing the material and reading the resultant densities with a densitometer. When the density of each deposit is plotted against the logarithm of the exposure which produced that density, a curve can be drawn through the points so plotted. This curve is the "characteristic curve" shown in Figure 4.

> NOTE: One should notice the striking similarity between this curve and a B-H curve of magnetic materials. This would indicate that the same considerations would be made in selection of either photographic film or magnetic tape, depending on the type data being recorded. For example, in the recording of digital data a high contrast material would be selected for film, and a magnetic material for magnetic tape would be selected which would require a relatively small magnetic field for proper molecular orientation, both curves being practically identical in form.

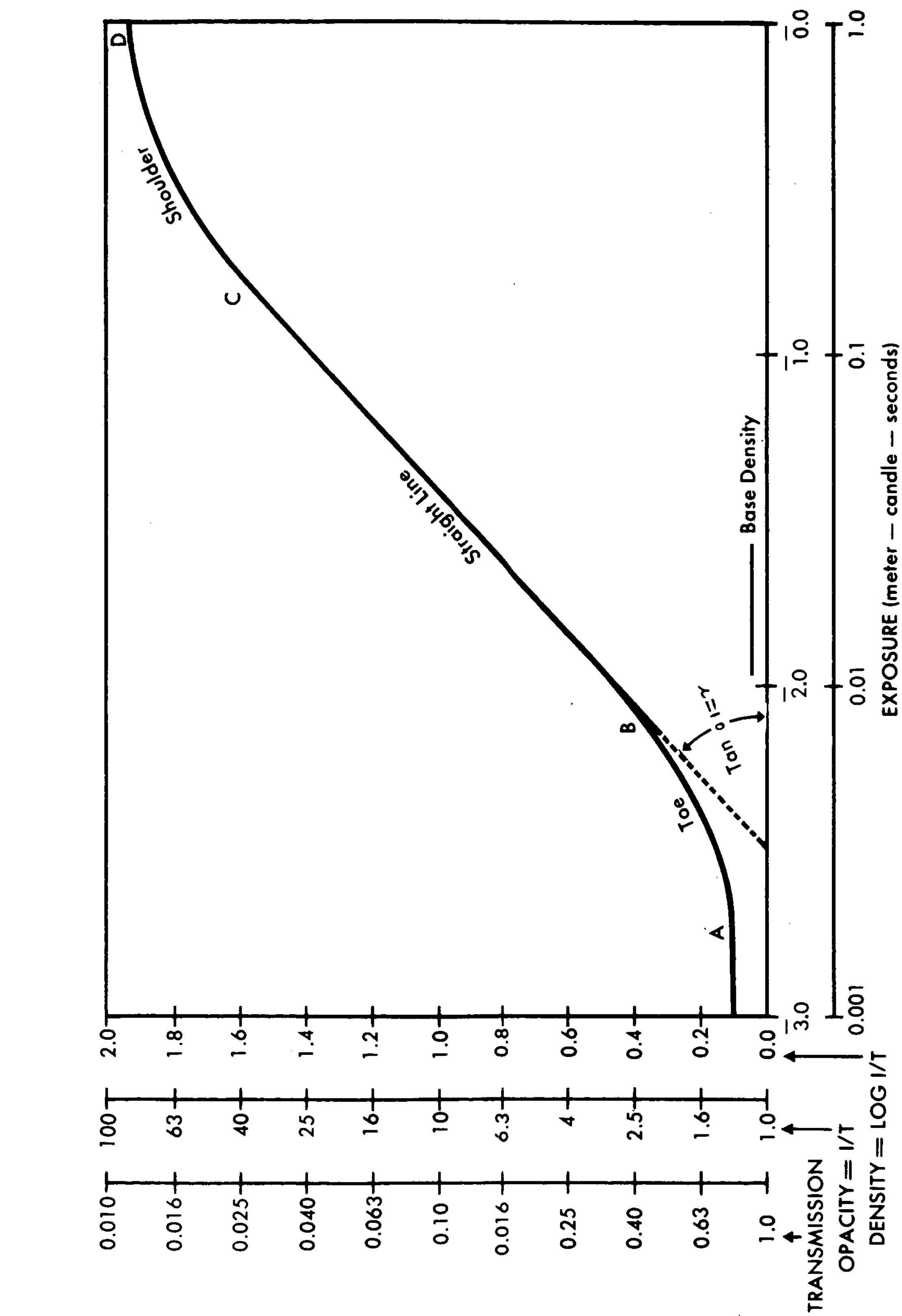


Figure 4 The Characteristic Curve

Density is defined as the logarithm of the opacity of the deposit. Density is derived as follows:

$$\text{Transmission} = \frac{\text{Transmitted Light}}{\text{Incident Light}}$$

Since the opacity is low if the transmission is high, and vice versa

$$\text{Opacity (O)} = \frac{1}{\text{Transmission (T)}}$$

and

$$\text{Density (D)} = \log O = \log \frac{1}{T}$$

In sensitometry, the term "exposure" refers to the total amount of luminous energy which acts on the photographic material. It is usually expressed in meter-candle-seconds; the logarithm of the exposure in meter-candle-seconds is used in plotting the characteristic curve.

The slope, or gradient, at any part of the curve indicates how rapidly the density changes with changes in exposure. Because of its general shape, the characteristic curve can be divided into three distinct regions, as follows:

<u>TOE</u> - For exposure less than that at A (Figure 4), no image density results upon development. The density at A (known as "gross fog") is the density of the base or emulsion support plus fog density produced in development. The point A represents the threshold exposure which will produce density above fog. From A to B (the toe region), the slope or gradient, increases with increasing exposure.

<u>STRAIGHT-LINE</u> - The portion of the curve from B to C is the range wherein the gradient is constant and the density increases as a direct or linear function of the logarithm of exposure. In recording of analog information on film, it is essential that the exposure be placed on the straight-line portion of the characteristic curve. Also, to reduce graininess, the exposure range should be held as low on the straight-line portion as possible.

<u>SHOULDER</u> - Above C, the region of overexposure, the gradient of the curve decreases for further increases in exposure. Eventually, the curve becomes horizontal, with exposure differences no longer recording as density differences. The density of the horizontal part of the curve is usually noted as D_{max}.

<u>GAMMA</u> - The slope of the straight-line portion of the characteristic curve is designated as "gamma (γ)." The numerical value of gamma is defined as the tangent of the angle made with the exposure axis. Gamma serves as a convenient method of expressing contrast and depends partly on the characteristics of the emulsion and partly on the degree of development.

Silver halide emulsion has been used for many years. There are well preserved photographs today, taken by Daguerre as early as 1847, which indicate the length of life of the silver emulsions with respect to opacity and permanency. This is due, no doubt, to the metalic nature of the image forming elements in this media. Silver halide emulsions may be obtained in both normal and high contrast grades. The normal grade yields a good gray scale with a log 1.0 density range for recording analog information with true photographic quality. A high contrast grade will give a sharper defined black and white boundary and is the type used for microfilming documents and records. This later grade is more suitable for recording of digital bits since it is capable of higher signal-to-noise, light to dark, ratio. The spectral transmittance of the silver emulsion is not confined to one particular area. Different type films have different spectral curves, each covering its own particular area.

Kalvar requires a high intensity ultraviolet light for exposure. Images are formed by a chemical change in a thin layer coating on exposure. This image is made up of minute spherical bubbles rather than silver particles. These bubbles disperse transmitted light instead of absorbing it but produce a similar type of image in projection. Kalvar is primarily a high contrast material intended to maximize the difference between light and dark areas. Its suitability to the reproduction of gray scale values is poor since the diffusion effects of the Kalvar are not as effective as the absorbtion effects of the silver emulsion. The chemical centers are developed by direct application of infrared to expand them into small uniform bubbles.

The Diazo material also requires high intensity ultraviolet light for exposure. Images are formed in the surface of the base material by dye impregnation rather than in a coating of emulsion. The image forming element is a dye nucleus considerably smaller than the silver grain or the Kalvar bubble. The dye image acts in a similar manner to the silver image under projection and viewing, however, it is considerably more transparent to the infrared wavelengths. Diazo images are printed by exposure to ultraviolet light. The image is intended for high contrast and is not ideally suited to true presentation of gray scale values since the dye is absorbed at a constant density.

Further discussion is required on environmental and dimensional stability of photographic film when an emulsion is bonded to the polyester bases. Kodak handbooks have many tables and graphs of characteristics of film when subjected to temperature differentials of 50°F and changes of 50% RH which indicate that care must be taken in storage of film to be able to retain dimensional stability. If temperature and humidity are controlled, photographic film is very stable. An example is cited of Estar base film where the temperature and RH at time of exposure was 90°F and 60%. At the time of printing the temperature was changed to 70°F and 50% RH. The net size change due to change in temperature and change in RH was -0.009%. These measurements were made in 35 mm X 10-inch specimens. Since the photographic film was a polyester base, above cited, the dimensional changes due to temperature and RH must be considered in analyzing magnetic tape since both photographic film and magnetic tape use the same base.

C. Investigation of Recording and Reproducing Techniques Associated with Storage Media

Work was directed toward the various methods and problems of recording and reproducing as associated with the three different storage media.

1. Photographic Disk

Some work has been done in the area of recording information in a digital format on a disk for use in archival storage [4] utilizing an electron beam. A storage density of 10^6 bits/cm has been attained. The method used, however, would not be directly applicable to our problem because of the requirement to record seven data tracks simultaneously. To maintain the same time relationship between each track requires that all tracks be recorded on the same disk. This would be difficult physically to locate seven electron beam recorders on one disk. If each data track was recorded on a separate disk, not only would the timing between disks on playback be a difficult problem but also, the volumetric efficiency would go down considerably. Another problem of electron beam recording is the requirement for a demountable vacuum system. The basic assumption should be made then, that all seven tracks would be recorded on the same disk.

First of all, calculations were made to determine how many bits are stored on an analog tape. If the tape is 2400 feet long and 0.5 inches wide, then the tape has 14,400 in.^{2} for storage. Further, if the tape speed is 120 in./sec., the frequency is 500kc, and from information theory, we can define one period of a sine wave with a minimum of two bits, then

$$\text{Bit Size} = \frac{(120)}{(500)\ 10^3\ (2)} = 0.120 \text{ mils}$$

in the longitudinal direction.

Regardless of each track width, the total width of the tape must be considered in volumetric efficiency; therefore, each track would be approximately 70 mils wide, so the total area per track per bit would be 8.4 mills^2/bit. The total storage per track would then be

$$\text{Total Storage} = \frac{14,400}{(8.4)\ 10^{-6}\ (7)} \cong 2.45 \ X10^{8} \ \text{bits/track}$$

For recording analog data, the recording on the disk would be made with a continuous motion transport; therefore, each track recorded from magnetic tape would have its own section on the disk, i.e. there would be seven separate sections on a disk. Following are calculations made to determine the size disk needed to store all the information from one reel of analog magnetic tape. Within each section of the disk the recording would begin at the outermost edge and progress inward in a spiral fashion. Let us assume a cathode-ray tube (CRT) is used as the light source, and a spot size of 0.25 mils is generated. Further, after making a complete revolution the spot will be displaced inward 1.5 mils radius from its original setting. The bit density will obviously be greatest near the center of the disk and decrease as we move outward so calculations are made for the bit density in each section progressing from the center outward, also the bit density remains the same from the inner radius to the outer radius of each section. The area per bit in the first section nearest the center would be

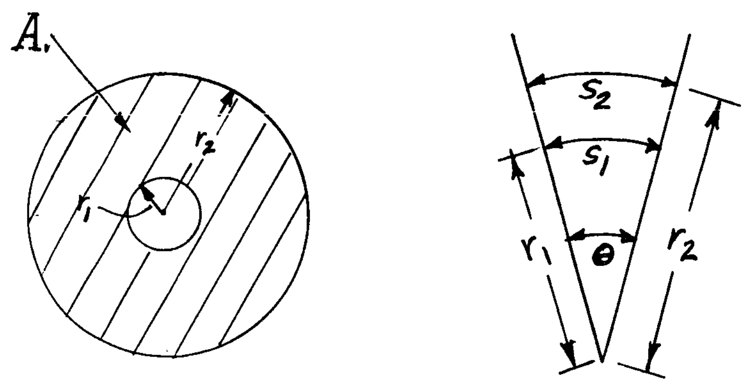
$$(0.25)(1.5) = 0.375 \ \text{mills}^2/\text{bit}$$

and if 2.45 X 10^8 bits must be stored per section, then,

$$(2.45)10^{8} \ (0.375)10^{-6} = 91.875 \ \text{in}^2$$

area is required for the first section.

Now the area of the section can be defined as



where A is the area of one section and s is the distance between bits. Let us assume the hub on the disk will require 0.5 in. radius. Then

$$A = \pi r_2^2 - \pi r_1^2$$

and $91.875 = \pi r_2^2 - \pi (0.5)^2$

$$r_2 = 5.431 \text{ inches}$$

Since θ is the only constant and $s = r\,\theta$ then

$$\theta = \frac{0.25 \text{ mils}}{0.5 \text{ in. radius}} = 0.5 \text{ milliradians}$$

If we assume no gaps between sections then the bit density for the second section will be

$$s = (5.431)(0.5) = 2.715 \text{ mils}$$

The area per bit in the second section will be

$$(1.5)(2.715) = 4.073 \text{ mils}^2/\text{bit}$$

and

$$(2.45)10^8 (4.073) 10^{-6} = 997.885 \text{ in}^2$$

is the area required for the second section. The inner radius for the third section is

$$997.885 = \pi r_3^2 - \pi(5.431)^2 - \pi(0.5)^2$$

$$r_3 = 18.638 \text{ inches}$$

One does not have to proceed further to show that we will have a huge disk to store all seven tracks of magnetic tape. Let us go back and examine the definition for distance between bits more closely. The nearer to the center of the disk we begin recording the larger the angle θ will be if s is held constant. The thought occurs then to decrease the angle θ by starting the recording farther away from the center. The question then is how far this distance should be. The spot size of the CRT must be considered as we decrease θ, therefore it would seem that we have a function similar to an equilateral hyperbola where we asymptotically approach some constant, this constant being a function of the CRT spot size. This would indicate that a relationship could be derived between the inner and outer radii of a section, where the bit density ratio would approach 1 for optimum packing density. If we again examine the diagram, then

$$A = \pi(r_2^2 - r_1^2)$$

and

$$s = r\theta$$

so

$$A = \pi \left(\frac{s_2^2}{\theta^2} - \frac{s_1^2}{\theta^2} \right)$$

$$s_2^2 = \frac{A\theta^2}{\pi} + s_1^2$$

$$s_2 = \sqrt{s_1^2 + C_1} \qquad \text{Where } C_1 = \frac{A\theta^2}{\pi}$$

Now to determine the optimum ratio

$$\frac{ds_2}{ds_1} = \frac{s_1}{\sqrt{s_1^2 + C_1}}$$

and as s_1 becomes larger we have

$$\frac{ds_2}{ds_1} = \frac{s_1}{\sqrt{s_1^2}} \cong 1$$

where

$$C_1 << s_1^2 .$$

C_1 can be neglected when $s_1^2 \geq 10C_1$,

therefore,

$$s_1 = \sqrt{10C_1} = \theta\sqrt{\frac{10A}{\pi}}$$

and by substitution,

$$s_2 = 1.049s_1$$

or

$$r_2 = 1.049r_1$$

and

$$A = 0.1\pi r_1^2$$

If we again make the same assumptions for spot size and bit storage as before, then

$$(2.45)10^{8}\ (0.375)\ 10^{-6} = 91.9\ \text{in}^{2}$$

$$\text{and } A = 0.1 \quad r_1^{\,2}$$

$$r_1 = \sqrt{\frac{91.9}{0.1\pi}} \approx 17.09 \text{ in.}$$

$$r_2 = 1.049\ r_1 = 17.93 \text{ in.}$$

In looking back at the initial calculations on the disk one observes that the ratio between r_1 and r_2 was 10.862, and 3.432 between r_2 and r_3, whereas, in the latter derivation the ratio remains constant.

Our conclusion is proper then, that we have optimized bit density.

To proceed, if the previous assumptions are made that there are no gaps between sections and the bit density remains the same from the inner to outer radius on each section, progressive calculations are made for each section outward to determine the diameter, or for a first approximation, the diameter of the disk to record 7 tracks of magnetic tape will be

$$d = (2)\ (1.049)^{7}\ (17.09)$$

$$d = 47.8 \text{ in}$$

Since we are interested in volumetric efficiency in the final result, let us assume the disk is 0.250 inches in thickness, then

$$V = 0.250\,[\pi\,(23.9)^2]$$
$$V = 448 \text{ inches}^3$$

The volume of a standard magnetic tape is

$$V = 0.5\,[\pi\,(5.25)^2]$$
$$V = 43.3 \text{ inches}^3$$

Then the volume for storage would have to be increased instead of decreased by a considerable degree. To take advantage of the excellent environmental characteristics of glass investigation should be made to generate a smaller spot size, however, this development would take time and would not fulfill the immediate needs of GSFC.

2. Magnetic Tape Recording and Reproducting

Some of the new investigations in magnetic tape recording indicates that higher order bit packing densities are possible [5] [6]. One method uses envelope orthogonal signals to encode binary data during the recording process, and matched filters are used to recover these signals during playback. Using a longitudinal instrumentation tape recorder, packing densities as high as 5000 bpi with error rates on the order of one part in 10^8 can be achieved. The other method uses vestigial-sideband phase modulation and synchronous detection techinques. Also using a longitudinal tape recorder, packing densities of 5000 bpi were achieved, and extrapolating from results 10,000 to 20,000 bpi could be recorded on available recorders. These methods, however, are concerned mainly with digital information and cannot be applied directly to the problem at hand.

In searching for a method of recording analog data, where we are effectively making an analog-to-analog conversion to increase the volume tric efficiency, the requirement of 500 kc bandwidth in each channel must be kept in mind.

Suppose, for example, a scanning system could be used where a scanner would electronically sample and rotate through each channel and generate one composite waveform which could be recorded on magnetic tape. This system would be analogous to the PAM system used in telemetry. Again, as stated elsewhere in the report, if one period of a sine wave could be defined with two samples, then a sample must be taken once each microsecond in each channel. This says that the scanner must, starting with channel 1, sample thru channel 7 and return to channel 1 for the second sample in 1 microsecond. The maximum time allotted for each channel would be approximately 143 nanoseconds. If allowance of 100 nanoseconds is made for rise and fall time and disappearance of ringing in the circuitry involved, the time remaining for the actual sample would be 43 nanoseconds. Because of the short time of the sample, the commutation and reconstruction of each channel, the use of this method would be highly questionable if the specification for an absolute accuracy of ±1.0 percent for analog system is to be maintained. It is certainly beyond the present state-of-the-art for high-speed scanners and could not be immediately utilized by GSFC.

A feasible method for multiplexing seven channels would be a frequency division system, or an FM/FM system as similarly used in space telemetry. Figure 5 shows the block diagram of such a system. Information is applied by frequency modulating each sub-carrier oscillator (SCO) by the appropriate channel. Each SCO has a unique frequency. All SCO outputs are summed together at the mixer amplifier, and the composite waveform is applied to the video tape recorder. In the playback mode, the output from the video tape recorder is applied to the band-pass filters (BP), which separate the composite waveform into the each individual unique frequency. The sub-carrier discriminators (SCD) and low-pass filters (LP) then reconstruct each channel frequency as originally applied by the instrumentation tape recorder.

Since a system of this type is complex when viewed microscopically, only a qualitative discussion will be made of each block to obtain a general understanding of the overall system concept.

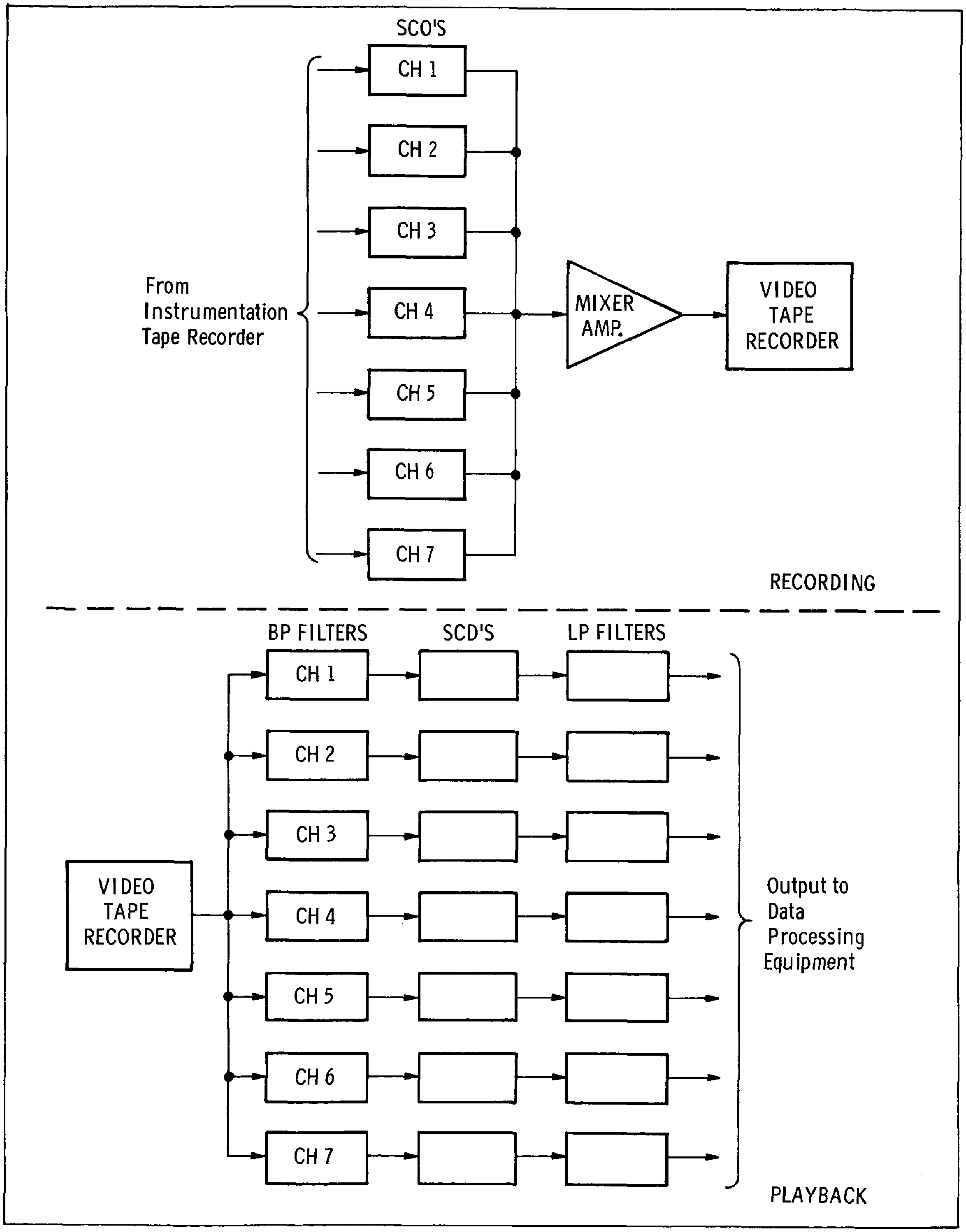


Figure 5 Frequency Multiplexing System

The SCO is a voltage-controlled oscillator of the relaxtion type, where the oscillator free-runs at some nominal frequency when 0 volts is applied to its input, and will deviate linearly from that nominal frequency as a function of the input applied voltage when changed from 0 volts. The problem then is: at what nominal frequency should each SCO operate, and how far should it deviate from its nominal frequency with maximum applied voltage at the input? Without getting involved in frequency-modulation theory and all of its ramifications, such as Bessel equations, one important definition can be used. This is the modulation index.

$$M_f = \text{modulation index} = \frac{\text{Frequency deviation}}{\text{Modulating frequency}} = \frac{\Delta f}{f_m}$$

A useful rule, also, as taken from Terman's textbook Electronic and Radio Engineering, is that a frequency-modulated wave contains sideband components of importance on either side of the carrier wave over a frequency interval approximating the sum of the frequency deviation and the modulating frequency. This indicates that the nominal oscillator frequency must operate well above the input frequency which is 500 kc. The thought occurs then, if each SCO operates at some discrete interval, and these intervals are a stair-step function, the uppermost frequency must not exceed the upper bandwidth capability of the video tape recorder. An upper bandwidth is assumed to be approximately 10 mc, judging from specifications of off-the-shelf hardware and development of this capability in the near future.

Without proceeding laboriously through Bessel functions, a modulation index of 0.4 will be assumed, based on the bandwidth capabilities of the video tape recorder, the maximum output signal voltages from each channel of the instrumentation tape recorder of one volt, and the 500 kc response requirement. Then,

$$\Delta f = f_m M_f = (500)\, 10^3\, (0.4) = 200 \text{ kc}$$

Further, if we assume the channel 1 SCO nominal frequency at 2.0 mc, then channel 2 would operate nominally at 3.4 mc, channel 3 at 4.8 mc, etc., to channel 7 operating nominally at 10.4 mc. Each of the seven channels would then be applied simultaneously to the individual SCO, the outputs all being summed together and applied to the mixer amplifier.

The purpose of the mixer amplifier is twofold: (1) Provides linear summing of the seven subcarrier oscillators resulting in a frequency division composite output, and (2) provides the necessary output to drive the video recorder. It is necessary that the mixer amplifier exhibit the following properties: (1) Low distortion in order to minimize generation of harmonics and cross-modulation frequencies; (2) uniform frequency response sufficient to pass the subcarrier frequencies used; (3) sufficient and adjustable gain to adequately provide the proper input to the video tape recorder.

Two different types of video tape recorders are in use currently. The types differ in the principle of the rotating head concept. Because of the high bandwidth requirement for recording video signals, resolutio n of magnetic tape to record high frequencies is a problem. The storage density prescribes a certain minimum speed for the tape-towards-head motion, e.g. for recording video signals the relative head-to-tape speed would be 1600 ips. The concept of the rotating head principle was introduced by Ampex in 1955. In this design there are four heads operating alternately and moving perpendicular to the direction of tape travel. Rotating at a high rate of speed, the relative head-to-tape speed requirement can be met. In 1958 , Wessels and Backers of the Philips Research Laboratories, Eindhoven, Netherlands, developed another version of the high-speed revolving head in which only one head is used in an orbit almost parallel with the direction of tape travel [7]. This is obtained by helically scanning the tape which is wound for just one complete turn over a drum. Perpendicular to its axis the drum is split into two halves with a gap in between, where the video head rotates. A single revolution of the head corresponds to one TV frame, recorded as a track of about one meter and making an angle of 3^{o} with the direction of tape travel. It is clear then, that in the systems just mentioned, with a moving head and where the single track is consequently cut into a number of pieces which are grouped together in some geographical way, a special synchronism has to be maintained for the two motions. Moreover, precautions are necessary to guarantee a constant tape strain. A variation in tape length cannot be compensated by a variation in tape speed because the scanning process has a reference to the constant length of the path of the heads.

To achieve a high packing density per unit area one obvious way is to record the tracks together as close as possible. However, the problem of crosstalk becomes significant as the distance between tracks is decreased. One method designed for recording video with a small distance between tracks and minimizing crosstalk, op. cit., states that each track will contain exactly one picture frame of information During recording, the rotation of the disc is synchronized with the picture frames, the phase being set so that the flyback coincides exactly with the moment at which the recording head moves from the end of one track to the beginning of the next. Under these conditions then, adjacent points of neighboring tracks will always represent practically the same part of a picture and hence the same brightness level with a very small incremental change in information. The crosstalk between tracks is then virtually eliminated. We cannot, however, apply this type of recording to our present problem. The frequency spectrum we must record is much broader, i.e. 2 to 10 mc as opposed to TV recording of 5 to 7 mc, and since the information from the instrumentation tape recorder is random in nature and changing rapidly, two adjacent tracks on the video recorder would necessarily have a large incremental change in information; therefore, separation between two adjacent tracks must be maintained to prevent the problem of crosstalk occuring. One added note: inquiries about this type of recorder disclose that, in the United States, the upper bandwidth is 3 to 4 mc for the present state-of-the-art machine. To achieve a 10 mc bandwidth would be, it seems, several years in the offing.

Of the two different type recorders, the alternating, rotating head type video recorder would be the more desirable for our system. Special attention should be given to the synchronism problem because of the longitudinal and vertical speeds to be maintained. Two adjacent tracks should also be separated to prevent crosstalk between tracks.

On playback, the BP filters operate in their respective channels, each one passing the band of frequencies produced from the SCO of that particular channel in the recording mode. Particular attention must be given to the problem of phase shift. The time relationship cannot be maintained between channels if proper design is not achieved.

The output from the BP filter is applied to the SCD. Detection of a frequency-modulated wave is carried out by modifying the frequency spectrum of the wave in such a manner that its envelope fluctuates in accordance with the intelligence involved. The resulting amplitube-modulated wave is then applied to an ordinary amplitude-modulation detector. The circuit arrangement that transforms the frequency-modulated signal into a wave possessing amplitude modulation is termed as a subcarrier discriminator.

The output from the SCD is finally applied to a LP filter. This LP filter could be of the Bessel polynomial type, which gives a constant delay in time over the band of frequencies it passes. For this particular stage, the time relationship could be maintained between channels.

3. Photographic Film Recording and Reproducing

Some further definitions are required to fully understand the process of recording and reproducing on photographic film.

Whenever a photographic image is viewed under magnification, it is seen that the image is not homogeneous. In fact, it actually consists of minute particles of silver. These particles are generally referred to as "grains". In talking about these grains, the terms "graininess" and "granularity" are used and, although different, are often confused or used interchangeably.

Granularity is the spatial variation in the transmitting or reflecting properties of the developed photographic image; it is therefore an objective quantity.

Graininess is the impression of nonuniformity in the image which is produced on the consciousness of an observer by the granular structure; it is subjective in nature.

A way of estimating granularity is by comparing the rms (root-mean-square) granularity values. These values, given in data sheets, represent the standard deviation in density produced by the granular structure of the material when a uniformly exposed and developed sample is scanned by a microdensitometer. Rms granularity values indicate the magnitude of the impression of graininess produced if the samples were to be examined visually.

One other parameter which must be defined is "resolving power". The term "resolving power" refers to the ability of an emulsion to record fine detail. In measuring resolving power, a parallel-line test chart is photographed at a greatly reduced scale. The lines of the test chart are separated by spaces of the same width as the lines. The image is examined under a microscope, and the number of dark lines per millimeter that are just recognizable is determined. Lines closer together (more lines per millimeter) than indicated by this number will appear on the plate, not as individual lines, but as unresolved gray mass. The resolution of an emulsion depends only slightly on the degree of development.

Resolution falls off greatly at both high and low exposure levels reaching a maximum at some intermediate exposure; it is for this intermediate exposure that the resolving-power classification is given. The maximum is sharpest for emulsions of high resolving power. In general, resolving-power maxima occur in the density range from 0.7 to 2.0.

Resolving power is usually higher at the short-wavelength end of the visible spectrum and is always higher in the far violet and ultraviolet. The spectral sensitivity of the emulsion has no significant effect when the exposure is made to radiation from ordinary heterogeneous sources, even for materials that are as diverse as blue-sensitive and panchromatic.

With the above-mentioned parameters, and the parameters as defined in the storage media section kept in mind, the problem then becomes: If photographic film is used as the storage media, what will be used as the light source? Also, after the information is recorded, what means should be used to reproduce it for use in data processing equipment?

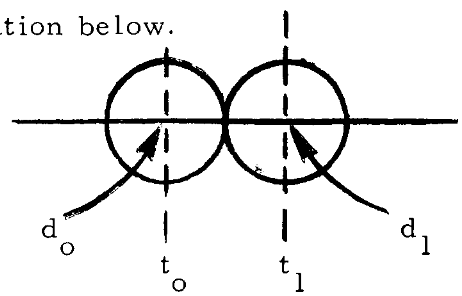
As indicated previously, electronbeam recording would be difficult to achieve because of the mechanical problems involved.

Link has had several years of extensive experience developing precision laboratory equipment using a CRT light source. The design of a reel-to-reel film recorder utilizing a flying-spot scanner system (FSS), was undertaken by Link to explore the practicality of the flying spot scanner approach for the ADDA. If this approach proved feasible, information would be provided for performance specifications of a device which could be utilized by GSFC.

Because of the wide variety of CRTs, photographic film specifications, and spectral properties of photomultiplier tubes (PM) as used in the reproducing mode, many calculations were made to obtain the optimum qualities of these items and still be compatible toward performance in the final system.

Phosphor Requirements - First of all, phosphors (even with aluminized backing) can only withstand a certain fixed radiant energy per unit area without harmful deterioration to the tube's radiating surface. This is in direct conflict with the requirements of any system where light must be maximized in order to increase the system S/N ratio. System requirements (i.e., the capability of high scan rates) immediately limit the type of phosphor which can be used. Therefore a phosphor type must be defined before phosphor deterioration can be discussed any further, since each phosphor type reacts differently when bombarded.

Whenever a FSS system is used for recording the decay time of the phosphor must be less than the 1/2 period of the highest frequency to be recorded. If this design criteria is not followed, the recorded information is in error. The error is due to the fact that the radiant energy of the flying spot at time t_o at position d_o has not decayed to zero when the flying spot has moved to a new position d_1 at time t_1. Refer to the illustration below.



Therefore the instantaneous radiant energy per unit area at time t_1 is $\left(\frac{E_1}{A} + \frac{\Delta E_o}{A}\right)$ where ΔE_o is the residual excitation of the phosphor from position d_o, caused by the slowness of the phosphor light level to sufficiently decay.

Bandwidth Requirements - The next step will be to define the system bandwidth. In this way the maximum phosphor decay time can also be defined by utilizing the criteria specified in the previous paragraph. The required system bandwidth can be calculated from the knowledge of spot size and the velocity of the spot across the image plane. For a circular spot, the rise time of the wave form when the spot traverses a perfectly sharp boundary (a sharp density change) can be given by

$$t_r = \frac{d}{v}$$

where

t_r = rise time
d = diameter of spot
v = velocity of spot

To calculate t_r two assumptions will be made: a spot size, and a sweep rate. In the following paragraphs analysis will be supplied to verify these assumed values. Spot size will be specified at 0.25 mil (0.00025 inches) and the sweep rate (velocity) will be 240 inches per second.

The rise time is then

$$t_r = \frac{(0.25)\ 10^{-3}}{240\ \frac{\text{inches}}{\text{sec}}} = 1.04 \times 10^{-6} \text{ sec}$$

Empirically Bandwidth (B) has been determined to be approximately equal to:

$$B \approx \frac{.45}{t_r} \approx \frac{.45}{1.04 \times 10^{-6}} \approx 433 \text{ kc}$$

$$\text{The period} = \frac{1}{B} = \frac{1}{0.433} \times 10^{-6} \text{ sec} = 2.31 \times 10^{-6} \text{ sec}$$

$$\text{The } 1/2 \text{ period} = 1.15 \times 10^{-6} \text{ sec.}$$

The phosphor which has a decay time specified less than 1.15 microseconds is a P-16 type. The decay time of this phosphor is 0.15 microseconds. Therefore it will be assumed that the requirements of the system specify the use of P-16 phosphor. Figure 6 shows the spectral energy emission characteristics and the persistance characteristics of P-16 phosphor.

Signal/Noise Requirements - With the phosphor type defined, a continuance of the discussion of harmful phosphor deterioration is in order.

The aging of phosphor can be represented, to a first approximation by

$$1. \quad I = \frac{I_o}{1 + CN}$$

where

I_o = initial intensity
I = aged intensity
C = burn parameter in cm^2
N = number of electrons deposited per cm^2

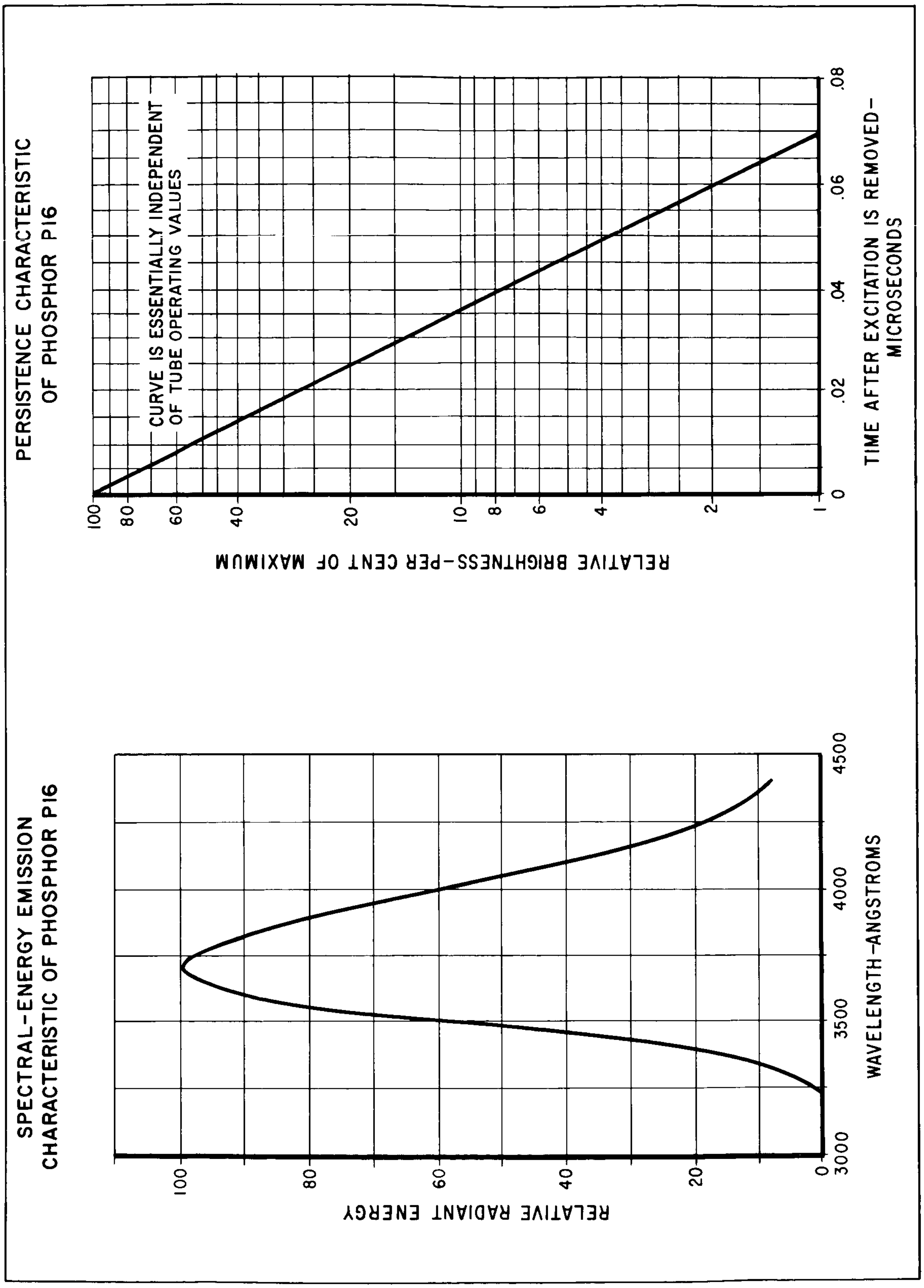


Figure 6 Phosphor Characteristics

C is a measure of the rate of destruction of the luminescense. $\frac{I}{C}$ is the number of electrons necessary to reduce the intensity of the luminescence to one-half its initial value. The number of coulombs per cm^2 necessary to reduce the intial P-16 phosphor intensity to one-half is 10^{-1}. From tests which have been performed by Bell Telephone Laboratories, a practical power density of .6 watt per cm^2 has been found to be small enough to avoid damage to the tube screen by overheating. At a power density of 1.5 watt per cm^2 the phosphor screen and aluminum backing will voltalize. It is most important therefore that the current density be controlled to reduce burning.

This is in direct conflict with system S/N ratio as mentioned previously. Therefore, it is necessary to match the spectral emission of the P-16 phosphor with the spectral response of the photocathode of the readout PM to conserve as much energy as possible within the system. Since the phosphor has already been chosen the problem narrows itself into finding the correct photocathode emissive surface.

The radiant flux incident upon the photomultiplier photocathode is given by:

$$2. \quad F_{pc} = P_{max} \int_{\lambda_1}^{\lambda_2} P(\lambda)\, d\lambda \text{ watts}$$

where

$P(\lambda)$ = the relative spectral emission characteristic of the phosphor

P_{max} = the maximum flux per wavelength interval, watts/A^o and λ_1, and λ_2, are chosen to include the entire wavelength region in which the spectral emission and the photocathode sensitivity are both non-zero.

The PM photocathode current is given by:

$$3. \quad I_{pc} = P_{max} S_{max} \int_{\lambda_1}^{\lambda_2} P(\lambda) S(\lambda) D(\lambda) \text{ amperes}$$

where

$S(\lambda)$ = the relative spectral sensitivity of the photocathode

S_{max} = the maximum photocathode sensitivity in amperes/watt at some particular wavelength.

The minimum flux which is required to produce a specified signal-to-noise ratio is found by combining the above two equations with the equation for photocathode current.

The photocathode current equation is derived in the following manner:

$$4. \qquad S/N = \frac{S^{2n} I_{pc}^{2} R}{2e\ B\ S^{n} \left(\frac{S^{n+1}-1}{S-1}\right) I_{pc} R + 4KTB}$$

where

S = the secondary - emission - current multiplication ratio per stage

I_{pc} = direct photoelectric current, amperes

R = load resistance, ohms

e = electron charge, 1.602×10^{-19} coulomb

B = bandwidth, cycles

K = Boltzman's constant, $1.372 \times 10^{-23} \frac{\text{watt sec}}{^{\circ}\text{K}}$

T = temperature in $^{\circ}$K

n = number of stages

For the noise voltage, due to shot noise, to be r times greater than the thermal noise of load resistor:

$$5. \qquad R \geq \frac{1}{20} \left[\frac{r^2}{I_{pc}} \qquad \frac{S-1}{S^n (S^{n+1} - 1)} \right]$$

Due to the extremely high gain of the PM, this condition (shot >> thermal noise) is nearly always satisfied even for relatively small values of load resistance. When this condition is satisfied the signal-to-noise ratio reduces to:

$$6. \quad S/N \approx \frac{(S-1)\, I_{pc}}{2\, S\, e\, B}$$

Expressed in terms of voltage

$$7. \quad (S/N)_v = \left[\frac{(S-1)\, I_{pc}}{2\, S\, e\, B} \right]^{1/2}$$

By substitution in equations 2, 3, and 8, the minimum flux required to produce a specified signal-to-noise ratio is:

$$F_{pc} \min = \frac{2\, S\, e\, B}{(S-1)\, S_{max}\, K_m} (S/N)_v^{\ 2} \text{ watts}$$

where:

K_m = the normalized factor which depends only on the spectral match between the emission characteristic of the phosphor and the sensitivity characteristic of the photocathode, and is defined by

$$K_m = \frac{\int_{\lambda_1}^{\lambda_2} P(\lambda)\, S(\lambda)\, d\lambda}{\int_{\lambda_1}^{\lambda_2} P(\lambda)\, d\lambda}$$

K_m has been tabulated for several different phosphors and photocathodes, and the best match for P-16 phosphor is a S-20 photocathode where $K_m = .98$.

From the preceding analysis it is evident that the S/N ratio is dependent primarily on the photomultiplier while the radiant emission from the CRT is limited by the phosphor aging. The design problem then resolves itself into designing an optics system which will collect and transmit a sufficient amount of light flux, emitted by the CRT, onto the photographic film and the readout PM photocathode. The Flying Spot Scanner analysis has defined the following:

1. System bandwidth(by assuming a sweep rate and spot size)
2. Radiant emittance limitations
3. The need for P-16 phosphor
4. S/N dependency on the PM
5. Spectral matching between the P-16 phosphor and S-20 photocathode.

This has been a general discussion to explain the approach Link pursued to define the system problems.

Design of Breadboard Photographic Film Recorder - In the design and building of the breadboard photographic film recorder, off-the-shelf hardware was used wherever possible because of the brevity of time for the study. This design was performed in such a manner, however, that the quantitative results obtained could be utilized in the ultimate design of a photographic film recorder for use in archive recording.

Mechanical considerations - The film recorder was built around an existing Link optical bench which allowed mounting and precision alignment of the light source and optical elements in the system, as shown in Figures 7, 8, and 9. The primary design considerations of the film transport portion of the recorder were two: (1) to move film at a constant, precisely controlled rate of speed past the aperture where the film was to be exposed and (2) to achieve control to very close tolerances, the position of the film as it passed the aperture. A capstan-pressure roller drive system was selected because of the possibility that a sprocket drive might cause periodic variations in film velocity and, in addition, the capstan-pressure roller system would be compatible with unperforated film, should the use of such film become desirable due to other considerations. The capstan was direct-driven by a servo speed-controlled direct-current motor. Film spools were loaded directly on shaft extensions of two alternating-current torque motors. Film tension, in the compliance loops of the system, was maintained by adjustment of the voltage applied to the motors. A film "gate", enclosing the aperture, was constructed in such a way as to spring-load the surface of the film against a polished stainless steel plate to insure that no buckling of the film occurred in this critical area. The gate was also designed to "edge-guide" the film, applying spring force to maintain the lower (reference) edge of the film in contact with a reference edge of the guide to assure lateral tracking stability and repeatability of track locations with respect to the optical path of the system. Precision bearings were used in all rotating guides and followers. A mechanical filter was installed in the film path just preceding the gate to seal off the aperture area from tension disturbances outside the critical area.

Electrical Considerations - Cathode-ray tubes with a P-16 phosphor and PM tubes with a S-20 spectral curve are standard items for the

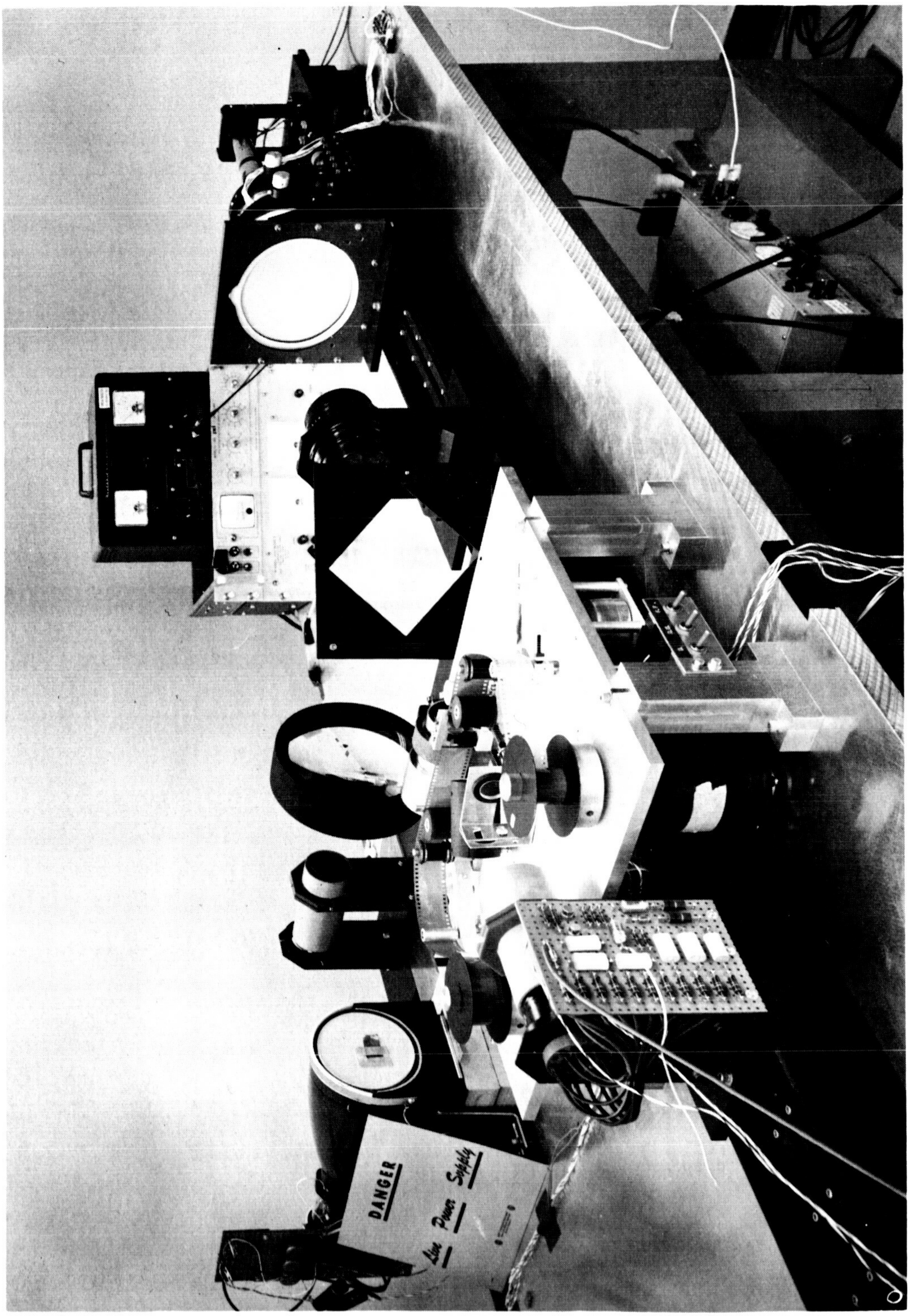


Figure 7 Overall View of Photographic Film Breadboard

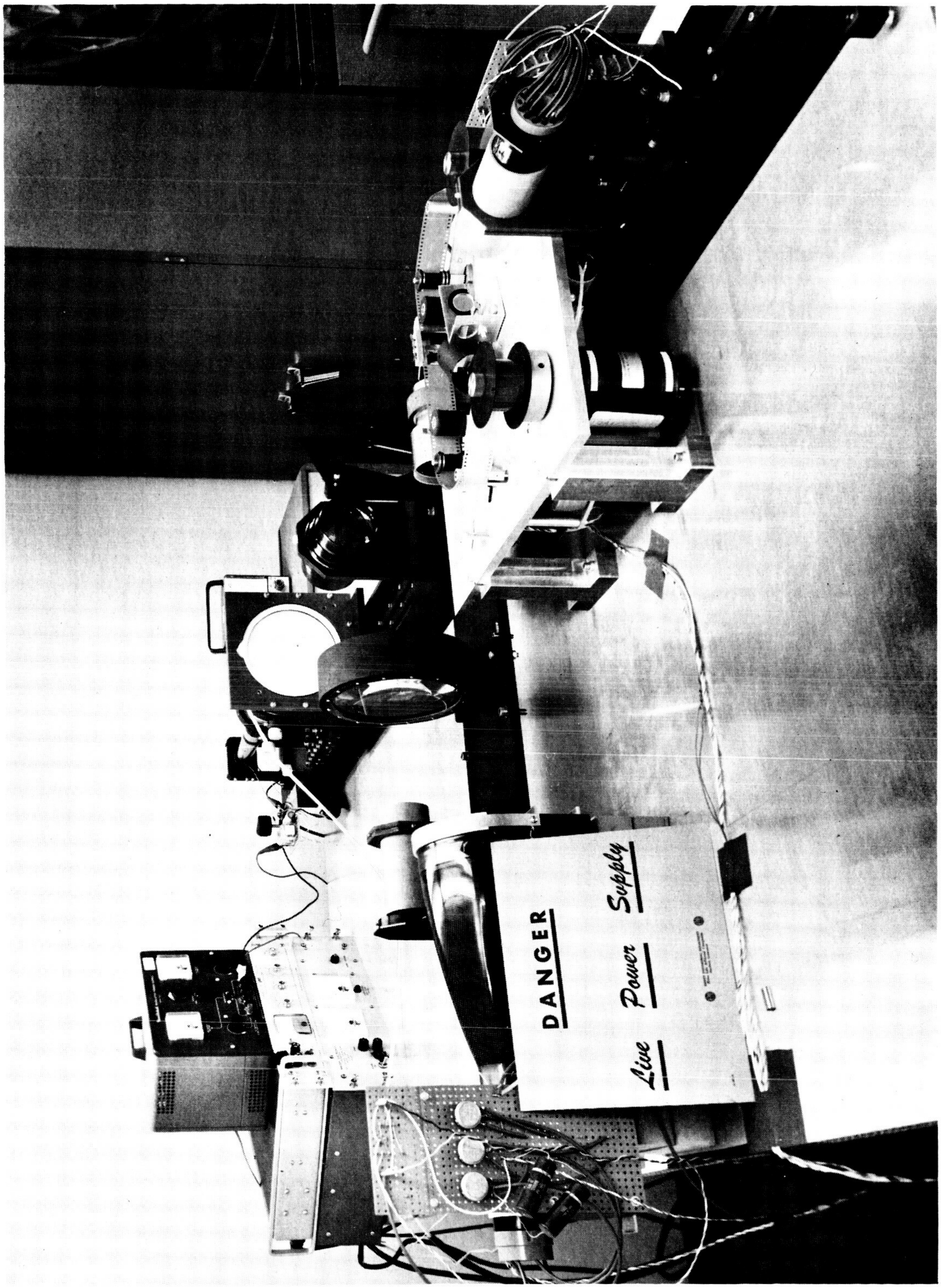


Figure 8 View of CRT and Optics

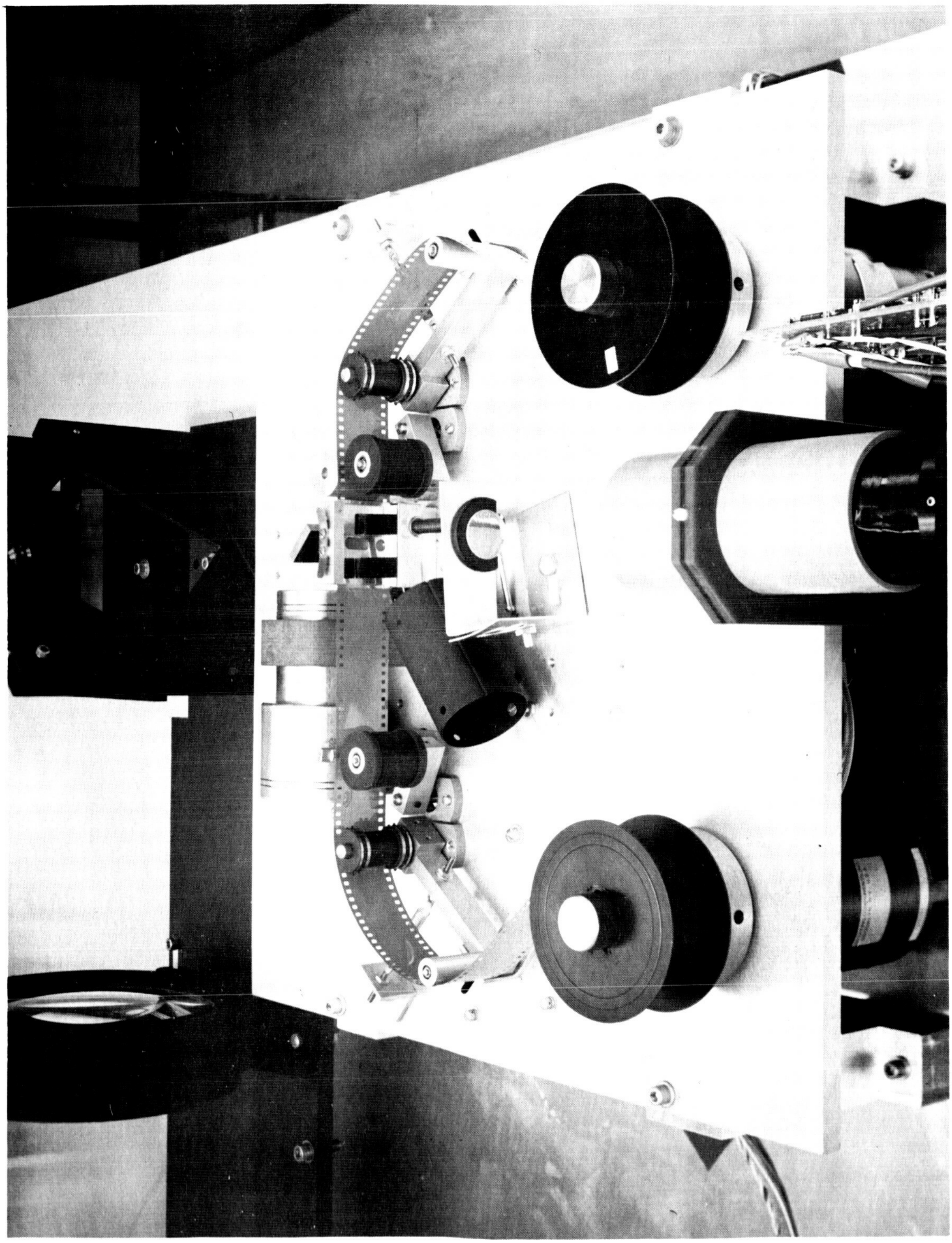


Figure 9 Detailed View of Film Transport

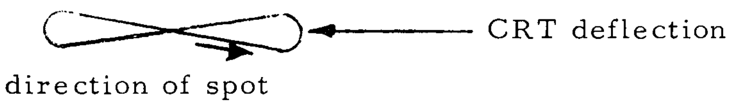
industry, so these tube types were used in the breadboard film recorder. To be compatible with these parameters, Eastman Kodak type SO-266 thirty-five millimeter perforated film was chosen because of the immediate availability of this size and the emulsion suitable for recording light with the spectral distribution produced by the specific cathode-ray tube. SO-266 film has a usable density of 2.0, and according to its specifications, with the use of the proper developer the density increments are approximately 0.040 or

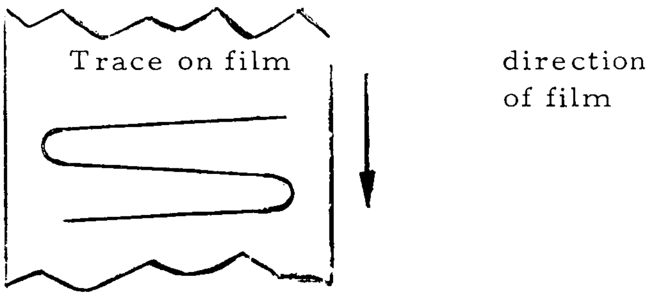
$$\text{Gray shades} = \frac{\text{Density}}{\text{Density Increments}} = \frac{2.0}{0.04} \approx 50$$

Therefore, with SO-266 film, one period of a sine wave can be defined with at least 5 digital bits, or to within 3% accuracy. The resolving power has a limit of 160 lines per mm, and the gamma is approximately 1.9.

The following recording criteria was considered as the most desirable for optimum performance of the breadboard recorder: the recorder should utilize the complete film width, the recorder should be capable of recording 7 or 8 channels simultaneously, the film should be completely exposed after one pass through the recorder, the light sources to expose the film should be small cathode ray tubes with deflection circuits, each of the 7 data channels should occupy about 1/8 the width of the film, the remaining 1/8 width space should be used for a control channel, the intensity of the light emitted from the cathode ray tubes should be related linearly to the amplitude of the signal to be recorded and should expose the film to varying levels of density depending upon the amplitude of the signal at any particular instant.

By deflecting the spot back and forth across its assigned track width on the film at the rate of 100 cycles per second and at the same time moving the film at a constant speed of 1 ips the actual writing speed on the film can be made 100 times the actual film speed. In order to maintain the accuracy of the incoming signal, the velocity of the deflected spot on the film must be held at a constant value. To achieve the constant spot velocity, the deflection on the cathode ray tube would be essentially a figure-eight pattern, as shown in the illustration.

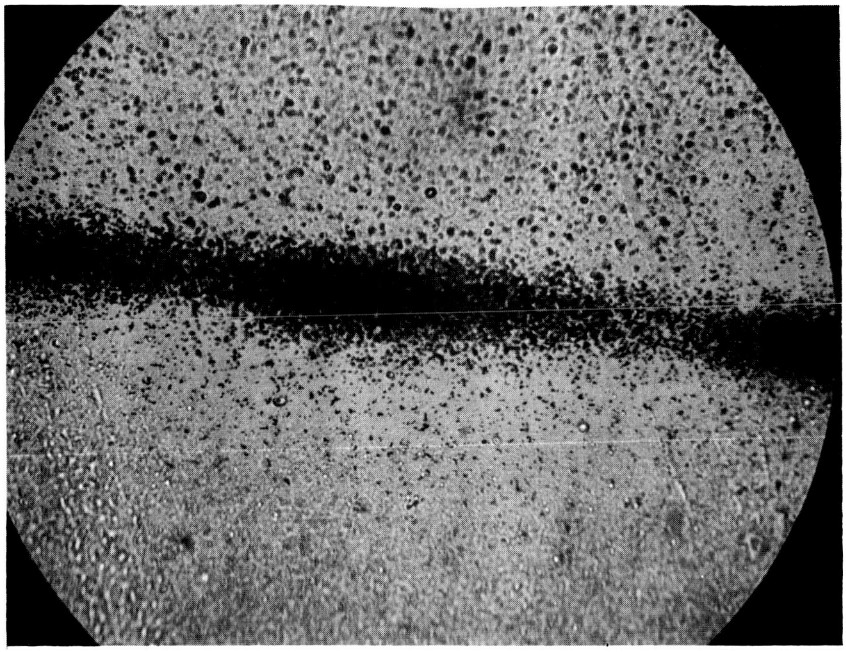




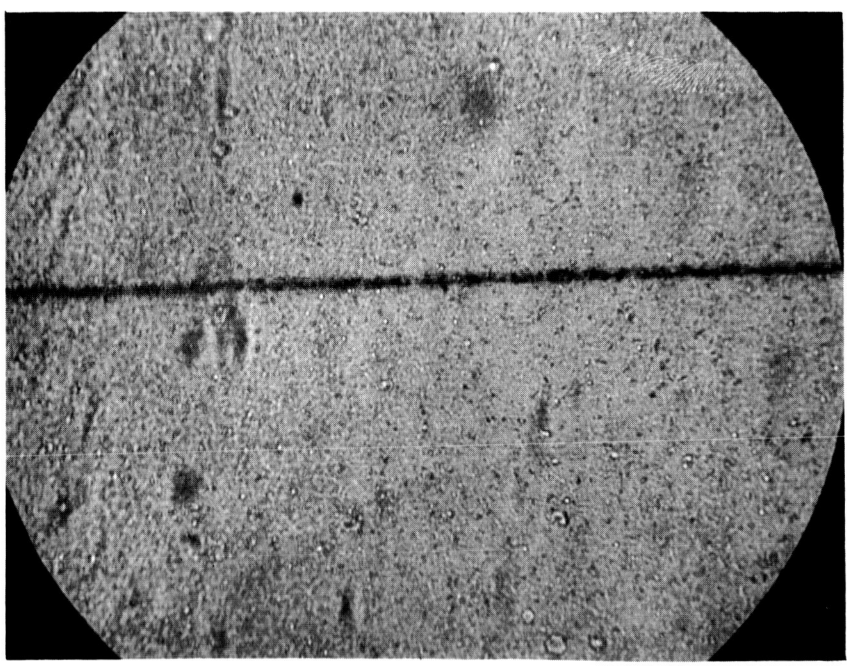
The end loops would be circles with straight lines connected to tangent points on the circles. When observing on the CRT, the tangential velocity around the circle must be constant, in other words, if a line is drawn tangent to the circle at some point in time, the slope of this line must change from positive to negative at a constant rate as this point progresses in time around the circle. This deflection will then produce a constant spot velocity on the film plane

The function for the horizontal deflection sweep is a triangular waveform with both sides of the triangle equal in length. The repetition frequency is 100 cycles per second. The vertical deflection sweep is more complex. The function generally appears as an inverted ramp; however, during the time when the total horizontal and vertical sweeps generate the circle portion, the vertical sweep follows a serpentine function in general. Tests of the above system indicated that the circuits designed for the breadboard were not precise enough in operation to perform satisfactorily. Because of the short time available and the complexity of the problem, the tests were discontinued and a slightly different approach implemented to obtain quantitave test results.

The decision was made to continue the tests on the breadboard by recording one data channel longitudinally along the film, using an undeflected spot, rather than continue with the previously described type of recording. Longitudinal recording requires much higher film speed, since the spot itself is not moving. The film transport had been designed to move the film at a speed of 1 inch per second, and because precise speed regulation is required, no changes were made to achieve higher speed. The effort was directed toward modulating the beam intensity of the cathode-ray tube, and recording this modulated spot on film. A section of this recording is shown in Figure 10. The photographs are magnified 120 times. At the above film speed and with a CRT spot size of 2 mils, the beam intensity was modulated from 0 to 1 kc. On playback, with the beam intensity and spot size held constant, the light source was directed through the recorded film track onto a PM tube with varying density of the recorded track, a varying voltage appeared at the output of the PM.



2 Mils Modulated Beam



0.25 Mils Line Width

Figure 10

The frequency was down to the 3 db point at 200 cycles per second No close analysis was made for harmonic content in the basic waveform. During these tests a spot size of 0.25 mils diameter was recorded, as shown in Figure 10. The beam intensity was held constant.

Light Pipes - Light pipes were also investigated for transmitting light from a CRT to the film plane. Two problems were encountered in using light pipes in the record mode. (1) Since the CRT light source operates in the near ultraviolet portion of the light spectrum, only quartz is satisfactory for transmission of light. Apparently, in fiber optics it is very difficult to draw quartz down to a 1 or 2 mil size diameter, therefore, a lens is necessary to reduce the spot to the size desired. (2) When a light pipe is drawn to a cone on the tip, most of the light rays transmitted down the sides of the cylindrical portion of the pipe undergo multiple reflections in the conical section. Upon emerging from the tip, the light rays are diverging in such a manner that a lens can collect only a small portion of the light emitted from the CRT source.

For use in the recording mode, more development must be done with quartz fibers, and investigation should be made into shaping tips differently to use light pipes efficiently.

Light pipes could possibly be used in the reproduce mode if a source is used which emits light in the visible spectrum. Plexiglass could be drawn and shaped to transmit the light from the film plane to each individual PM tube.

Optical Diodes - Most of the development of light emitting diodes has been in the infrared region of the spectrum so far. Since the resolving power of film is higher in the ultraviolet region, the two devices would be incompatible. Optical diodes could be used, however, if future development progresses in the ultraviolet or blue region of the spectrum.

IV CONCLUSIONS

Several factors must be considered further for arriving at a logical conclusion.

Photographic Disk - As a smaller spot size is achieved to obtain a higher bit packing density, the dimensional stability of glass becomes a significant problem. Since an archival storage area is usually temperature controlled to a $\pm 5^{\circ}F$ tolerance, conceivably then, the disk dimension could change 45 microinches per inch. In the report cited on electron beam recording, data tracks were separated by only 3 microns. Therefore, careful temperature control of the disk during recording and reproducing would minimize the dimensional stability problem.

Frequency Multiplexing - Frequency multiplexing cannot be effectively utilized as applied to archival storage requirements. The 500 kc bandwidth per channel specification covers a total bandwidth of 3.5 mc in itself. The FM method of recording, as outlined in the Magnetic Tape Recording section, is a narrowband FM type at best. In this method, only a single carrier and two sideband frequencies for each channel could be reproduced at the output of the system. Since the modulation index is proportional to the amplitude of the modulating signal where increases in signal amplitude generate new sidebands, it would be highly questionable if the output signal could be restored to within 20 db of the original signal as applied to the input of the system. If the modulation index would be increased to an assumed value of 5, which is, incidentally, the standard for space telemetry work and FM broadcasting, the bandwidth requirement for each channel would increase the overall bandwidth to over 35 mc, which is well out of the limits of any recording device.

Conceivably, the FM bandwidth could be reduced by closely analyzing the overall frequency spectrum to determine the points where there might be absence of significant sidebands. The carrier of some particular SCO could be deviated in such a way where the sidebands produced would fill these vacancies. This method is used in color TV. Comb filters on the output restore the signal to the proper channel. However, there is the difficult problem of phase shift as a function frequency which must be considered if the time relationship between channels is to be maintained. This problem must also be considered in BP filter design as used in the Magnetic Tape Reproduce system.

Magnetic Tape - Magnetic tape could not be used in archival storage where data would be stored for five years or more. As pointed out in this report previously, the problems of magnetic print-through and cross-talk exist regardless of the frequency incorporated. As Daniel has shown (report published in Appendix) there exists a certain finite print-through signal for every recorded wavelength. If the magnetic layer is made thinner to minimize print-through, then a magnetic material with higher resolution capabilities must be used and the problem of demagnetization becomes significant. The polyester base cannot be arbitrarily decreased to achieve higher volumetric efficiency because the layer-to-layer distance is reduced and print-through certainly must be considered

Polyester Base - With either magnetic tape or photographic film, the base material dimensional stability must be considered in long term storage. According to tests made by Kodak, the Estar 2.5 mil base changes 0.05%, 4.0 mil base changes 0.03%, and the 7.0 mil base changes 0.02%. If an extrapolation is made, this would indicate that the ability to faithfully reproduce a signal after several years storage is seriously impaired as the base thickness is decreased.

From these factors discussed, this summary is made: As an archival storage medium, magnetic tape is not desirable because of the cross-talk, print-through, and demagnetization problems. Link can only conclude that photographic film on a polyester base should be used as the storage medium. This conclusion has been reached after careful and intensive investigation of a variety of storage media.

Photographic film has been used for many years as an archival storage medium. The parameters which define film are well known to the point where quantitative analysis and calculation can be made for the design of an optimum performance film recorder for use in archival storage work.

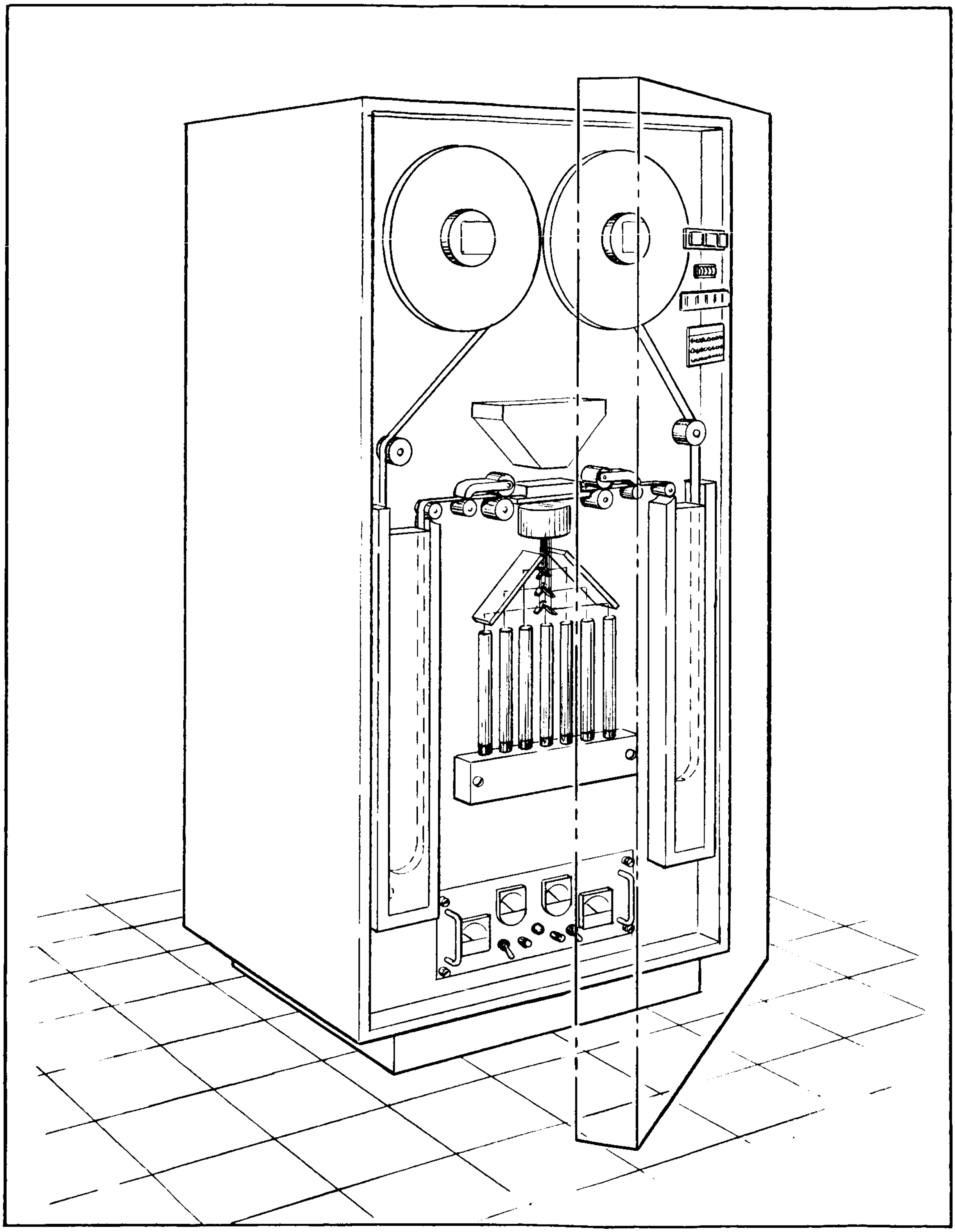


Figure 11 Artists Conception of Film Transport

V. RECOMMENDATIONS

Based on intensive study and test results, film, in the form of reels, would be used as the best recording medium to preserve data for a long period of time, and to reduce the storage space required as compared to the anticipated magnetic tape storage.

Sixteen millimeter perforated film of Kodak Type SO-337 with a 2.5 mil polyester base would be used as the storage medium. The silver halide emulsion would have optimum spectral response in the ultraviolet region, the resolving power would be 160 line-pairs per mm, and the usable density range would be 2.2.

As will be stipulated in the system requirements, controlled environment in processing and storage of film is essential to maintain accuracy and permanency of data. The film should not shrink more than 0.05% after three years of storage.

1. PROPOSED DEVICE

The proposed film recording device as shown in Figure 11, will be housed in a specially constructed, air-conditioned, light-tight cabinet, approximately 72" high x 36" wide x 30" deep. Lightweight alloy materials will be used extensively to achieve the necessary rigidity and prevent overall weight from becoming excessive.

The film transport itself will be designed to cope with the unique problems arising from the overall system concept. In general, it will be a highspeed, continuous-motion transport, capable of bi-directional operation. Some of the problem areas which will require further investigation include the following:

(a) Film Handling - The system concept involves recording many sets of data tracks down the length of the film. Since it seems most practical to record only seven analog channels of information at one time (corresponding to the seven tracks on a magnetic tape reel) it is evident that the film must be re-wound and recorded upon many times. The film must be handled with extreme care to prevent damage to the un-processed emulsion, resulting in scratches and, as a result, unusable data tracks. The transport area must be kept free of dust for the same reasons.

(b) Film Guiding - The large number of parallel tracks and the consequent small size of each track make longitudinal guiding of the film a major problem. If the film is allowed to "wander" as it is moved through the exposure area, the tracks will be impossible to follow with the extremely small size light source required for playback.

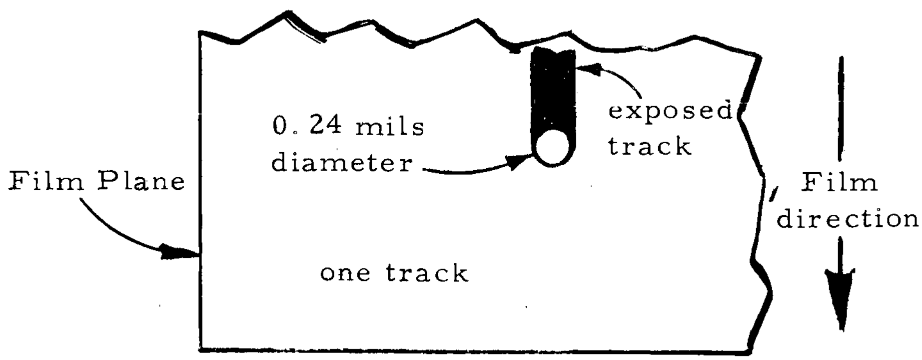
(c) Track-set Alignment - A mechanical shifting device must be included in the transport/optics assembly, to allow precise, repeatable registration of track sets on the film during recording and alignment of readout lights with track sets during playback.

(d) Speed Regulator - The constancy of film velocity past the record/playback area must be held to very close tolerances to avoid introducing extraneous signals ("wow" and "flutter") into the recorded material.

The entire device will be light-tight, so all operations may be carried out in a normally-lighted room. External controls and indicators will include transport function control switches/indicators, footage counter for accurate location of desired data, "track-set" indicators, film load condition and malfunction indicators, and front panel outputs for monitoring inputs or reproduced signals.

Seven channels of information would be recorded simultaneously along the length of the film. The light source would be a CRT using a P-16 phosphor. The light exposing the film would not be deflected during the recording, in other words, longitudinal recording would be used, and the intensity of the light source would be changed linearly with the amplitude of the incoming signal. Note: As discussed in the film recorder breadboard design, further investigation should be made in the deflection of the light source to obtain a higher equivalent film speed, and consequently, lower the actual film transport speed requirements. Quite possibly, relaxation of the 500 kc bandwidth per channel could be reduced to a requirement where only 1 or 2 channels would be required to reproduce 500 kc. If this is possible, requirements for tracking and speed regulation could be relaxed considerably using this method.

The light exposing the film for each channel would be focused down to a very small spot on the film and would expose only a very narrow line as the film is moved at a constant speed. This spot is illustrated below.



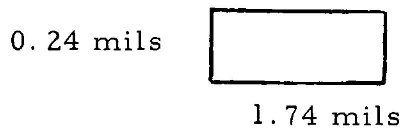
The dimension of the spot is defined to take into consideration the 160 lines per mm resolving power of the film used.

For any given upper frequency to be resolved accurately the longitudinal film speed must be fast enough to obtain varying shades of gray on the film track when the light beam intensity is modulated. With the frequency requirement of 500 kc and the spot size defined, the film speed is

$$\frac{(500)\ 10^{3}\ (2)\ \text{bits}}{\text{second}} \cdot \frac{(0.24)\ 10^{-3}\ \text{in}}{\text{bit}} = 240 \text{ in. per second}$$

The film transport should be capable of recording and reproducing DC to 500 kc to an accuracy of ± 1 db over the entire frequency range.

In the reproduce mode, a light source of the dimensions as illustrated would be used.



This spot is rectangular in shape to compensate for an assumed 1.5 mils possible lateral movement of each film track in the playback mode.

Volumetric Reduction - If as previously assumed in the report, the area per bit on magnetic tape at 500 kc is 8.4 mils, then at an assumed thickness of 1.5 mils, the volume per bit is 12.6 mils^3. The area per bit on photographic film is

$$(0.24)\,(1.74) \cong 0.418 \text{ mils}^2$$

If the assumed thickness is 2.5 mils then the volume per bit on photographic film is 1.04 mils^3. The volumetric reduction of photographic film is then

$$\frac{12.6}{1.04} = 12.1$$

when compared with magnetic tape. Since the packing density of digital magnetic tape is approximately 8 times less than the analog record, a volumetric reduction of 96.8 could be realized when compared to digital magnetic tape. If a digital-to-digital reduction is performed where one shade of gray defines 4 digital bits, then a volumetric reduction of approximately 380 could be achieved.

In determining the size of photographic film used the dimensional stability parameter was considered. If after 3 years the film has changed 0.05% and 0.2 mils width shrinkage is assumed, the total available width for recording would be

$$\text{Total width} = \frac{(0.2)}{(0.05)\ 10^{-2}} = 400 \text{ mils}$$

The nearest size photographic film to the width calculated is 16 mm. If a track width of 1.74 mils is assumed then the number of tracks recorded is

$$\frac{400}{1.74} \cong 230 \text{ tracks}$$

and the equivalent rolls of magnetic tape would be

$$\frac{230}{7} = 33 \text{ rolls of magnetic tape}$$

Economic Realizability - Based on the ability to record 33 rolls of magnetic tape on film, the economic realizability can be calculated. If a roll of magnetic tape costs approximately \$20.00, then 33 rolls of magnetic tape cost \$660. According to the film manufacturer, a roll of SO-337 would cost \$85. and in addition, 10% of the total cost of one roll for processing for a total of approximately \$94. Therefore, the economic realizability would be

$$\frac{660}{94} \cong 7.0$$

Further reduction can be made if, at the start of the phase two portion, as outlined in the Proposed System, after the data has been recorded on film, the tapes are erased and new data is re-corded. GSFC would determine how many times these tapes could be utilized before the accuracy and reliability is imparied.

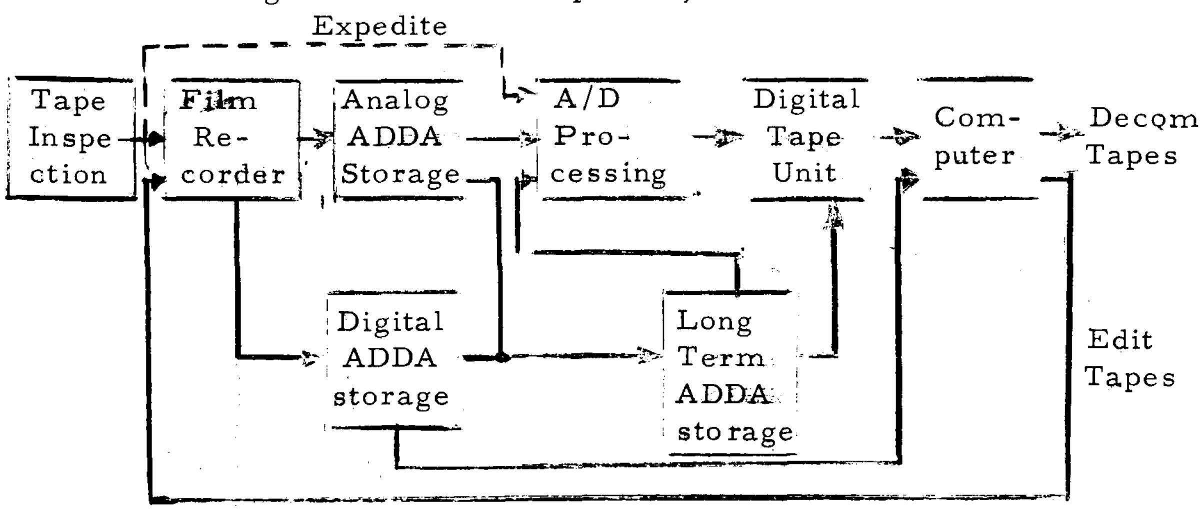
2 PROPOSED SYSTEM

To be able to maintain dimensional stability of film for archival storage care must taken to control both temperature and relative humidity. Keeping in mind the longevity of the record, both unprocessed and processed films should be stored in the same type environment. The temperature should be 70-75^{O}F and the relative humidity 45 ± 5%. Since unprocessed film establishes its own equivalent relative humidity, a two week period is required to establish equilibrium, therefore, new film must be stored for this period in the above environment before it can be exposed and processed. The film transport and processing equipment should also be housed in the same area to maintain a consistent environment for the film.

Device Integration - Three distinct steps must be taken for integration into the total system. (1) To prove the accuracy and reliability of the device, it should be kept in the role of an off-line processor for a period of time. During this interim period, along with processing the normal telemetry data, test tapes (both analog and digital) with known information should be generated and processed through the device and system to determine that the accuracy and reliability requirements are met. This procedure should be performed at least once every two weeks to insure that these requirements are maintained. (2) At the end of this period, the device should be intetrated into the main system with the philosophy being that the film record will be the prime source for both analog and digital data. If any updating of the prototype is required, test tapes should again be processed through the device and system to insure that the changes have not degraded the accuracy. (3) Upon installation of a manufacturing model, the prototype should be maintained at the same engineering level to realize the maximum utilization of the equipment. At this point, manufacturing models can also be installed at the various tracking stations. The same specifications would apply to the tracking station models as applies to GSFC equipment because the same environmental, accuracy, and reliability requirements must be maintained.

Data Flow - During the first phase, with the emphasis placed on accuracy, no effort should be made to record all telemetry data on film since some time must be used in processing and verification of test tapes. The amount of data to be recorded and processed on film would be determined by GSFC to obtain optimum performance from the device and overall system.

In the second phase, with the film record becoming the prime source for data processing, a data flow diagram is illustrated below with the device integrated into the complete system.



With the estimate in the specification that 130 analog and 45 digital tapes are processed each day, the assumption could be made that 12 hours would be required to process analog data and 4 hours for digital, for a total of 16 hours processing time of the devices.

To augment the capability of automatic indexing in data retrieval, the following procedure would be used: (1) All film headings would be stored on a digital computer. (2) Each heading would contain the satellite, orbit number, type of data (digital or analog), storage location (short term or long term), reel number, and location of section on reel (a section being one of several since several magnetic tapes are recorded on one reel). (3) When particular data is to be processed, the computer will produce a punched card with the above heading information. (4) The film reel would be taken manually from storage and placed on the device. (5) There would then be a verification mode where the heading on the film reel would be compared with the heading on the punched cards. (6) The device would then go into the reproduce mode and the data would be processed.

Since the interest in an experiment remains active for about a year, after the data has been acquired from the satellite, this thought can be implemented into the storage of data. Both analog and digital films would be stored in the short term storage, and after one year of elapsed time, be rotated to long term Federal Archive Storage. The retrieval time in short term storage would be minutes as compared to days in long term storage. If the estimate of 7 tapes per cu. ft. and 100% floor space for aisles is used, 13,560 cu. ft. of space would be required for one year of storage. With the volumetric reduction of film, 1230 cu. ft. would be used for the analog storage, which would be a very small percentage of the space allotted in the new data processing complex. The digital storage would require 53 cu. ft. With past operating procedure established that no original record be taken from the library, but only reproduced at that location, this procedure would be followed also in the using of the film record. The only exception in the data flow diagram is indicated by dotted line where the need would be for some particular data being processed immediately after it is acquired from the satellite. Immediately after tape inspection, the analog tape would be processed on the A/D line and then returned to the device for recording on film.

For the third phase, no major changes would be required in the data flow diagram, except that now all incoming data to GSFC would be on film, and headings placed on the beginning of the film would be done at the tracking station. The floorspace requirements at the tracking station would be very small since the data, as it is acquired, is shipped immediately to GSFC.

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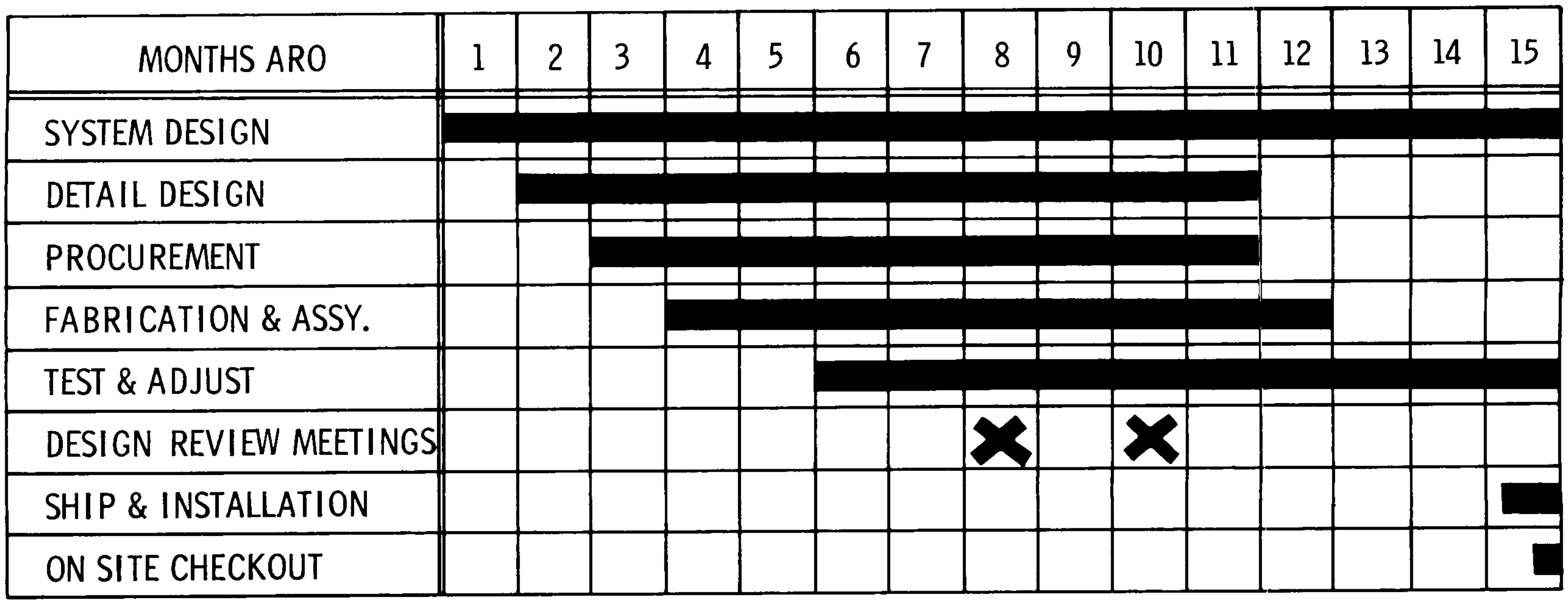
APPENDIX

COST ESTIMATE

To build a functional prototype system requires a carefully planned program which will have, as an end result, a state-of-the-art device and not be excessive in cost. Link has shown two programs to achieve these goals, (1) through the building of a feasibility model to define design parameters and with full utilization of this model, build an operational prototype, (2) building only a feasibility model with the express purpose of defining final design parameters and objectives.



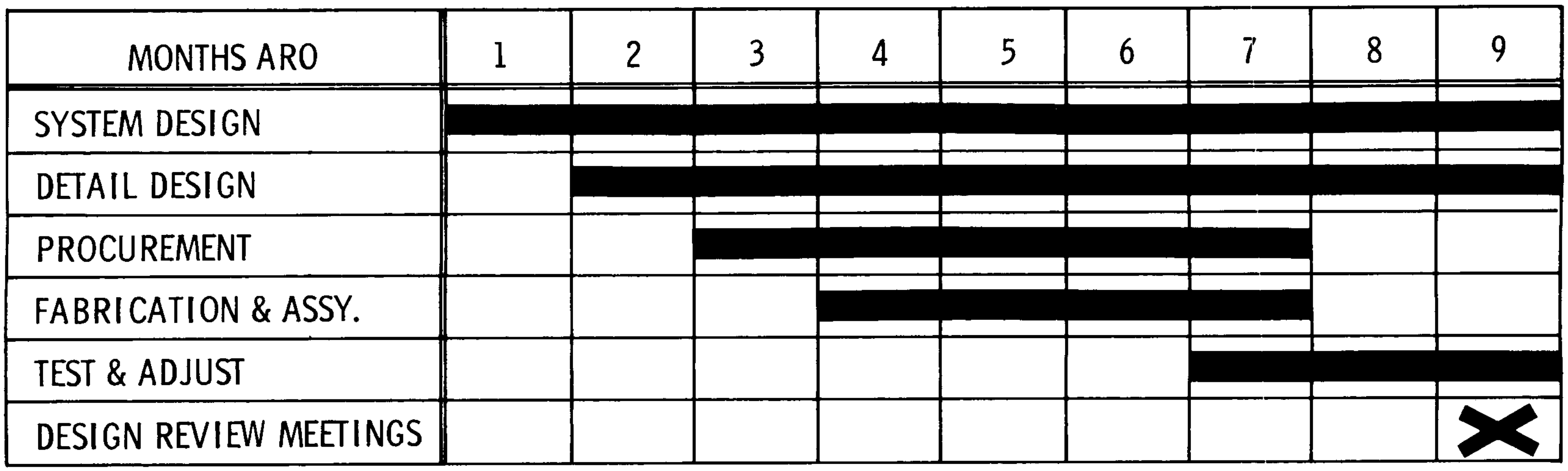
ADDA DEVELOPMENT MODEL AND PROTOTYPE SYSTEM

SUMMARY PROGRAM SCHEDULE

COSTS FOR DEVELOPMENTAL MODEL AND PROTOTYPE SYSTEM

Labor Classification	Man Hours
Senior Electronic Engineer	3600
Senior Mechanical Engineer	3720
Electronic Technician	3200
Mechanical Model Shop	1960
Electronic Model Shop	560
Drafting	4220
Inspection	400
Administrative Assistant	1600

Material (Includes material in prototype model which can be utilized from the developmental model). $77,300



ADDA DEVELOPMENT MODEL - SUMMARY PROGRAM SCHEDULE

COSTS FOR
FEASIBILITY MODEL PROGRAM

Labor Classification	Man Hours
Senior Electronic Engineer	1600
Senior Mechanical Engineer	1600
Electronic Technician	1600
Mechanical Model Shop	800
Electronic Model Shop	240
Drafting	1340
Inspection	220
Administrative Assistant	800
Material	$42,000

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ACCIDENTAL PRINTING IN MAGNETIC RECORDING

By E. D. Daniel, M.A., and P. E. Axon, O.B.E., M.Sc., A.M.I.E.E., Research Department, B.B.C. Engineering Division

IN a previous article in THE B.B.C. QUARTERLY* a brief description was given of the process of magnetic recording, and some factors were considered which affected the fidelity of the magnetic record in subsequent reproduction. The article described how the magnetic record was made by creating a variation of magnetic intensity along the length of a magnetic tape (or wire) in a pattern corresponding to the time variation of the signal being recorded. The present article will describe an investigation into an undesirable phenomenon which can take place in magnetic tape after it has been recorded.

The magnetic tape at present in common use consists of a plastic backing, a quarter-inch wide, on one side of which is deposited a layer of magnetic material consisting of one or more of the oxides of iron. In some tapes the plastic medium may be uniformly impregnated or mixed with the iron oxide, this type of tape being known as 'homogeneous', while the first variety described is known as 'coated' tape. The particular mixture of iron oxides coated upon, or mixed into, the plastic medium varies from one manufacturer to another. So also does the overall thickness of the tape, and in the coated type both the magnetic layer and plastic backing vary in relative thickness between manufacturers. Magnetic tape is supplied and stored wound up into reels, this practice having obvious advantages which it is unnecessary to enumerate. In recording or reproducing, the tape is always fed from one reel past the recording or reproducing head and is wound up into a second reel. The thickness of the magnetic tape issued by various manufacturers has varied from about 0·002 in. up to 0·003 in., but the upper limit of this dimension has now been standardised at 0.0024 in. From these figures it will be appreciated that adjacent layers of magnetic material upon a reel of magnetic tape are separated only by a small distance. Thus, when a reel of tape has been recorded, so that it has a varying intensity of permanent magnetisation along its length, the weak magnetic field radiated by each tape layer can cause some small magnetisation of the magnetic material in adjacent layers. The amount of magnetisation created depends upon various conditions, such as the separation between the layers, the level of the original recording, and the temperature. These effects will be described in detail in later paragraphs. In any event the newly formed intensity pattern always bears a recognisable resemblance to the adjacent pattern which created it. On some occasions conditions are such that the magnetisation created on one layer by the magnetic field of another gives an audible signal or 'echo' upon reproduction and the result can be very irritating. Some properties of this phenomenon, which is known as 'accidental' or 'spurious' printing or as 'copy effect', were first described by German workers [1, 2], and further experimental work has since been reported in America.[3] The accidental printing can take place in layers on either side of the original recorded intensity, so that on reproduction some echoes can appear before the main signal (pre-prints) and others after it (post-prints).

It is, of course, possible to set up conditions under which one magnetic tape

* Vol. 5, No. 1, Spring 1950

[1, 2, 3] See page 22

may be used as a 'master' to print its intensity variation fairly efficiently upon a second or 'slave' tape, and this has obvious applications in the large-scale commercial production of magnetic records. The purpose of this article, however, is to describe the properties of accidental printing and some methods of alleviating it, and not to describe the process of intentional printing, although much of the analysis and discussion given is applicable to both phenomena. In the present article, therefore, the originally recorded layer of tape will often be referred to as the 'master' tape and the layer on which accidental printing has taken place as the 'slave' tape, this terminology being convenient for each type of printing.

Theoretical Considerations

General Problem

The physical process involved in accidental printing is merely a complex example of one magnet being magnetised by another and, as in the simplest case, the problem of determining the induced magnetisation is largely one of evaluating the magnetising field. Briefly, an analysis of accidental printing can be made by establishing the following characteristics:

(*a*) The nature of the magnetisation resulting from the recording of a sinusoidal signal.
(*b*) The distribution of the magnetic field created by the recorded magnetisation.
(*c*) The magnetisation induced in a nearby layer of tape by this field.
(*d*) The output obtained when the master or slave tape is passed over a reproducing head.

In each of these steps of the problem, an analytic solution can be obtained easily only if a number of simplifying assumptions is made. The complete justification for some of these assumptions requires a very detailed analysis of the phenomenon of accidental printing, all of which cannot be produced here. The discussion that follows is, however, written in the light of the conclusions of a full analysis.

Conditions of Accidental Printing

In practice the recording field applied to a tape when it is passed over a normal 'longitudinal' recording head is of a very complex nature. Elements of tape at various distances from the surface which is in contact with the head, experience bias and audio fields differing in absolute and relative magnitude, in direction, and in rate of decay on either side of the gap. This leads, in general, to a non-uniform distribution of intensity of magnetisation through the thickness of the tape and to the existence of at least two components of intensity, one along the length and one perpendicular to the plane of the tape, these components not necessarily being in phase. Both longitudinal and perpendicular components of intensity will be formed in the slave by each of the components of the master. The short analysis given in this article will deal only with the longitudinal components of both master and slave. This simplification leads to predictions of the properties of the printing phenomenon which are little different from those obtained by considering both components in master and slave.

It will be assumed that this longitudinal magnetisation is constant over the cross-section of the magnetic medium of the master. This is not strictly true, for the recorded intensity must be of greater magnitude near the surface which was in contact with the recording head. However, it is clear that a layer which has a magnetic intensity which decreases through its thickness may be replaced, for analytical purposes, by a thinner layer of equivalent constant intensity over its cross-section. This substitution implies that the slave layer on one side of the master tape may be at a slightly different effective distance from the master than the slave layer on the other, so that if the intensity of printing is a function of distance from the effective master a difference of level may be expected between pre-prints and post-prints. The value of permeability used in the calculations is another factor of importance. The permeability of most tapes does not much exceed three for normal recording conditions. However, under the conditions encountered in accidental printing we are concerned with the initial region of the magnetisation curve of the material, where the slope of the intensity rise is small and the permeability is probably nearer unity. This allows of considerable simplification of the field calculations, for boundary effects between magnetic coating and plastic backing may be neglected when the permeability is approximately equal to unity. Now the relative levels of recorded and printed signals obtained in practice are such that it is unlikely that poles created in a slave will appreciably affect the magnetisation of the master. It follows, therefore, from the last two assumptions that the field from a single length of recorded tape will remain unaltered if other lengths of tape are reeled alongside it.

It will be further assumed that the mean induced magnetisation in the slave tape is proportional to the field along a line through the centre of its magnetic coating, parallel to its length. This should not lead to much error provided that the magnetisation induced in the slave may also be considered substantially uniform over a cross-section. Both recorded and printed magnetisation are then of the same kind, and any losses occurring in the replay chain must be identical in the two cases. The magnetisation of a slave tape should be effectively constant over an appreciable part of its width when the separation between master and slave is very small in comparison with the width of the tape. This is always the case in practice since printing between layers separated by more than three or four intermediate layers is not of interest. Similar remarks apply to the uniformity of magnetisation through the thickness of the slave tape as were made in connection with the master tape, except that the rate of decrease of magnetic intensity with thickness will not be so large as in a normal recording.

Finally, self-demagnetisation of the slave during the printing process will be ignored. The results of the detailed analysis indicate that self-demagnetisation of the slave will, in fact, be small over the range of wavelengths considered when the permeability of the tape is low.

Printing Field from Longitudinal Recorded Magnetisation

Fig. 1 represents two parallel lengths of magnetic tape of width 2W, each with a thickness of magnetic medium 2c, and separated by a distance d. Let right-handed axes, x, y, z be set up with Ox lying along the centre line of the lower tape (the slave) parallel to its length and Oy perpendicular to the plane of the tapes.

Let the intensity of magnetisation of the master be of the form

$$J_x = \hat{J}_x \sin \frac{2\pi}{\lambda} (x + \alpha)$$

where J_x is uniform throughout a cross-section of the magnetic medium, $\hat{J}_x$ is the peak value of intensity, and λ is the wavelength of the signal recorded on the tape.

It is required to find the longitudinal field, H_x, at points along the x axis (the centre line of the slave). This can be accomplished in several ways, but it is perhaps most interesting to evaluate the field directly from the distribution of magnetic poles along the master tape. The master magnetisation possesses a volume density of pole ρ, where

$$\rho = - \operatorname{div} J_x = - \frac{dJ_x}{d_x}$$

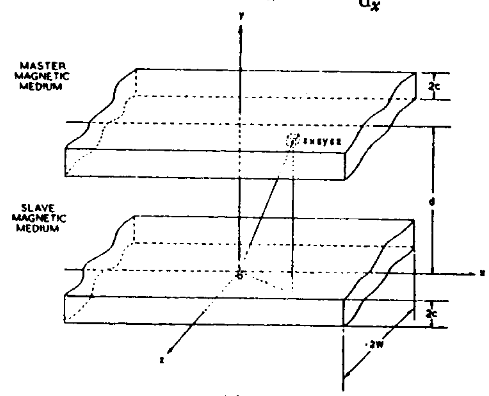

Fig. 1

$$\rho = -\frac{2\pi}{\lambda}\hat{J}_x \cos\frac{2\pi}{\lambda}(x+\alpha) \;\ldots\ldots\; (1)$$

The master magnetisation possesses no surface poles since there are no components of magnetisation normal to the sides of the tape.

The magnetic pole contained in a volume element of the master situated at the point (x, y, z) is therefore $\rho.\ \delta x\delta y\delta z$.

The field at the origin due to this element is δH, where

$$\delta H = \frac{\rho.\ \delta x\delta y\delta z}{r^2}$$

and $r = \sqrt{(x^2+y^2+z^2)}$ is the distance between the element and the origin.

The longitudinal component of this field is δH_x, where

$$\delta H_x = \frac{\rho.\ \delta x\delta y\delta z}{r^2}\cos\theta = \frac{\rho.\ x.\ \delta x\delta y\delta z}{r^3}$$

θ being the angle between r and the x axis.

The total field at O is obtained by integrating over the volume of the master tape.

$$\text{Thus } H_x = \int_{-\infty}^{\infty} dx \int_{d-c}^{d+c} dy \int_{-W}^{W} \frac{\rho x dz}{(x^2+y^2+z^2)^{3/2}}$$

By making one small approximation which involves neglecting y^2 in comparison with W^2, the integral can be reduced to the form

$$H_x = 2\int_{-\infty}^{\infty} \rho.\ \frac{W}{\sqrt{(x^2+W^2)}}\tan^{-1}\frac{2cx}{x^2+d^2-c^2}dx$$

Substituting for ρ from equation (1) and putting the remainder of the terms in the integral equal to $f(x)$, we have

$$\begin{aligned} H_x &= -\frac{2\pi}{\lambda}\int_{-\infty}^{\infty} f(x)\,\hat{J}_x \cos\frac{2\pi}{\lambda}(x+\alpha)\,dx \\ &= -\frac{2\pi}{\lambda}\int_{-\infty}^{\infty} f(x)\,\hat{J}_x \cos\frac{2\pi\alpha}{\lambda}\cos\frac{2\pi x}{\lambda}\,dx \\ &\quad + \frac{2\pi}{\lambda}\int_{-\infty}^{\infty} f(x)\,\hat{J}_x \sin\frac{2\pi\alpha}{\lambda}\sin\frac{2\pi x}{\lambda}\,dx \end{aligned}$$

But since $f(x)$ is an odd function, the first of these integrals is zero, so that

$$H_x = \frac{2\pi}{\lambda}\hat{J}_x \sin\frac{2\pi\alpha}{\lambda}\int_{-\infty}^{\infty} f(x)\sin\frac{2\pi x}{\lambda}\,dx$$

Thus the longitudinal field component is of the form

$$H_x = \hat{H}_x \sin\frac{2\pi\alpha}{\lambda} \;\ldots\ldots\ldots\ldots\; (2)$$

$$\text{where } \hat{H}_x = \frac{4\pi}{\lambda}\hat{J}_x\int_{-\infty}^{\infty}\sin\frac{2\pi x}{\lambda}.\frac{W}{\sqrt{(x^2+W^2)}} \times \tan^{-1}\frac{2cx}{x^2+d^2-c^2}dx \;\ldots\; (3)$$

Now the major contributions to H_x will come from elements of tape in the range $-W \ll x \ll W$, and therefore

$$\frac{W}{\sqrt{(x^2+W^2)}} \simeq 1$$

This approximation is of course equivalent to assuming the master tape to be of infinite width.

Now the smallest value of d which will be of interest in accidental printing will be equal to the overall thickness of the tape, and this for normal coated tapes is of the order of ten times c, the thickness of the magnetic medium. Therefore the maximum value of $2cx/(x^2+d^2-c^2)$ will never be greater than about 0·1, and hence

$$\tan^{-1}\frac{2cx}{x^2+d^2-c^2} \simeq \frac{2cx}{x^2+d^2}$$

Making these approximations equation (3) becomes

$$\hat{H}_x = \frac{8\pi c}{\lambda}\hat{J}_x\int_{-\infty}^{\infty}\sin\frac{2\pi x}{\lambda}.\frac{x}{x^2+d^2}dx$$

This expression can be evaluated by means of a contour integral transformation which gives a solution

$$\hat{H}_x = \frac{8\pi^2 c}{\lambda}.\hat{J}_x.\exp\left[\frac{-2\pi d}{\lambda}\right] \;\ldots\ldots\; (4)$$

The complete expression for the longitudinal field near the tape is then

$$H_x = \frac{8\pi^2 c}{\lambda}\hat{J}_x.\exp\left[\frac{-2\pi d}{\lambda}\right]\sin\frac{2\pi\alpha}{\lambda} \;\ldots\; (5)$$

The Printed Magnetisation

Now suppose that the remanent value of the intensity of magnetisation induced in a slave at a distance d from the master will be of the form

$$J'_x = KH_x$$

where K is related to the susceptibility of the magnetic medium. From equation (4), therefore, the ratio of the peak printed magnetisation, $\hat{J}'_x$, to the peak recorded magnetisation, $\hat{J}_x$, is

$$\frac{\hat{J}'_x}{\hat{J}_x} = \frac{8\pi^2 cK}{\lambda}.\exp\left[\frac{-2\pi d}{\lambda}\right] \;\ldots\ldots\ldots\; (6)$$

This will be taken also as the ratio of the reproduced outputs of the printed and recorded signals.

Thus, for a given tape speed, the approximate analysis shows that the ratio of printed to recorded magnetisation should first rise with frequency at approximately 6 db/octave, reach a maximum, and then decrease rapidly as the frequency is raised still further. By differentiating Equation (6) and equating to zero it may be shown that the maximum occurs when $\lambda = 2\pi d$. At a given frequency, the print level should decrease exponentially with distance from the master tape, the attenuation per layer being proportional to the frequency. The family of curves in Fig. 2 shows the calculated variation of print level with wavelength on the tape for a series of values of d, the separation between the tapes.

Experimental Investigation

Method of Measurement

In an investigation of accidental printing, one of the main difficulties is in measuring printed signals which are more than 50 db lower in level than the recorded signal, but are closely spaced about it on the tape. A method which has been used to overcome this difficulty is to record the master signal on a strip of tape, to stretch this strip in contact with an erased strip over a drum and, after a certain time, to measure the level of the signal printed on to the erased strip. The measurement of the print will normally mean joining the printed strip of tape into a reel or loop and running it past the reproducing head of a recording machine or loop tester.

This procedure is rather laborious and, moreover, does not correspond very well to practical conditions. In particular, there is bound to be an appreciable time delay between the separation of the master and slave strips and the replay of the printed signal. The present investigation shows this to be a factor of considerable importance.

In the measurements described here a new method of test was used, a short master strip of tape, on which a signal had been recorded, being wound into a reel of (slave) tape on the recording machine. Strips approximately six inches long were used, and each strip was wound into the reel (normally about two-thirds full) on the left-hand spool of a recording machine by carefully inserting its end and then spooling back in the normal way for approximately ten seconds of playing time. On replay, static charges usually caused the master strip to adhere to the slave tape as it left the reel, but by placing a tape guide in an appropriate place, the strip was ejected before it reached the heads, so that only the printed signals were replayed. The system is illustrated diagrammatically in Fig. 3. The insertion of a master strip in a reel of tape simulates the observed practical condition of printed signals occurring before and after the master signal. The relative magnitude of both series can then be measured almost immediately in the absence of the master signal.

The output of the recorder was fed to a valve voltmeter or pen (level

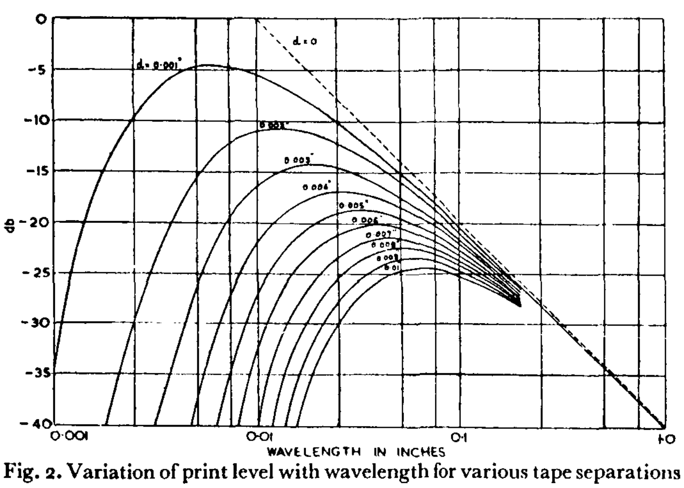

Fig. 2. Variation of print level with wavelength for various tape separations

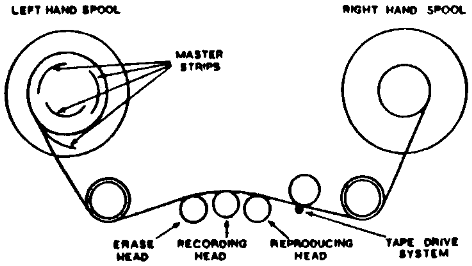

Fig. 3. Method of creating accidental prints

recorder through a system of band-pass filters which reduced background noise. The master signal was a pulse of tone of just over 0·2 seconds duration. On replaying at a tape speed of 30 in/sec. the printed signals were spaced approximately 1 second apart, the spacing varying according to the position of the master strip in the reel. Measurement of the level of successive layer prints was therefore difficult, and except when the valve voltmeter was replaced by an automatic level recorder only the strongest of the series of prints was measured.

Most of the tests were made at 1 kc/s on a reel of low-coercivity coated tape (designated Tape A) using a tape speed of 30 in/sec. (76·2 cm/sec.), but tests on a high-coercivity Tape B and another low-coercivity Tape C were also made, where necessary, for comparison purposes. The 'peak level' referred to in the tests on these tapes was the highest level that could be used without producing more than 3 per cent. total harmonic distortion. Unless otherwise stated, the reels were wound with the magnetic coating outside.

Time-Decrease of Print Intensity

In the method of test used, the time intervals between the separation of the printed layers from the master magnetising field and the initial replay were approximately 0·5 seconds for the first series of prints (pre-prints) and approximately 1·5, 2·5, 3·5 . . . seconds for the prints in the second series (post-prints). Delays of this order were found to have negligible effect on the level of the major prints, and so the initial replay could, for most purposes, be considered to take place instantaneously.

With longer delays, however, the effect on the level of print was very marked, and it was found that the level decreased with time. This effect has been investigated in some detail by Lippert.[1] It is illustrated in Fig. 4, where the observed decrease in the level of a first-layer 1-kc/s printed signal on Tapes A and B is plotted against time. Measurements were made at various intervals after the release of the master strip by spooling back and replaying as required. When the reel and master had been stored for only five minutes, the level of print fell considerably on successive replaying: after one minute the drop in level was 6 db, after five minutes the total drop was 9 db, and the level was still decreasing after sixteen minutes. As shown in the figure, the time decreases given by the low-coercivity Tape A and a commercial high-coercivity Tape B were almost identical. The results (Fig. 5) of similar tests made when the reels had been stored overnight show that the decrease of level with time was still appreciable, but less pronounced than before. Even in this test, however, it was found that the level was still decreasing, though very slowly,

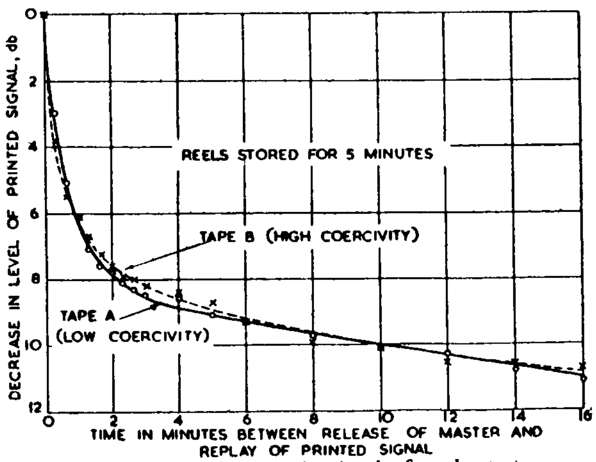

Fig. 4. Time-decrease of print level after short storage

after several hours. The initial level of the prints resulting from overnight storage was, not unexpectedly, higher than that after only five minutes storage. The effect of storage time on printing is described in more detail later.

Experiments were next made to check whether the phenomenon of a time-decrease of intensity was peculiar to the printing of a signal on a tape or whether it also occurred when the signal was recorded on a tape in the normal way. These experiments were made on a loop tester, on which a recorded signal of short duration could be replayed a fraction of a second after being recorded and, subsequently, replayed automatically at just under three-second intervals.

At normal output levels, recorded with or without high-frequency bias, the die-away was less than 0·2 db and took place in the first five seconds. With a level on the tape of the same order as that occurring in printing, however, the results obtained depended upon whether or not bias had been used. An unbiassed signal showed a fall in level of even greater magnitude than that shown by a printed signal, but when bias was used and the recording level decreased to give the same output level, the die-away was only 0·2 db. The results were substantially independent of frequency. Thus it appears that a fall in the level of a signal with time occurs also when the signal has been recorded in the normal way, but the fall is only appreciable (on a decibel scale) at very low recorded levels or, more precisely, at low values of total (signal plus bias) recording head flux.

Attenuation per Layer of Printed Level

The observed decrease of the level of a 1-kc/s printed signal with distance from the master is shown in Fig. 6, together with the calculated decrease. The decrease of level with distance at this frequency was very nearly exponential and equal to approximately 4 db per layer. Within experimental error the theory and measurement of this effect are in complete agreement. As would be expected from the theory, however, the decrease in level with separation was found to depend very greatly upon frequency; at low frequencies it was quite small, but at frequencies much above 5 kc/s the decrease in level per layer was so large that only the first-layer prints were measurable. This is illustrated by level-recorder records which are shown in Fig. 7.

To assist in distinguishing between the pre-prints and post-prints, a low-level signal of short duration was put on to the tape before inserting the master strip in the reel. This signal was so placed that, on reproduction, a marker would appear on the level-recorder record midway between the two sets of prints. This can be observed on the traces shown in the figure.

It is also evident from the level-recorder test that the layers on either side of the master strip do not give the same measured level of print on reproduction. One reason for this, the non-uniform magnetisation through the master, has been discussed in the theoretical consideration earlier in the article. Other factors will, however, affect the result in practice. For instance the actual intensity

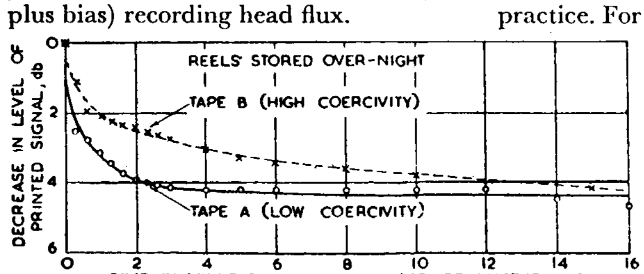

Fig. 5. Time-decrease of print level after over-night storage

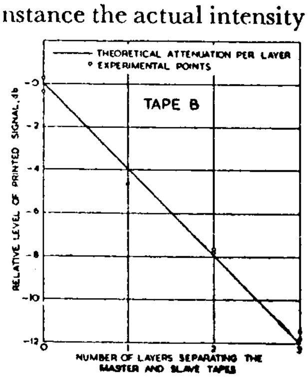

Fig. 6. (right) Attenuation of print level with separation

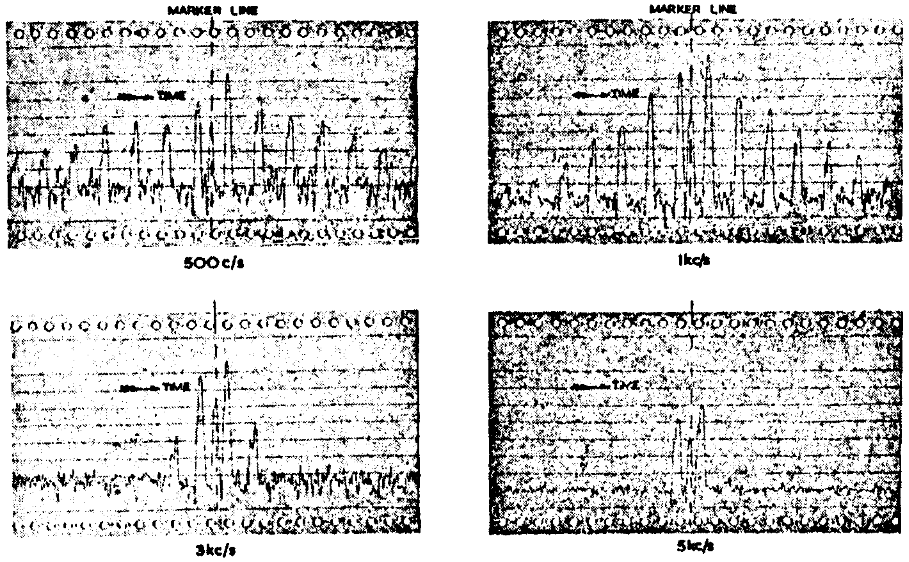

Fig. 7. Records of printing at various frequencies

of magnetisation printed on to the slave layers will also not be quite uniform over the whole magnetic layer. It is to be expected that the intensity will be greater in that part of the slave tape nearest to the master. Fig. 8, which illustrates this point, represents three adjacent layers of tape. The various magnetic coatings are designated C1, C2, and C3, and the associated backing of each layer, B1, B2, and B3. Suppose that a signal has been recorded at normal level, with bias, on C2. The intensity of magnetisation associated with this signal may be assumed to decay through the thickness of C2 away from the recording head. As pointed out previously, such a master tape may be replaced, for analytic purposes, by an equivalent tape of constant magnetisation which will be effectively further away from the coating C3 than from coating C1. When printing takes place, however, the greatest intensity of printed magnetisation in C1 will be adjacent to its backing B1, while the greatest intensity of printed magnetisation in coating C3 will be nearest to its surface. In absolute units the maximum intensity in C1, which is nearer the 'equivalent' master, may be larger than the maximum intensity in C3. When these two layers pass the reproducing head, however, the region of maximum intensity in C1 will be further removed from the reproducing head than will the maximum intensity in C3. The effect on the reproducing head will diminish as any given maximum intensity passes further from it.

There are thus two opposing considerations which will determine whether C1 or C3 gives the greater reproduced level of print. The conditions shown in Fig. 8 would result in a reduced printed intensity in C3 but a greater relative effect on the replay head. At the same time the intensity induced in C1 will be larger but its effect on the reproducing head less. It is not easy to predict the final outcome in all cases, but it is clear that pre-prints and post-prints are unlikely to be equal. It is probable that the effect of separation from the replay head is of greater importance, and this factor indicates that C3 should give a bigger reproduced level

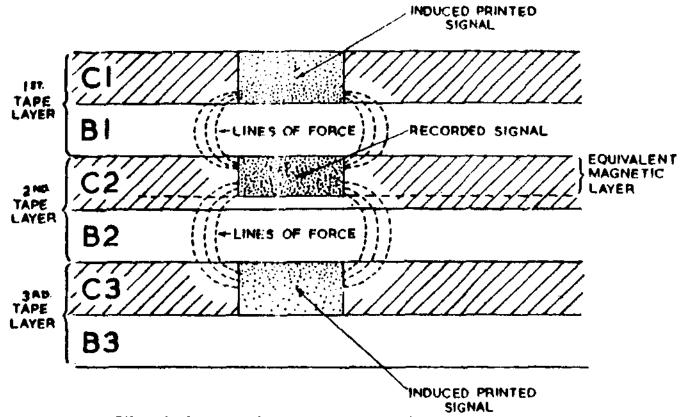

Fig. 8. Induced magnetisation in adjacent layers

than C1. Either C1 or C3 may be played first by winding the tape so that the coating is facing either outwards or inwards. Fig. 9 shows pen records of pre-prints and post-prints formed by winding the tape in these two ways. Clearly the relative magnitude of the two sets depends on the winding convention adopted. The experiments indicate that the difference is not as great, and does not vary so much with wavelength, as would be expected from reproducing considerations alone. The result is probably affected, therefore, by the non-uniform intensity of magnetisation through the master tape.

An examination of several records similar to those shown in Fig. 9 showed that an average difference of approximately 2–3 db existed between the two sets of prints at the frequency of test (1 kc/s). There seemed to be little evidence that the slightly different time delays between the separation of master and print layers for pre-prints and post-prints affected the results to any extent.

Relative Frequency Response of Printing

Experimental results for the print levels on the first four layers at various frequencies are given in Fig. 10. In making the master strips for these tests, the recording level was adjusted to give the same reproduced level at each frequency, and the level of print was measured relative to this reproduced level. The theoretical curves (based on Equation 6) are also shown in the figure. The agreement between experiment and theory is obviously fairly close.

Effect of Coating Thickness

The influence of coating thickness on print level was determined by making measurements of the first-layer accidental printing on two reels of low-coercivity tape, one of Tape A, and the other of Tape C, which has nearly twice the thickness of an identical coating material. The signal-to-print ratio obtained from Tape C was of the order of 4 db worse than that obtained from the normal Tape A. This increase of print level with increase of coating thickness is to be expected from the previous discus-

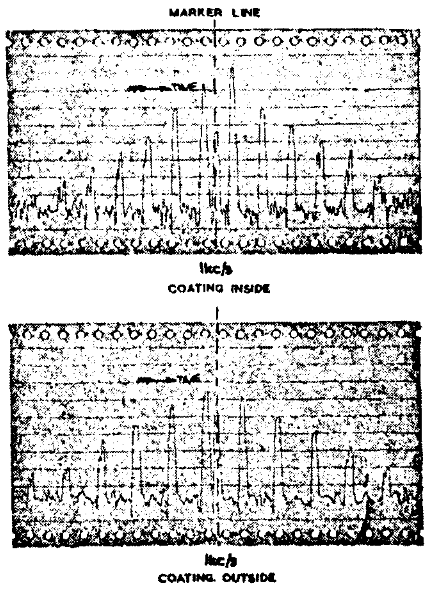

Fig. 9. Records of magnetic printing for different spooling arrangements

sion. The original recorded magnetisation on the tape is not uniform but decreases through the thickness of the magnetic coating. In fact for normal recording with bias it may be shown that a thickness of coating much beyond the present limit gives rise to only a small increase in reproduced level for the same recording level. In accidental printing, however, although a similar kind of non-uniformity is present, the magnetic intensity distribution does not fall away so steeply. At 1 kc/s, for instance, the print level should vary by only about 1 db from one surface of the slave coating to the other. Consequently an increase in coating thickness should result in a larger comparative increase of print level than of recorded level. In other words it should result in a worse value of the signal-to-print ratio.

Effect of Storage Time

The variation of the initial level of a printed signal with storage time is shown in Fig. 11. The master strips were recorded with peak level at 1 kc/s, and the level of print was measured in db below peak output level.

For storage times of less than 30 minutes the level of print was approximately −58 db relative to peak level (8 db above the normal level of background noise). After an hour the level rose to −55·5 db, and on leaving the reel overnight the resulting initial level of the print was −53 db. Further storage caused only a small increase, the level of print after three days being −52 db (14 db above background noise).

Another effect of storage was to make the printed signal more stable. Even after overnight storage the decrease in the print level after separation from the master was, however, still considerable, dropping by 5 db during fifteen minutes. Thus, if the overnight prints measured in the test on storage time had been left for fifteen minutes, their level would have dropped to −58 db.

When a recording is made in practice, it is normally spooled back from the take-up spool before storing. On playback, therefore, the comparatively high-level prints resulting from storage are replayed at their initial level. An improvement might be made if the recording were stored on the take-up spool and spooled back shortly before the playback was due to take place. The high-level prints resulting from storage would then have time to fall off appreciably before replay. The prints occurring on the left-hand spool during this time would be replayed at their initial level, but this would not be so high owing to the small storage time. The improvement mentioned above could be only of the order of 5 db, but when the printed signals are near the noise level, the masking effect of the latter is such that a change in the

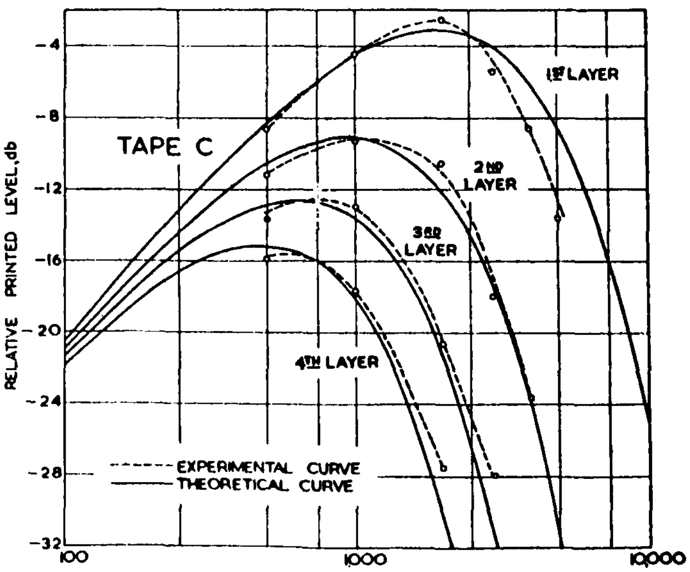

Fig. 10. Frequency characteristic of accidental printing

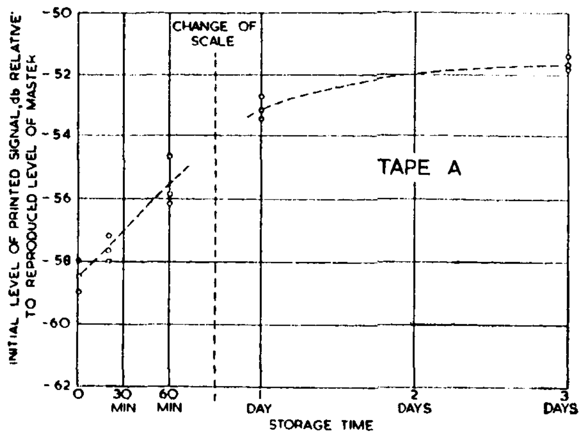

Fig. 11. Increase of print level with storage

level of printing of 5 db may make all the difference between the printing being inaudible or troublesome.

Effect of Master Level

Fig. 12 gives the variation of the level of printing with the level of a 1-kc/s signal recorded on the master strip. The graph shows that, over the range tested, the relationship was approximately linear. It would seem, therefore, that the effects of printing cannot be lessened to any extent by an alteration in recording level. The only result of lowering the recording level would be to increase the masking effect of background noise.

Effect of Spooling Tension

Changes in the level of printing were found to occur on varying the spooling tension, and the results are shown in Fig. 13. The initial level increased less than 3 db on raising the spooling tension from 1 oz (28 gm) to 12 oz (340 gm), but the corresponding change in the level measured three minutes later was 5 db. This variation in the time-decrease of the printed signals is shown more clearly by Fig. 14.

These tests were made after the reel, with the master strips inserted, had been stored for only five minutes. On storing the reel overnight it was found that it made little difference whether the reel had been spooled at a high or at a low tension. In practice, therefore, the spooling tension is not likely to be a very important factor as long as it is kept within reasonable limits. The influence of tension on printing is probably a magnetostriction effect. Applying a tension to the tape could cause a condition of crystal strain to be set up which can act as a kind of bias in the printing process by allowing the domain orientations to acquire a more permanent set. The very small differences in the separations between layers likely to rise from changes in tension cannot account for the observed variation in the level of printing.

The results given in Figs. 13 and 14 were obtained by spooling back by hand against the brake on the take-up spool of a recording machine. The resulting tension in the tape could thus be adjusted quite accurately by varying the pressure of the brake. In these tests only the reel itself was spooled under tension: the tension in the master strip was nominally zero. If the explanation of the effects is

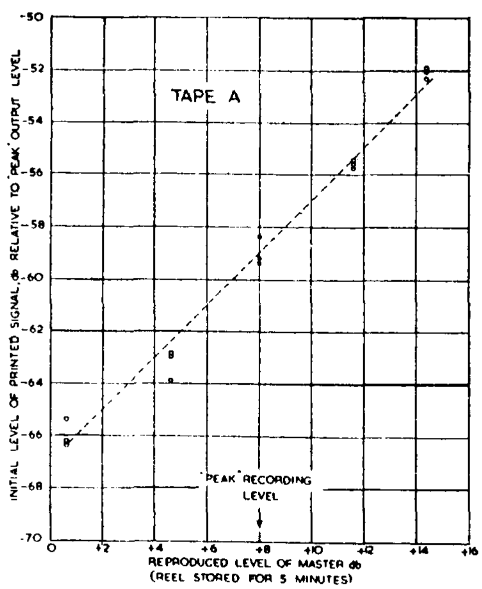

Fig. 12. Increase of print level with recorded level

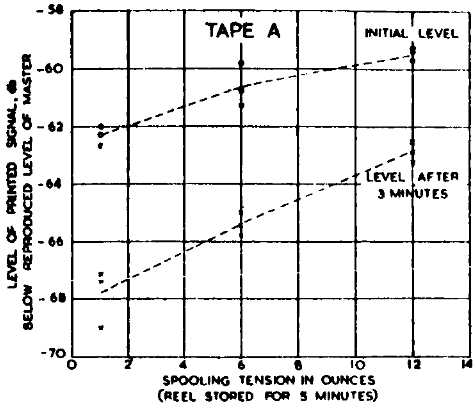

Fig. 13. Increase of print level with tape tension

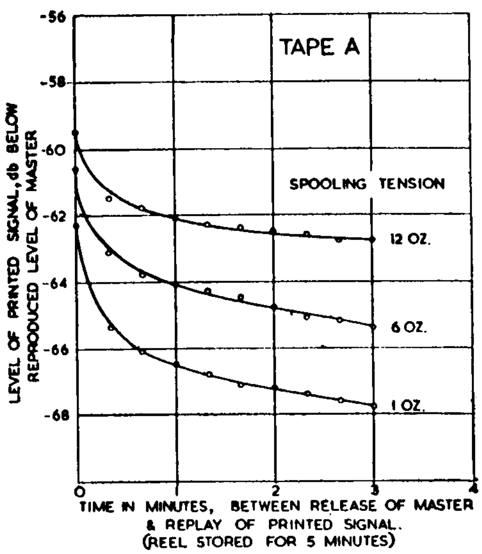

Fig. 14. Effect of tape tension on time decrease characteristics

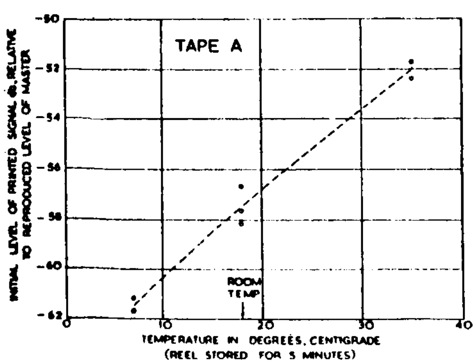

Fig. 15. Effect of temperature on print level

on the lines given, however, this should not affect the results obtained. The printing process occurred in the reel, and the master strip served merely to provide a magnetic field, the magnitude of which would be unlikely to alter appreciably with tension.

The level of printing was found to be substantially independent of the position of the master strip in the reel. Strips were inserted at intervals throughout a reel, which was then left for approximately one hour before the prints were replayed. The results obtained were constant to within $\pm$ 1 db.

Effect of Temperature

An approximate measure of the extent to which printing was affected by temperature was obtained by using trays of ice to cool the reel on the machine and a stream of hot air to warm it. In both tests, the reel and master strips were allowed to reach a steady temperature before making a test. When this condition was reached, part of the reel was run off, the strip was inserted, and the tape spooled back. The reel was then stored for five minutes at the required temperature and finally replayed.

The results obtained are given in Fig. 15, and they show that a rise of some 20° C can increase the print level by 7 db. The values of temperature shown are, of course, only approximate. A thermometer was placed near the surface of the reel, and the mean temperatures of the tape were probably rather nearer to room temperature than the values measured. This would mean that the true increase in the level of printing with temperature is even greater than that shown.

Effect of an External Magnetic Field

Experiments were made to determine how the level of printing varied with an externally applied magnetic field. The method used was similar to that described for the tests on the effect of temperature. The reel was stored for a total of five minutes, during two minutes of which it was rotated in a calibrated 50-c/s magnetic field. The remaining time was required to transfer the reel between the machine and source of field. The results are given in Fig. 16, and show that the increase of the level of printing became quite considerable for fields greater than approximately 5 oersteds. It is very unlikely, however, that stray fields of this magnitude would be encountered in normal recording premises.

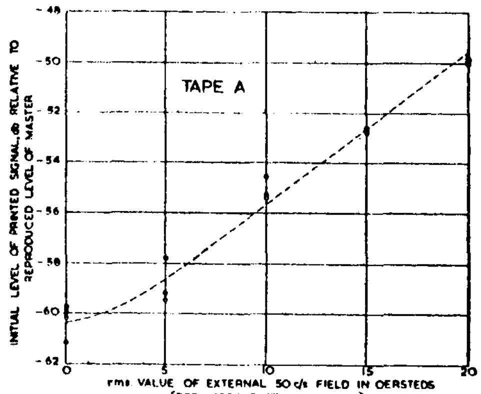

Fig. 16. Effect of external magnetic field on print level

Alleviation of Accidental Printing

Stability of Recorded and Printed Signals

The experiments have indicated that the magnetisation associated with a printed signal is much weaker, and of a far less permanent nature, than the magnetisation produced by recording an audio signal with h.f. bias in the normal way. It is to be expected, therefore, that a printed signal will be more easily erased than a recorded signal, and this might provide a simple method of reducing the relative level of unwanted to wanted signal on replay. The experimental investigation was therefore extended to establish whether the application of a small erasing field would appreciably reduce the level of printing without seriously affecting the master signal.

Relative Ease of Erasing

An experiment was first made on Tape B and Tape C using a normal erasing head supplied with various values of h.f. current. It became evident that, for a comparatively small reduction in master level, the print level on both tapes could be considerably reduced by controlled erasure. For instance, with an erasing current of 30 mA, Tape C showed a reduction in 1-kc/s print level of 10 db for a loss in master level of less than 2 db. The effect was even more marked on the high-coercivity tape. With this tape, for a loss in master level of 2 db, the print level was reduced more than 14 db, and a 10-db reduction in print level corresponded to a negligible loss in master level.

The printed signal in these first tests was the result of overnight storage. The experiments on the influence of storage time on printing level make it clear that the printed signals become more stable the longer the recorded reel is stored before replay. Thus, if the reels of tape used in erasure tests are stored for several weeks, the relative reduction of printing may be less. Instantaneous prints, on the other hand, will be reduced considerably more in level.

A very important result is that after the initial decrease in master level caused by the first partial erasing successive applications of the same erasing field result in little further decrease. This implies that a recording can be treated in this way to reduce printing any number of times without entailing a cumulative series of losses in recorded programme level. In practice the choice of the intensity of the partial erasing field must be a compromise between the two conflicting requirements of maximum print erasure and minimum reduction in the level of the master. Apart from considerations of the signal-to-noise ratio, too great a reduction in programme level will also introduce appreciable non-linear distortion, and it may also be found that the high frequencies are erased more than the low frequencies.

The question of relative erasure of various frequencies is one of some complexity. The general tendency is for the high frequencies to be reduced more than the low, but the effect is found to depend upon both the head used to record the signal and the head used for partial erasing. Various combinations of nominally identical heads, however, give very different results. The phenomenon appears to be connected with the non-uniform distribution of the recorded magnetisation through the tape. At high frequencies it is known that the magnetisation is rather more confined to the outer surface of the magnetic medium than it is at low frequencies. Thus an erasing field applied from a head in contact with the outer surface might be expected to affect a larger fraction of the total magnetisation of the high frequencies. If this explanation is correct, it should be possible to make the erasure at various frequencies more constant by ensuring that the erasing field is substantially uniform over a cross-section of the tape. This can be done by separating the erasing head from the tape, by erasing from the reverse side of the tape, or, best of all, by passing the tape through the centre of some form of solenoid to carry out the partial erasure. All these methods have been tried, and all gave better results than those given by an erasing head used in the normal way.

Figs. 17 and 18 show the results obtained using Tape C when partial erasure was carried out by means of a simple solenoid fed with h.f. current. For a given loss in master level, Fig. 17 shows that the reduction in the level of a printed signal (48 hours' storage) was slightly greater than that obtained using a normal erase head. A greater erasure of high than of low frequencies in the recorded signal still occurred, but it was not as great as that generally obtained using a normal erasing head. Fig. 18 shows how the total harmonic distortion at various recording levels was affected by a partial erasure due to a current of 65 mA through the solenoid. It can be seen that, over the normal working range of recording level, the increase in distortion introduced by this amount of partial erasure was quite negligible. Results similar to those shown in Figs. 17 and 18 were obtained using the high-coercivity Tape B, except of course that considerably higher values of h.f. current were needed in the solenoid.

Erasure of an Unbiassed Recorded Signal

It was noted earlier that a low-level signal recorded without bias showed similar instability to that shown by a printed signal. It has also been found that an unbiassed recorded signal, like a printed signal, is much more readily erased than a biassed recording. This is shown by the full-line curve in Fig. 19. The decrease in the level of the unbiassed signal was even more rapid than that of a printed signal, possibly because the unbiassed signal lacked the stability that a printed signal can gain with several hours of storage.

It is also of interest to know whether the same degree of erasure of an unbiassed signal can be obtained in the presence of a normally recorded signal. This would indicate whether a print superposed on part of the master recording could be easily erased, or whether the master might act as a bias in the printing process.

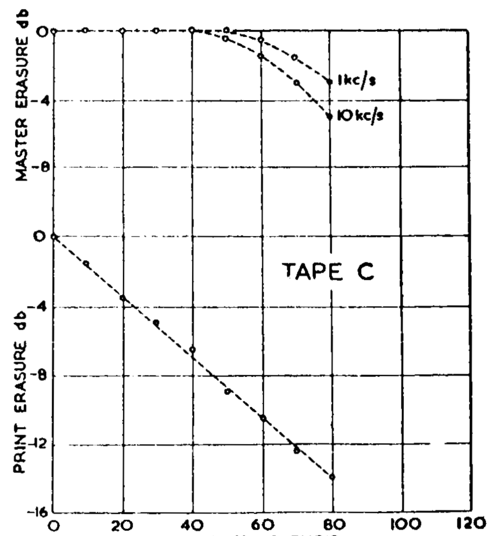

Fig. 17. Relative erasure of recorded and printed signals

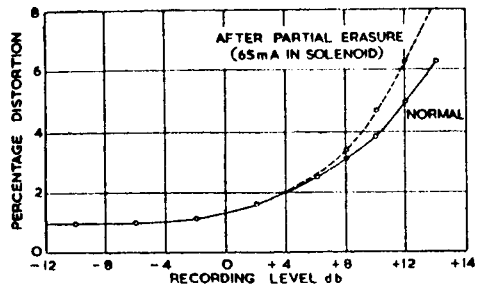

Fig. 18. Effect of partial erasure on the total harmonic distortion at 1 kc/s

The test on the unbiassed 1-kc/s signal was therefore repeated using a tape on which a 10-kc/s signal had already been normally recorded at zero level. On replay, the level of the 1-kc/s output was measured through a band-pass filter which eliminated the 10-kc/s reproduced signal. As shown by the dotted curve in Fig. 19 the results obtained were, within experimental error, identical with those obtained in the first test.

Conclusion

The theoretical and experimental conclusions of this investigation are in agreement that the level of accidental printing which may take place between one layer and another depends on the recorded intensity and wavelength of the original signals and on the separation between the layers. Thus, for a given make of tape recorded at a chosen speed there is some frequency which gives a maximum level of accidental printing, and if the programme recorded, be it either music or speech, has a large frequency content of this value, printing will be especially noticeable. The level of printing is well below that of the master recorded signal in normal circumstances, and hence its audibility is particularly dependent upon the general level of background noise. As tapes and recording systems become quieter the effects of accidental printing may become more irritating unless effective alleviation is possible. The experimental results are in agreement with earlier findings that the level of accidental printing increases with the temperature at which the tape is stored and with the intensity of alternating magnetic fields to which it may be accidentally exposed. Of these two factors the important one is that of temperature, and this should be a first consideration in the alleviation of accidental printing. Clearly, recorded tapes must be stored in cool surroundings, and recording premises should not be maintained at higher temperatures than are necessary for comfort.

The investigation has revealed the importance of the time-decrease of level which takes place in the accidental print after it is removed from the field of the master signal. This loss of level will be obscured by any experimental technique in which the print is measured some time after separation from the master. The time-decrease of level shows that the printed signal is rather unstable in comparison with the normally recorded master, and this leads to a fairly promising

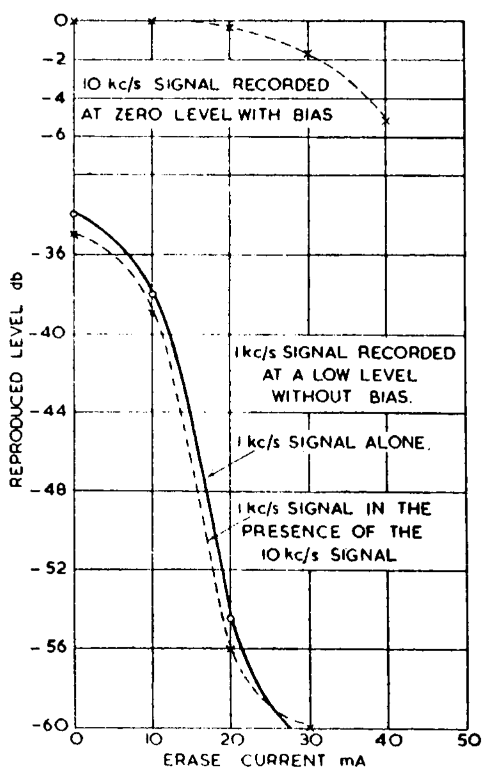

Fig. 19. Effect of erase current on reproduced level

method of accidental print alleviation. By the use of h.f. partial erasure on replay it is possible to remove much of the printed signal without losing an unacceptable percentage of the intensity of the master recording. Nevertheless, this process must be carried out with care, and its efficacy varies according to the time for which the recorded tape has been stored. Using a normal erasing head the relative wipe of high and low frequencies is usually unfavourable to high frequencies. The most consistent partial erasure which has yet been discovered here is provided by the field of a simple solenoid of suitably small cross-sectional area through which the tape is made to pass.

However, the audible effect of applying a partial erasing field to a badly printed tape can be very marked. The prints can, under the best conditions, be reduced well below the limit of intelligibility, and the effect immediately noticeable is one of reduction in the general background of noise, the recording sounding definitely 'cleaner' in quality. In practice there seems to be no reason why a partial erasing head or solenoid, providing a suitable field distribution, should not be permanently mounted on a magnetic recording machine, providing that it is placed before the three conventional heads. Such a partial erasing head need not affect the recording of a new programme and can often alleviate printing troubles to a marked extent when replaying previously recorded reels. The final remedy must, of course, rest in the development of magnetic tapes that are not subject to accidental printing troubles. Clearly the thickness of the magnetic medium should not be greater than is necessary to provide normal sensitivity, and the magnetic medium itself should be insensitive to the low printing fields while showing normal sensitivity to the higher fields of a correctly biassed recording head.

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A. RUSCH, C. P. LASCARO, E. BEEKMAN, U. S. Army Electronics Research and Development Laboratory

HIGH-STABILITY MAGNETIC TAPE FOR DATA-PROCESSING SYSTEMS

The performance of high-speed information-sensing and data-processing systems depends on the reliability of the magnetic-recording-tape subsystem. Presently available tapes fail to provide the required degree of dimensional stability. Tests on a recently developed experimental tape-backing material, composed essentially of ultra-thin glass fabric impregnated with polycarbonate resin, indicate the feasibility of developing a magnetic recording tape which will be free from excessive elongation, permanent set, tearing and oxide flaking. Steps in the development of the improved tape are described and comparative data are given.

MAGNETIC RECORDING TAPES currently used in high-speed information-sensing and data-processing equipment suffer from excessive elongation, permanent set and magnetic oxide flaking under severe operating conditions. This has become particularly apparent in military equipment. The flaking effect, for example, is increased under conditions of high humidity, such as those which might be encountered during field operations. Loss of magnetic oxide results in a loss of signal response. Figure 1 shows the separation of magnetic oxide in polyester (polyethylene terephthalate) tapes due to elongation and humidity. In addition to the usual mechanical tests, the fact that magnetic tapes sometimes elongate and acquire a permanent set may also be demonstrated by appropriate electrical tests. Such tests have indicated that efficient operation is adversely affected when magnetic tapes elongate over 6 per cent and retain a permanent set greater than 0.75 per cent. In order to overcome this deficiency, data-processing machines are required to operate slower than their maximum speeds. In some cases, it is necessary to add bulky mechanisms to decrease the tensile stress exerted on the magnetic tapes during high acceleration and braking.

Military Requirements

Since it is apparent that the physical and mechanical performance of presently available tapes has not kept pace with improvements of general electromagnetic responsiveness and information-handling requirements of field data-processing systems, special criteria have been established for a satisfactory military-grade magnetic recording tape. These criteria are detailed in the panel on the next page. Essentially, they call for:

- Increased physical strength, a minimum of elongation and permanent set and a maximum of dimensional stability.
- Minimal thickness to provide increased memory storage per unit volume.
- Optimum adhesion between backing material and the magnetic coating to obtain increased efficiency, life and reliability.

Magnetic Tape Evaluation

Comparative test data on representative specimens of commercially available magnetic recording tapes were obtained to provide a point of reference in determining the amount of improvement necessary to meet military requirements in tapes.

Tensile Characteristics. Table I shows the relationship between tensile stress, elongation and permanent set of representative regular polyester, tensilized polyester and acetate magnetic recording tapes. It will be

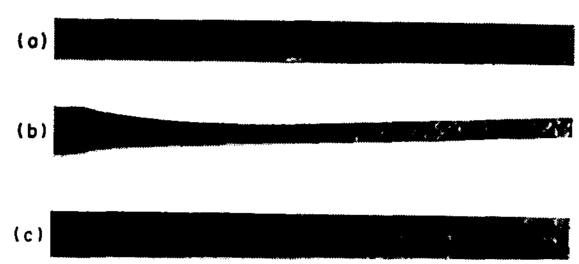

Fig. 1 — Typical defects in best commercial-grade polyester-base magnetic recording tapes as tested by the Signal Corps in field digital magnetic-tape transports for computers and communications systems. (a) and (c) show flaking of magnetic coating under temperature and humidity cycling, tested under environmental conditions of MIL Standard 170, "Military Moisture-Resistant Test Cycle for Ground Signal Equipment," and 2-hr operation. Tape speed, 150 in./sec; stop rate, 3 msec; temperature, 84 F; RH, 95 per cent. (b) shows necking caused by tensile loading beyond elastic limit. Abrupt stop: tape speed of 60 in./sec.

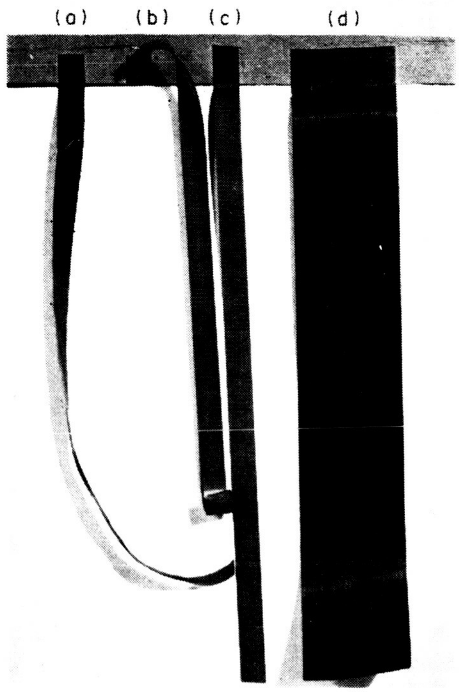

Fig. 2 — Four types of magnetic recording tape exposed to temperature of 160 F for 240 hr. (a) is acetate tape, ¼ in. wide, 1.3 mil thick; (b) is tensilized polyester, ¼ in. wide, 0.98 mil thick; (c) is regular polyester, ¼ in. × 1.3 mil; and (d) is regular polyester, 1 in. × 1.3 mil.

noted that all of these tapes have relatively high elongation when subjected to tensile stress over their elastic limit. This is particularly evident in the regular polyester magnetic tapes where the elongation under ultimate tensile stress is considerably over 100 per cent.

Heat Resistance. To determine the effect of exposure to the elevated temperature which magnetic tapes are required to withstand in operation and storage, samples of the same tapes were exposed to a temperature of 160 F for 240 hr in an air-circulating dry-heat oven. The results of the test are shown in Fig. 2. The ¼-in.-wide regular polyester magnetic tape sample (c) retained perfect dimensional stability. The 1-in.-wide regular polyester magnetic tape sample (d) showed slight longitudinal curling probably due to the effect of heat on the magnetic coating; otherwise the sample retained good dimensional stability. The acetate magnetic tape sample (a) curled badly and the tensilized polyester magnetic tape sample (b) curled, shrank and cupped. This test indicated that regular polyester magnetic tapes are the only commercially available ultra-thin plastic magnetic tapes which retain their dimensional stability under exposure to 160 F dry heat.

Humidity Resistance. To simulate some of the extremes of temperature and humidity encountered in field use, magnetic-tape transports were operated in environmental chambers in conformance with MIL STD 170 (Military Moisture-Resistant Test

Criteria for Military-Grade Magnetic Recording Tape

Thickness (backing and magnetic coating): 0.7 to 1.0 mil.

Width tolerance: Tape edges shall be parallel so that the rate of change of width shall not exceed 0.002 in. per 100 ft.

Stability: The tape shall maintain dimensional stability by not curling, crinkling or cupping. It shall not deviate more than 1.5 deg from a flat plane when tested in conformance with Para. 4.4.6 of MIL-T-21029. Shrinkage or extension shall not exceed 1.1×10^{-5} in./in. at any RH up to 100 per cent at 75 F. The tape shall be free from edge splitting and raveling.

Tear strength: The tape shall resist 15 gm at 75 F, 35 per cent RH when tested in accordance with ASTM D689 (Plastics).

Tensile strength: 36 lb ultimate strength longitudinal for 1-in.-wide tape, 9-lb ultimate strength longitudinal for ¼-in.-wide tape and 13 lb/in. transverse. Elongation shall not exceed 6 per cent at ultimate tensile stress and permanent set shall not exceed 1 per cent under peak load when tested at 25 C and 50 per cent RH.

Shock tensile strength: At least 0.59 ft-lb when tested at 70 F, 50 per cent RH per Para. 3.4.2 of MIL-T-21029.

Temperature resistance: Operating conditions —25 to +140 F. Storage conditions —80 to +160 F for 240 hr.

Humidity Resistance: Maximum moisture absorption less than 1 per cent.

Initial reliability: Each reel of tape shall be tested for freedom from permanent errors. The error of "dropout" is a loss of read-signal amplitude in which the level falls below 25 per cent of normal signal amplitude. This test shall be based on at least one full pass in each direction. The tape shall also be free of spurious noise output exceeding 10 per cent of full signal level when magnetized to saturation in one direction.

Service life: Tape shall withstand at least 50,000 bidirectional passes (25,000 in each direction) in a standard wear test. The wear test requires that a 50-in. length of tape selected at any point in a full reel be cycled on a Digital Tape Unit Tester used in conjunction with an RD-224( )/TYK Field Digital Magnetic Tape Transport Computer Type. Speed of tape shall be 150 in./sec using NRZI recording and 300 bits/in. density. During the wear test, a continuous digital signal is recorded and reproduced. End of tape life shall be defined as the time when the signal error rate (signal falls below 25 per cent) suddenly increases by several orders of magnitude or is greater than 1 part in 10^5. In a typical test, the error rate is zero with an occasional random few errors until end of life occurs. End of life is primarily caused by surface breakdown of the coating and caked oxide on the heads.

Table I — Tensile Properties of Magnetic Tapes

Characteristics	Type of tape backing					
	Regular polyester		Tensilized polyester	Cellulose acetate	Military requirement	
Width, in.	¼	1	¼	¼	1	¼
Thickness (approx), mils	1.3	1.3	1.0	1.3	0.7-1	0.7-1
Tensile load, lb to break (average)	7.54	27.8	6.62	4.15	36	9
Elongation at break, per cent (average)	169	117	32.6	19.18	6 or less	6 or less
Safe operating tensile load (approx), lb	4	16.5	4.0	3.4	35	8.75

Cycle for Ground Signal Equipment). The complete test requires a total of five 48-hr cycles. Near the end of each cycle the magnetic-tape transports were operated at a tape speed of 150 in./sec and a stopping rate of 3 msec from 1 to 2 hr at 183 F and 95 per cent relative humidity. The test was made on representative regular polyester magnetic tape, 1 in. wide with a nominal 1-mil-thick backing such as is regularly used for Field Digital Magnetic Tape Transports, Computer Type, RF-224( )/TYK. The extremes of temperature and the high humidity caused flaking in certain sections of the magnetic coating. [See Fig. 1 (a) and (c).]

Oxide Adhesion. Most of the information regarding the adhesion of magnetic coatings to magnetic-tape backing materials was gained from a study of the behavior of magnetic tapes before, during and after operations in such systems as field digital magnetic tape transports, computer-type and satellite-type recorders and transmitters. To study the effect of prolonged operation on magnetic tapes used for field applications, a test breadboard was made containing electronic parts similar to those found in some transmitting and recording equipment. A representative ¼-in.-wide magnetic tape with a 1-mil regular polyester backing was tested on this breadboard at a room temperature of 25 C and 50 per cent RH; the tape was given 14,000 passes through the recording and transmitting heads on the test breadboard at a speed of 30 in./sec. Continuous passage of the magnetic tape caused flaking of the coating and distortion of the tape on the reel due to elongation.

The physical and mechanical responses of magnetic recording tape to humidity, heat and tensile stress are primarily functions of the plastics film or backing material. However, the adhesive coating which serves as the magnetic oxide carrier also affects the responses to some degree.

There are two types of adhesive coatings on magnetic tapes. The autogenous type is a solution of the same resin that is used in the backing material. The heterogenous type uses a different resin because the backing material is insoluble in all usable solvents. Heterogenous adhesive coatings are used on polyester tapes and are subject to flaking because their physical properties are different from those of the backing material.

Film Evaluation

A study of commercially available organic films and film-forming resins was made to determine those most suitable for the development of a high-stability reinforced-plastics backing material for magnetic recording tape. As a result of extensive evaluation, the polyester and the polycarbonate-type films were found to have the best overall properties for this task. Both types have similar physical properties such as good heat resistance, low moisture absorption and good flexibility under extremes of temperature, and neither of them contain plasticizers. Films without plasticizers are usually more stable over long periods of time.

Tensile Strength. Results of tensile tests on polyester, tensilized polyester, acetate and polycarbonate uncoated films are shown in Table II. Relationships between tensile stress, elongation and permanent set are shown in Figs. 3, 4 and 5.

Temperature Stability. Samples of the same uncoated films were exposed to a temperature of 160 F and 50 per cent RH for 240 hr. The regular polyester and polycarbonate films were unaffected. However, the tensilized polyester film curled and the acetate film curled and twisted, indicating poor dimensional stability under the referenced temperature and humidity conditions.

Reinforcing-Yarn Selection

The previously described tests on available magnetic recording tapes indicated that significant improvement could be obtained only by using a reinforcement consisting of ultra-fine glass or saponified acetate fibers, or a combination of both. Glass filaments are the strongest reinforcing material for plastics. They have good dielectric properties and are available in many forms such as chopped strands,

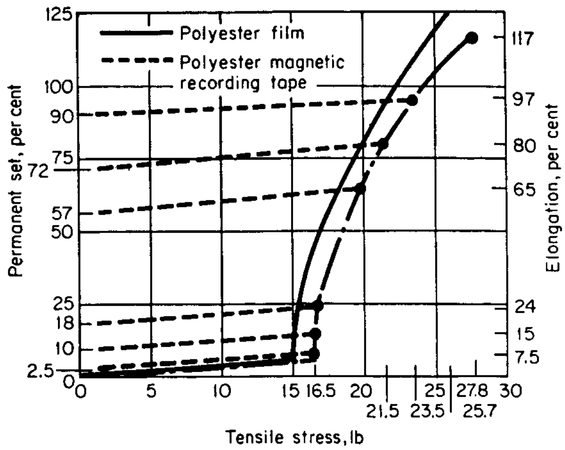

Fig. 3 — Relations between tensile stress, elongation and permanent set for polyester film and for polyester-film-backed magnetic recording tape. Film is 1 mil thick × 1 in. wide; tape is 1.3 mil thick × 1 in. wide.

Table II — Tensile Properties of Uncoated Plastics Films

Characteristics	Type of film				
	Regular polyester	Tensilized polyester	Cellulose acetate	Polycar-bonate	Military require-ments
Width, in.	1	1	1	1	1
Thickness (approx), mils	1	0.65	1	1	0.5-0.7
Tensile load, lb to break (average)	25.7	25.3	15.5	19.0	36
Elongation at break, per cent (average)	125.2	30	25.3	125	6 or less
Safe operating tensile load (approx), lb	15	15.2	12.8	10.5	35
Tensile strength longitudinal, psi (average)	25,700	38,923	15,500	19,000	60,000

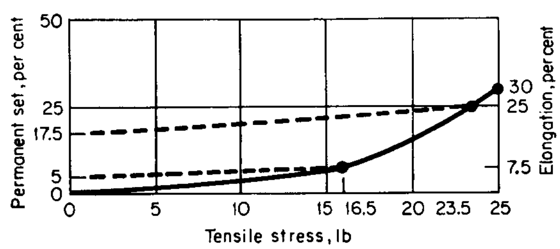

Fig. 4 — Relation between tensile-stress elongation and permanent set for typical tensilized polyester film. (Approximate thickness, 0.65 mil; width, 1 in.)

rovings, yarns and woven fabrics. Continuous multifilament yarns combined with a low twist produce the thinnest and strongest reinforcement. However, continuous flexing of the tape during the high-speed operation of data-processing systems may cause loss of strength in glass-reinforced tape-backing materials. In order to overcome this problem, it was found advisable to use a softer, nonabrasive organic yarn which could be woven in conjunction with glass yarns to serve as a cushion for the glass to prevent glass-to-glass friction.

Requirements were as follows: 1) thickness equal to or less than that of finest-size glass yarns, 2) tensile strength as close as possible to that of glass yarns, 3) extremely low elongation and permanent set under tensile stress, and 4) construction of multicontinuous filaments for maximum strength properties.

Tensile, elongation and permanent-set tests were conducted on viscose, polyamide, cellulose-acetate, saponified-acetate, acrylic, polyester and natural-silk yarns. In addition, consideration was given to the effect that polycarbonate resins and solvents would exert on the yarns. As a result of these tests it was found that saponified-acetate yarns had the highest tensile strength combined with lowest elongation and permanent set. Table III lists the results of the tests for both glass filament and saponified acetate yarn.

Fabric and Weave Development

A reinforcing fabric for high-stability tape should have a thickness of 0.7 mil or less in order to allow for an overlay film coating. It should have a high tensile strength of at least 40 lb lengthwise for a 1-mil-wide tape, a safety factor of at least 4 lb over the 36-lb requirements. Other requirements include a strength of at least 13 lb/in. cross-section transverse, elongation under 6 per cent and permanent set under 1 per cent. A very smooth surface is necessary for a perfectly smooth laminated film overlay and for the application of a smooth, polished magnetic coating.

An ideal theoretical fabric construction for this task, which would more than meet these requirements, was planned. It consisted of a woven fabric with at least 150 ends in the warp composed of No. 1800 multicontinuous-filament glass yarns having a very low twist woven with a filling consisting of 84-88 picks of either 12-denier multicontinuous-filament saponified-acetate yarn, or a multicontinuous-filament glass yarn of a finer size than the No. 1800. This fabric was to be woven with either a 5-shaft satin or a 4-shaft broken-twill weave construction. Because available commercial looms could not weave No. 1800 glass yarns in the warp, this weave was abandoned in favor of the following construction.

A small experimental apparatus for making plastic

Table III — Data on Ultra-Thin Reinforcing Yarns Used in the Development of High-Stability Magnetic Tapes

Property	Reinforcing Material		
	Saponified acetate		Glass
Size	20 (denier)	12 (denier)	No. 1800
Filaments	40	20	51
Twist	0.5	0.5	1
Yards/lb	223,288	372,145	180,000
Strength, lb	0.31	0.18	0.39
Elongation, per cent	4½	6	3
Thickness, mil	0.39	0.25	0.30

Table IV — Comparison of Experimental High-Stability Magnetic-Tape Backing with Best Commercial Grades

Property	Best commercial grade available for military use	USAELRDL experimental development
Thickness, mil	1	0.7
Width, in.	1	1
Ultimate strength, lb	26	62
Usable strength, lb	15	50
Ultimate elongation, per cent	>100	<5
Ultimate permanent set, per cent	> 90	0.5
Adhesion of magnetic oxide	fair	good

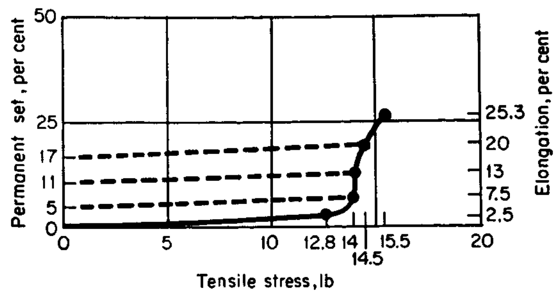

Fig. 5 — Relation between tensile stress, elongation and permanent set for representative cellulose-acetate film. (Approximate thickness, 1 mil; width, 1 in.)

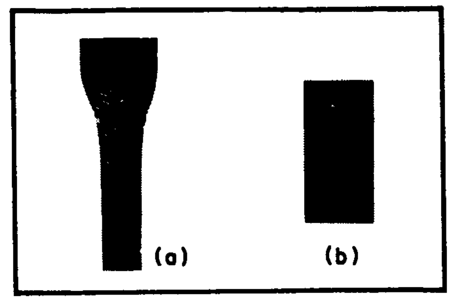

Fig. 6 — Dimensional stability under tensile load. (a) Conventional highest-military-grade magnetic tape, 1 in. wide × 1 mil thick, under tensile load of 25 lb, shows elongation of over 100 per cent and necking. (b) USAELRDL experimental improved high-stability tape, 1 in. wide × 0.7 mil thick, under tensile load of 50 lb, shows elongation of under 5 per cent and no necking.

magnetic-tape backing material reinforcements was built at USAELRDL. (It utilized a patented method for constructing an unwoven fabric; the filling was layered on top of the warp. This method was developed in earlier work on epoxy- or polyester-resin bonded glass-based filament-wound storage-battery cases). Short-length experimental samples closely meeting the ideal construction were made; these consisted of over 150 ends per inch of No. 1800 multi-continuous-filament glass yarns in the warp and 80 picks or cross threads of 12-denier saponified-acetate yarn in the filling. The experimental samples were made 1 in. wide and 10 in. long.

An Instron tensile-testing machine was used for testing polycarbonate film reinforced with this material. Results were as follows: a longitudinal tensile strength at break of 62 lb/in. and a transverse tensile strength per inch cross section of approximately 13½ lb. The material had an elongation of 3½ per cent and a permanent set of ½ per cent at 50-lb tensile stress. It had a thickness of 0.7 mil and had a very smooth face. Figure 6 and Table IV indicate that these results adequately meet the original objectives.

To date, only short lengths of this material have been made on a laboratory scale. Preliminary techniques have been developed, however, which would allow for the continuous production of greater lengths on automatic machinery.

Further work is required to improve the polycarbonate resin formulations in order to achieve better impregnating, laminating and calendering techniques. Also needed are more reliable magnetic-coating bonding systems, and the capability to produce longer lengths of uniform-quality magnetic tape.

General Electric Company has been pursuing this objective under USAELRDL Contract No. DA-36-039-AMC-02203 (E), titled "Reinforced Plastic Magnetic Tapes;" it seems that an ultra-thin high-stability magnetic recording tape as described in this article will be made available for military and commercial use in the near future. Studies are also now under way to use the reinforcement techniques in improved miniature flat flexible multiconductor cable now used in micromodule assemblies. ○○○

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